# Accelerated Insertion of Materials – Composites (AIM-C)

# Methodology

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# FOREWORD

The Accelerated Insertion of Materials – Composites (AIM-C) Methodology was jointly accomplished by Boeing and the U.S. Government under the guidance of NAVAIR, agent to the Defense Advanced Research Projects Agency (DARPA). Materials and Processes provide the foundation from which all Department of Defense (DoD) systems are built. New materials and designs are continuously being developed that have potential to provide significant improvement in system performance. However, due to the long and difficult process of maturing a material to the state where the designer's knowledge base is ready for use, few materials ever get transitioned. The Accelerated Insertion of Materials (AIM) program seeks to develop and validate new approaches for materials development and characterization that will accelerate the insertion of materials into hardware. Currently, the development of a designer knowledge base (which incorporates design allowables, reliability, manufacturing, reproducibility, and other essential information about materials) is a time consuming and costly endeavor, requiring thousands of tests and millions of dollars. Consequently, new material insertion into hardware is extremely difficult, typically taking 15-20 years if successful at all. Emerging efforts in materials modeling are leading to incremental improvements in specific areas, e.g., materials processing and mechanical behavior. The time between development of a new material and its implementation into production can be significantly shortened through a radical change in materials development methodologies. Introducing change with credibility to the users and certifiers is the exact mark of Accelerated Insertion of Materials – Composites (AIM-C).

Dr. Leo Christodoulou, the DARPA Program Manager, and Dr. Ray Meilunas, NAVAIR technical agent for the program, led integration of the effort. The AIM-C technical team was led by Gail Hahn, Dr. Karl M. Nelson, and Charles Saff of Boeing.

The objective of the Accelerated Insertion of Materials – Composites program was to demonstrate concepts, approaches, and tools that can accelerate the insertion of new materials into Department of Defense systems. The AIM-C concept involves the use of existing knowledge, analysis techniques, tests, and demonstration articles to develop a designer knowledge base (technical and production readiness information) from the outset, rather than the more traditional approach of sequential, unlinked research and development, sometimes locally optimized without a production-readiness transition path.

The objective of the AIM-C Methodology document is to provide a disciplined framework that captures the insertion problem statement, communicates the problem with the AIM-C system to the Integrated Technology/Product Team, and provides a suite of knowledge bases, analytical tools, and test/validation approaches for the team to use with confidence levels, risks/drivers, risk mitigation options, and links to further detail. The methodology follows a building block approach to achieve material insertion from material basic material characterization to certification in field applications. The methodology is intended to provide guidance at all levels of the certification process. This methodology can also be used without the AIM-C system.

The attachments to this volume were provided by American Optimal Decisions under the direction of Dr. Stanislav Uryasev.

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# 1. Introduction

The objective of the Accelerated Insertion of Materials Program is to provide the concepts, approach, and tools that can accelerate the insertion of composite materials onto Department of Defense (DoD) systems. The primary concepts used to enable accelerated insertion of materials include: the definition of an integrated product team (IPT) made up of both the technology and application development members; the use of a disciplined, coordinated maturation plan developed by this IPT; the combination of this maturation plan with existing knowledge, analysis tools, and test techniques, that enable accelerated development of a design knowledge base (DKB) from which maturity of the material system is determined; and the incorporation of an early key features fabrication and test article to focus the insertion, qualification, and certification efforts.

This document describes the approach taken to combine these concepts into a cohesive plan to accelerate maturation for successful insertion. During the development of this methodology, several analytical and test tools were developed to aid the IPT in developing their plan and in predicting and assessing the capabilities of the material system being introduced. The alpha version of the software system used to make these tools available is described in a Users' Manual provided as Appendix E to this report.

**1.1. Purpose** – The purpose of this volume is to present the methodology developed during the AIM-C program that can accelerate development of the design knowledge base (DKB) required for insertion of new materials into DoD systems. To accomplish this purpose, this report presents the key elements of the methodology, their content, how they are applied, and how they each contribute to the acceleration of insertion defined by the process. Before summarizing these key elements of the methodology there are some important concepts and relationships that must be defined.

**1.2. Qualification and Certification Definitions** – Throughout this document, the words qualification and certification will be used frequently. In general, unless the context provides a different interpretation, qualification will be used to mean the knowledge base developed on a material system, under particular process conditions, that demonstrates ability for meet a specific set of materials and process specifications. Certification will be used to refer to that knowledge base for a material system, fabrication process, and assembly procedure that meets the design requirements for a given component of a DoD system. In this definition set, qualification refers to the general acceptability and limitations of a material and process and certification refers to the ability of the material and process to perform as required in a specific application. These definitions are depicted in Figure 1.1 to show that the DKB developed by the AIM-C methodology consists of both data sets and while there is much shared between these datasets, specific applications often do require more data focused toward that application than is contained in the qualification dataset.

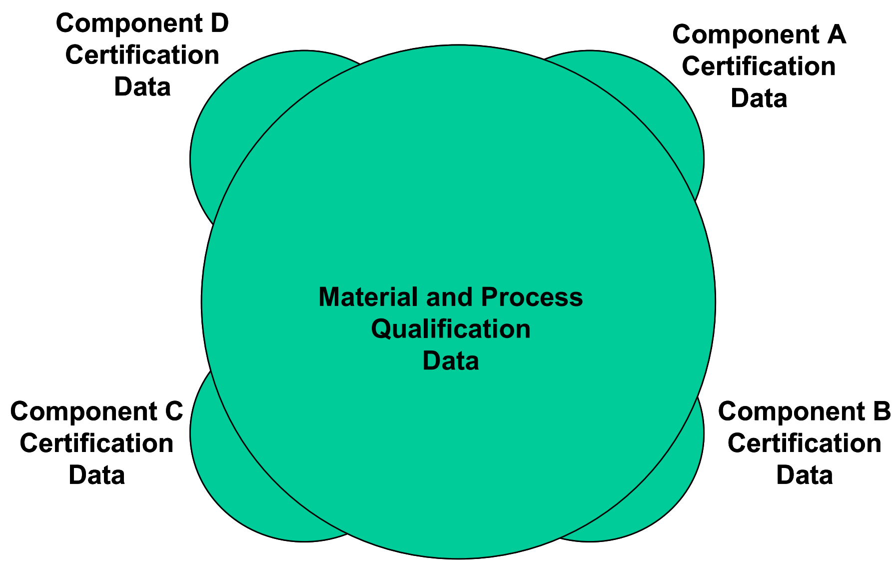



Figure 1.1 – The Design Knowledge Base Includes Both Qualification And Certification Data

The design knowledge base developed by the AIM-C system includes both qualification data and certification data for a specific application. This was intentionally done because accelerated qualification does not necessarily ensure accelerated insertion. The development of the DKB must go beyond qualification data to the certification data for the given application in order to ensure insertion.

## 1.3. Definition of Designer Knowledge Base

– The Design Knowledge Base as defined in Figure 1.2 includes both the qualification data for a given material and process as well as the additional testing (or analysis or existing knowledge) required to demonstrate that the use of this configuration, material, process, and assembly technique meet the design requirements for the application. As the material system is applied to additional components within even a given system the design knowledge base grows

The Design Knowledge Base (DKB) for AIM-C is defined as that knowledge that qualifies the materials for use and certifies the material for use in specific components of the aerospace system being to which it is applied. In general terms the elements of a design knowledge base for aerospace systems was defined by a set of experienced leaders of integrated product development teams as shown in Figure 1.2. This figure identifies everything that the IPT desired in the DKB, a portion of which was the focus of the AIM-C Phase 1 effort.


**Figure 1.2 Integrated Product Team's View of the Design Knowledge Base**

It should be noticed that while the AIM-C team focused on the materials and processing, manufacturing, and structural aspects of this DKB, we did address some elements of the Supportability and Miscellaneous categories. In general, the methodology in AIM-C was developed at high levels for the majority of the categories shown in Figure 1.2 and in depth for only a few of the elements shown. This allowed us to address the broad issues surrounding accelerated insertion, while still allowing us to focus on a few for more complete development. Those few that are more fully developed will pave the way toward the understanding required to extend the methodology to those elements that were addressed at only the higher levels.

## 1.4. Approach Overview

- The AIM-C approach is a multi-faceted plan to achieve safe, reliable, and rapid insertion of a material system into a DoD application with minimum risk of failure as the application approaches certification. The approach consists of assembling an integrated product team of the technology and application development members, assessing the readiness of the material for insertion, determining the requirements for the application, determining how the IPT will determine conformance with those requirements, gathering the knowledge by existing knowledge, test, and analysis to fulfill the requirements, assessing the conformance to requirements to determine if the knowledge gathered can be committed to the design knowledge base, or whether there are elements of the knowledge that require a different approach to ensure robustness.

There are gates at each step denoted by technology readiness level throughout the maturation process; however, there are two primary gates which are impacted most by AIM-C methodology. The first is the technology readiness review (TRL= 0) in which the IPT reaches the consensus that the material, its support materials, and its processes can be obtained with sufficient reproducibly that materials evaluated can be obtained using rudimentary requirements sheets to achieve the same pedigree. Another key review (TRL= 3) is at the time of the decision to proceed with the key features fabrication and test article(s). The materials, processes, and fabrication techniques must be capable of producing full-scale parts consistent with the designs for this application. Moreover, the key features article should demonstrate predictable geometry, response, strength, failure modes, and repair capabilities so that parts subsequently fabricated are not outside of tooling, processing, analysis, and repair capabilities.

As the AIM-C methodology is expressed in this report, please note that it is also applicable to the insertion of other technologies.

**1.4.1 Baseline Best Practices** – There were a number of Best Practices that were used in the development of the AIM-C methodology. These Boeing Best Practices include: Integrated Product Teams, Quality Function Deployment, Technology Readiness Levels, and ISO 9000. These practices and methods are defined here and their use within the AIM-C System is examined so that as the methodology is presented the use of these practices will be evident.

First, Integrated Product Teams are multi-disciplinary teams used throughout much of industry so that the knowledge base resident within each discipline can be brought to bear on the solution of a problem. Design solutions are a known compromise among affected disciplines and must not result in a design having a weakness overlooked by a discipline that is not represented. IPTs have been so successfully applied to design, build, and test of high performance products that they are now being introduced into manufacturing and most recently into technology development to reap similar gains to those achieved in design. The benefit of a multi-functional team to develop a DKB is the rapid assessment of the requirements imposed by affected disciplines in the development and evaluation of a new materials system even before it is ready for evaluation in trade studies.

One of the key points encountered during the course of the AIM-C Program was that IPTs doing technology development are usually separate from those doing product development. If these teams are going to successfully and rapidly insert a new material into an application, these two teams must become one team throughout the course of the insertion process. There are some very good arguments for maintaining the tie between the groups even after this point in the maturation process, but the key is that the applications team must know what the technology development team knows about the material and processes that are proposed and the technology team must know what the requirements, environments, and expectations of the materials will be in the proposed application. Neither team can be successful without the information from the other team. They must be made into one team.

Quality Functional Deployment, via a House of Quality concept is used in the AIM-C Program to simply document the relationship of requirements from the systems level to the component and technology levels. Insertion cannot be successful without meeting the requirements. Unsuccessful insertions have most often been stopped, not by a lack of knowledge about potential show stoppers, but because people did not carefully document and share the requirements for the component or material or manufacturing process or did not address the issues they knew existed. Without documentation these issues can be ignored to the peril of the insertion. An example of Quality Function Deployment is shown in Figure 1.3.

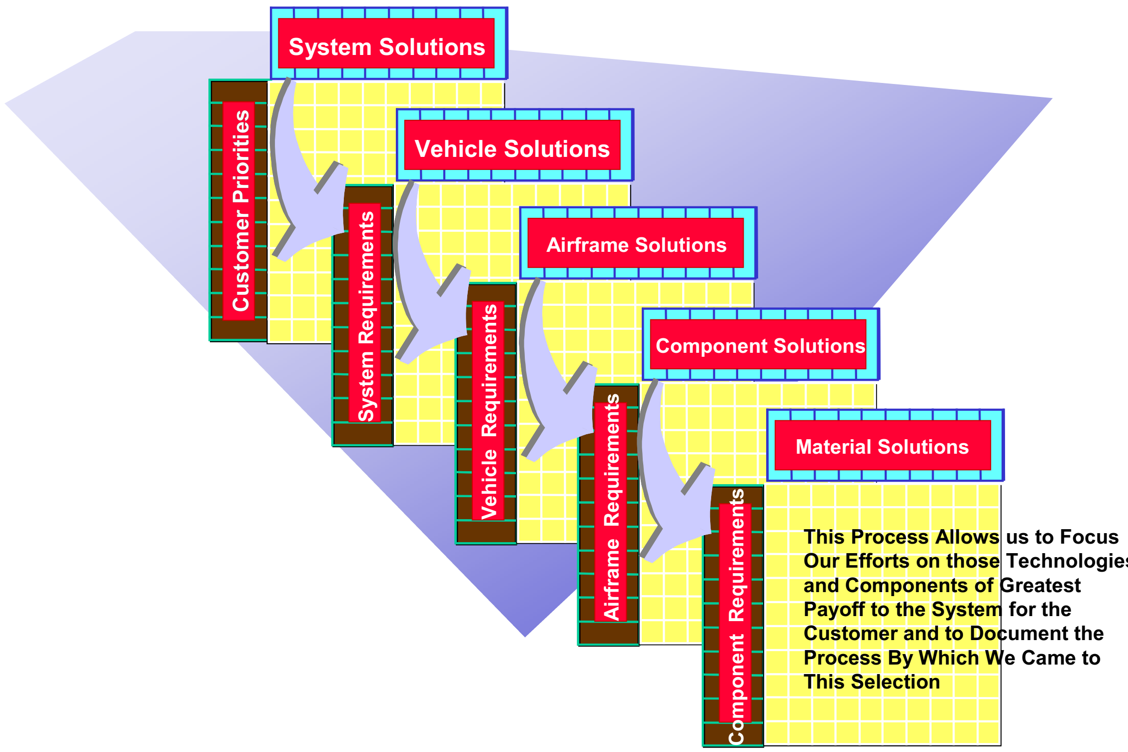



**Figure 1-3 Quality Function Deployment Is Used in AIM-C to Document the Linkage of System Level Requirements and Technology Requirements**

Evaluations of the applicability of a material or process to a specific component are best performed at the component level. But often it is difficult to interpret component level performance or benefit at the systems level. The house of quality process offers a tie between systems level requirements and payoffs to component level requirements and payoffs. But the relationship is not one to one. There are often component level requirements that limit how a material can perform or what processes can be used that impact the application of the material to the component. These are often requirements not defined at the systems level, but are part of the disciplinary knowledge base that comes through the IPT. Documenting these requirements is just as important as documenting the system level requirements and priorities.

The AIM-C Methodology used Technology Readiness Levels to track the maturation of the technology (material) through the insertion process. It did not take long as we formulated IPTs under the AIM-C Program to realize that although various disciplines used Technology Readiness Levels (TRLs) to track technology maturity, they did not interpret their TRLs consistently. Technology developers tended to start their TRLs with the discovery and documentation of a new capability. Application developers tended to start their TRLs at the stage when the technology was reproducible and when they could receive a specified product using an initial definition or specification. As shown in Figure 1.4, these TRL definitions are out of phase with one another.

| Technology Readiness Levels | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Technology Development** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | | | | |
| **Application Development** | | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

**Figure 1.4 The Discrepancy Between Technology Based TRLs And Application Based TRLs**

This discrepancy in definition between these two TRL definitions, led to confusion between the technology development teams and the application development teams. This discrepancy was not unique to AIM-C but has existed since the formation of the Readiness Level definitions. The Air Force has always focused on a more applications oriented set of TRLs fostered by Dr. Jack Lincoln the specialist in airframe certification for so many years. At the same time NASA used a set of TRLs that was more closely aligned with the technology development TRLs, since they were so often looking at embryonic technologies at the research level.

Once the discrepancy was realized, a single set of Technology Readiness Levels was determined focused on the application as shown in Figure 1.5. Technology Readiness Level 0 was defined to encompass all the development work from discovery to the development of a reproducible process at the laboratory or pilot plant scale. At TRL of 0, an IPT between the technology development team and the application development team is formed and a Technology Readiness Review is held to determine that its properties and projected costs are attractive, that the technology (or material) is reproducible, and that the system ready to begin the AIM-C insertion process. If that review is positive for the material, then that team continues to work toward maturation of the system to insertion. While the process works through all TRL levels, it is really most focused on levels 0-4 for the AIM-C program because that is where most of the risk reduction is done that eliminates the showstoppers and risks for insertion to the application. Levels 5-8 deal with design certification and readiness for production. While levels 9-10 deal with production and support for the product.

| Technology Readiness Levels | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Technology Development | 0.25 | 0.50 | 0.75 | 1 | 2 | 3 | 4 | 5 | 6 | | | | |
| | | | | One Team | | | | | | | | | |
| Application Development | | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

**Figure 1.5 The Common TRL Numbering Scheme Adopted by AIM-C**

Once a common definition for the meaning of each TRL was defined, then the progress of the entire IPT could be tracked according to a single TRL-based chart. This chart is shown in Figure 1.6, but its use is described in greater detail in later sections of this report. This chart became the IPT's primary means of assessing the maturation of a material, or technology, through insertion.

| TRL | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Application/ Design | | | | | | | | | | | |
| Certification | | | | | | | | | | | |
| Assembly/ Quality | | | | | | | | | | | |
| Survivability | | | | | | | | | | | |
| Fabrication/ Quality | | | | | | | | | | | |
| Supportability | | | | | | | | | | | |
| Structures & Durability | | | | | | | | | | | |
| Materials | | | | | | | | | | | |
| Cost/Schedule/ Benefits | | | | | | | | | | | |
| Intellectual Rights | | | | | | | | | | | |
| | | | | | | | | | | | |
| IPT Reviews | Technology Insertion Readiness | System Requirements | Material & Process Readiness | Key Features Design and Fabrication | Key Features Test/ Conformance | Preliminary Design | Critical Design/ Ground Test Readiness | Flight Test Readiness | Production Readiness | Operational Readiness | Decommission and Disposal Readiness |

**Figure 1.6 Technology Readiness Chart for a Materials Insertion IPT**

ISO 9000 concepts were used to ensure that in each discipline at each TRL, there was an approach and a plan for how the IPT was going to achieve conformance with the requirements for the application and an assessment of the conformance of the knowledge (existing data, analysis, heuristic data, or test data) with the requirements before the data was committed to the Design Knowledge Base (DKB). Each discipline develops its own approach to meeting the requirements of the component, but the IPT has to approve the integrated plan including the approach to achieving conformance and assuring that each discipline will get knowledge consistent with its needs at each stage. The IPT must also validate conformance was achieved prior to committing the data to the DKB. Therefore, the approach for each element of IPT plan for conformance with requirements, there was an approach defined, data gathered, an assessment of the data gathered against the requirements and a committal to the DKB or a rework (or changed approach) in order to achieve conformance for that element of the plan.

The overall approach applied for each element of the plan is shown in Figure 1.7. This approach to DKB development used in AIM-C is entirely consistent with the concepts of ISO 9000. To have an approach defined prior to application, to monitor the application of the process, measure results to ascertain conformance, and to apply corrective measures if conformance is not achieved are all consistent with ISO 9000 concepts. The serendipitous product of this approach is that any DKB developed by the AIM-C approach is readily documented as ISO 9000 compliant.

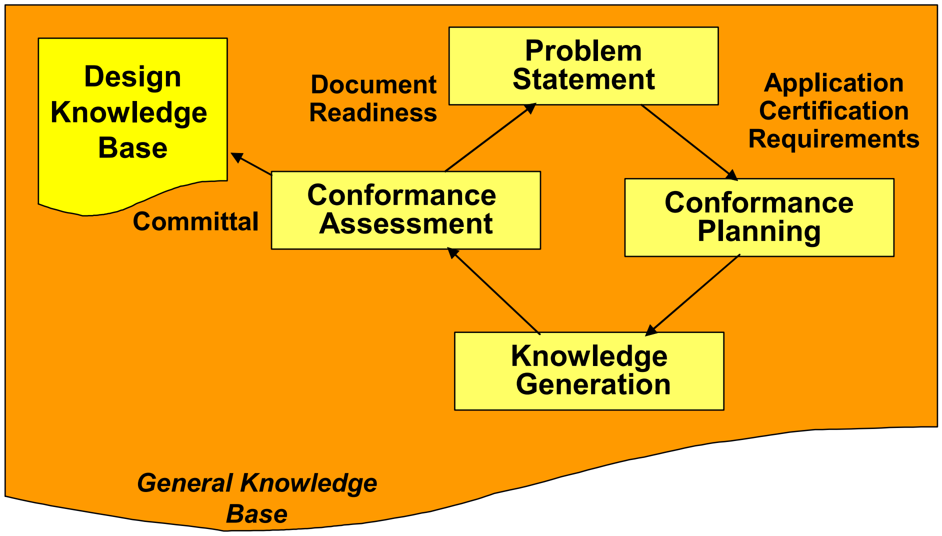



**Figure 1.7 The AIM-C Process for Design Knowledge Base Development**

**1.4.2 Methodology Ground Rules** - Methodology provides the disciplined process that captures the designer's problem statement, communications the problem to the integrated technology/product team via the AIM-C system, and provides solutions for the designer with confidence levels, risks/drivers, risk mitigation options, and links to further detail. Our methodology is built on the following ground rules:

a. Integrate the building block approach to insertion.
b. Involve each discipline in maturation.
c. Focus tests on needs identified by considering existing knowledge and analyses.
d. Target long lead concerns, unknowns, and areas predicted to be sensitive to changes in materials, processing, or environmental parameters

The methodology is imparted to users via the following formats:

a. User interface screens/prompts
b. Linked text files
c. Software documentation
d. Training
e. Methodology/process definition and change procedures document

The foundational practice used in the development of the AIM-C approach was the Building Block approach to structural maturity that has been used since the introduction of composite materials into aircraft structure before we had the kind of accurate and comprehensive toolset that we now have for these materials. Faced with the need to be able to certify such structures from a single static and fatigue test as had been done with metallic structures (and because the airframes were then primarily metallic), application development teams, in conjunction with certification agents, developed a method based on increasing complexity of testing that linked the final airframe test through component tests, subcomponent tests, critical detail tests, element tests, to the coupon level tests which could be used to wring out the performance limits of the materials under various service environments. The basic Building Block Approach is shown in Figure 1.8.

The Basic Building Block Approach as presented in Figure 1.8 is a solid and secure foundation for certification of aircraft structures and makes no assumptions about the level of analytical capability available since it was developed when composite analysis techniques were unproven. However, AIM-C also applies validated analysis tools that can radically reduce the amount of testing required to achieve the same level of confidence demonstrated in the Building Block Approach in an accelerated manner as shown in Figure 1.9. Here instead of relying on test data from each level of complexity to feed the next, the focus is on developing the database needed to support the fabrication and test of a full-scale key feature test article. This test article is used to ascertain readiness for certification of the application of the material, processes, fabrication technique, assemble, and the design.

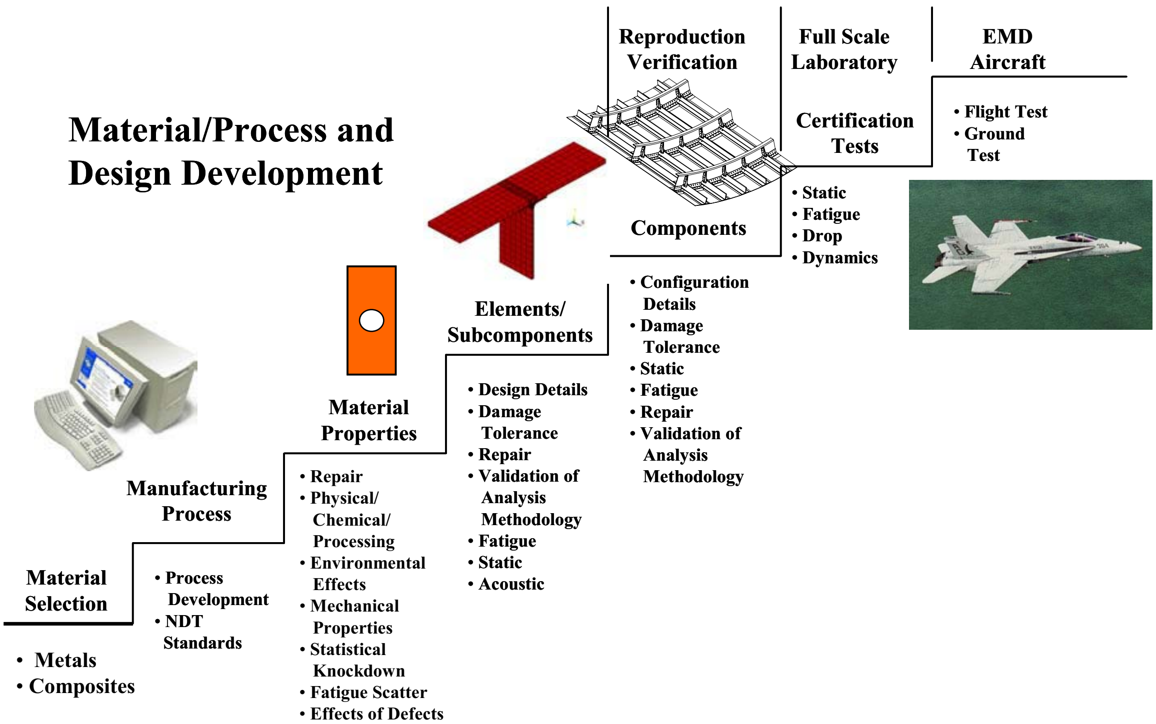



**Figure 1.8 Conventional Building Block Approach to Airframe Certification**

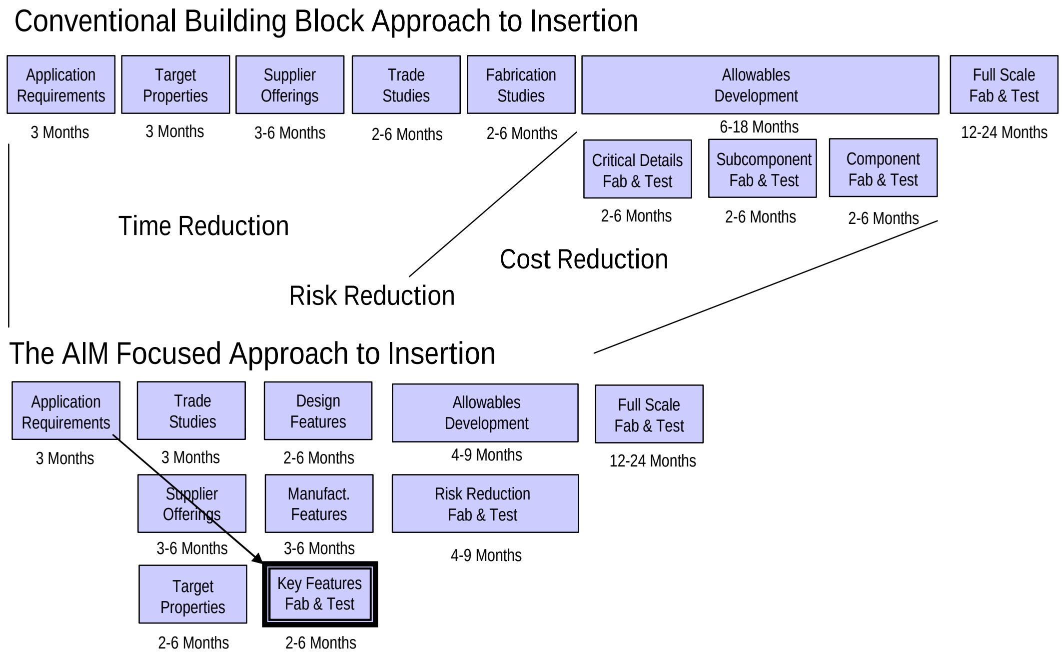



**Figure 1.9 Comparison of the Conventional Building Block Approach with the AIM-C Approach**

The AIM-C approach differs from the conventional Building Block approach in two ways to accelerate insertion of a new material system. First, and most obviously, the multi-disciplinary, integrated product team concept develops the DKB much more rapidly than the sequential Building Block approach. This is true even without acknowledging the effect of analysis capability, but is dependent only on the ability to cover a number of needs with a few tests when they are jointly planned. Second, the focus on the key features fabrication and test article provides a focus for the early knowledge development, a gate for the technology into certification, and a source of failure mode and repair information that can help focus and reduce certification testing.

**1.4.3 AIM-C Features to Accelerate Insertions –** A summary of the features introduced in the AIM-C approach is given in Figure 1.10.

## Accelerated Insertion of Materials Is Achieved in AIM-C Methodology by

- Focusing on Real Insertion Needs (Designer Knowledge Base)
- Approach for coordinated use of
  - Existing Knowledge
  - Validated Analysis tools
  - Focused Testing
- Application of Physics Based Material & Structural Analysis Methods
- Use of Integrated Engineering Processes & Simulations
- Uncertainty Analysis and Management
  - Early Feature Based Demonstration
  - Tracking of Variability and Error Propagation Across Scales
- Rework Avoidance
- Disciplined approach for pedigree management

**Orchestrated Knowledge Management to efficiently tie together the above elements to DKB**

**Figure 1.10 AIM-C Features to Accelerate Insertion**

**1.5 Summary -** The AIM-C approach integrations these best practices, ground rules and acceleration methodologies into a process that can accelerate the risk reduction required to safely insert new materials into applications.

AIM-C methodology accelerates the insertion of materials providing a disciplined approach toward developing the design knowledge base as rapidly as possible to enable the fabrication of a key features test article that focuses the certification testing on the failure modes and loading conditions that control the design of the component. At the IPT level, and for each of the disciplines that make up the IPT, the approach revolves around problem definition to focus the team, conformance planning to determine as a team how they will pursue the DKB required to fulfill the requirements of the application being considered, knowledge gathering, conformance assessment, and committal of the data to the DKB and documentation of a remaining issues for maturity cycles or other approaches applied to meet the conformance criteria. This philosophy is consistent with that used in the ISO 9000 standards.

The AIM-C philosophy, with its focus on the key features fabrication and test article to guide development toward those features which drive design requirements, has embodied in it a planned rework cycle. In fact the Problem Statement to Conformance Planning, to Knowledge Development, to Conformance Assessment, to Committal or refinement has embedded within it a planned cycle, while working to minimize the reliance on that "rework" cycle in certification. The objective of this philosophy is to provide a gate for the technology at the key features test article to evaluate and mitigate the risks associated with successful certification. This is crucial. In examining past insertion failures, we found that the most expensive failures came when the technology could not be scaled-up to the sizes, or geometric requirements for the design. These lessons, learned the hard expensive way, led to incorporation of the key features full scale test article early in the development process and to evaluate risks before going further with certification.

Just to emphasize this point further, Figure 1.11 shows the benefit of understanding the new material and application in the context of experience as one progresses through the technology readiness levels toward production. Figure 1.11 shows an element called distance from experience. The further one deviates from known capabilities, the greater risk of rework is incurred. Therefore, the AIM-C philosophy is based on gaining experience with the technology as early as possible to develop as much knowledge as possible focused on the applications being considered so that the deviation from the knowledge base is as small as possible throughout the development and insertion process. This reduces risk and reduces the penalty associated with discovering that the technology was not as ready or as capable as was originally perceived.

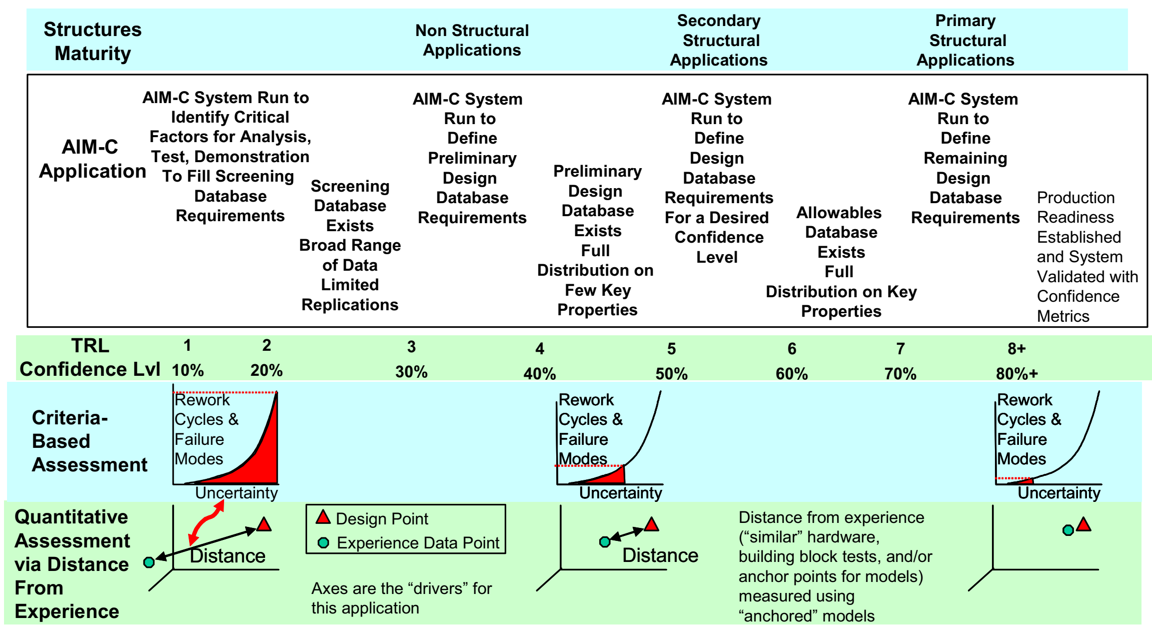



**Figure 1.11 The AIM-C Methodology Impact on Traditional Certification from a Structures Perspective**

The purpose of the AIM-C approach is to ensure that the distance between the insertion case and the design knowledge base is small so that risks are controlled and unknown risks are identified and mitigated early in the qualification and certification process.

# 2. Problem Statement

The problem statement bounds the qualification program by providing a clear statement of the desired outcome and success criteria. It delineates responsibilities for appropriate aspects of the program to the material supplier, processor, test house, prime contractor and the customer. It serves as the foundation for many decisions and as the basis of the business case as well as divergence and risk analyses on which the technical acceptability matrix is built. When the problem statement is found to be deficient in specificity, or to be so specific as to limit approaches, or to have a clear technical error, modifications must be made with the agreement of the qualification participants and stakeholders.

The Integrated Product Team (IPT) often encounters a situation in which there are several candidate materials for a given application having multiple fabrication process possibilities. Choosing the proper material and process combination for the application is made more difficult because very often the database supporting each combination is very lightly populated and rarely uses the same lay-ups, fibers, or processes to fabricate the specimens from which the dataset was developed

Having defined issues and the desired outcome, the problem statement is written to clearly describe and define the problem. It is the critical prerequisite to initiating the qualification program.

An effective problem statement contains a number of elements. First, the problem statement must state a clearly defined objective. It also must define what is new with the particular material or process under evaluation and indicate to what it is being compared (for instance, in terms of property thresholds or an existing baseline defined by a particular database). The problem statement gives a definition of the equivalence required for a stated objective. The statement should include cost targets for testing, for procurement, for fabrication, for assembly and for quality systems to be properly bounded. The problem statement also focuses on how the material or process will be used. The problem statement, together with the divergence assessment and business case, establishes the boundaries of the qualification effort before the qualification program begins.

Sample problem statements are as follows:

- A contract requirement for a prepreg second source has been established. The objective of the qualification program is to qualify a second source prepreg system in which the second source resin has the same formulation as the original resin. In order to meet the formulation requirement, the second source supplier is required to license the resin from the original supplier. There will be no changes in fiber reinforcement. The same laminate orientations and fabrication approaches are used as those used for the original material source.

- Program prepreg requirements have grown to the point where the prepreg supplier must add additional qualified prepreg lines to meet demand. The objective of the qualification program is to qualify a new prepreg line. There will be no changes in resin mixing or fiber reinforcement.

- A prepreg supplier is notified by one of their resin constituent raw material suppliers that they are relocating the fabrication of the raw material. The objective of the qualification program is to qualify the new raw material fabrication site.

- The current prepreg-based process for making a part (or class of parts) has unacceptable scrap/rework rates due to out-of-tolerance profile conditions. A resin transfer molded process offers the dimensional control needed. The objective of the qualification program is to qualify this new process.

- The program desires a second fiber source for the baseline AS4 and IM7 fibers in order to achieve the benefits of a true competitive pricing environment. The new fibers in this case would not be licensed, but would have properties equivalent to those of the current fiber system. The basis for comparison will be the results of the original material qualification for the baseline products rather than the material purchase specification values or the current quality control properties being achieved with the material. The aircraft is designed to the material qualification properties. Variations from those properties would require reexamining the structural analyses and would probably eliminate any cost savings that could be realized. The baseline resin will be utilized. For the materials to be classified as equivalent, the modulus of the new prepreg must match the original modulus within industry-typical modulus statistical boundaries and the failure strains must be equivalent or greater.

## Practical Check of Problem Statement

- Is the problem statement (or application requirements documentation) captured in writing like a story problem?

- Is the objective clearly identified?

- Has the information necessary to solve the problem been identified?

- Has extraneous information been identified as such?

• Is this statement an identification of the problem or erroneously identification of a desired or anticipated solution?

• Are the critical checks/issues being captured for the next stage of the qualification/certification process, conformance planning?

• Are all of the appropriate stakeholders (including customers) involved and concurring to the statement?

• Have applicable assumptions, compromises, and contingencies been identified in writing?

• Is the problem statement in a useable form for a Strengths, Weaknesses, Opportunities, Threats (SWOT) analysis?

• Was a check made of past showstoppers/major issues related to problem statements of a similar nature? (This will be addressed in more detail in planning for conformance, but should also be addressed in the problem statement to help achieve early understanding among stakeholders.)

• Does the problem statement consider the applicable inputs needed from the following readiness level categories?

Application
Certification
Legal Considerations
Design
Assembly
Design Allowables Development/Structures
Materials and Process Development
Fabrication/Producibility
Supportability
Business Case

# 3. Conformance Planning

Conformance planning addresses what is known and what is unknown relative to the problem statement objectives and requirements. A series of questions are answered to form the foundation of conformance activities and from which conformance activity/area/item check sheets are generated (Figure 3.1).

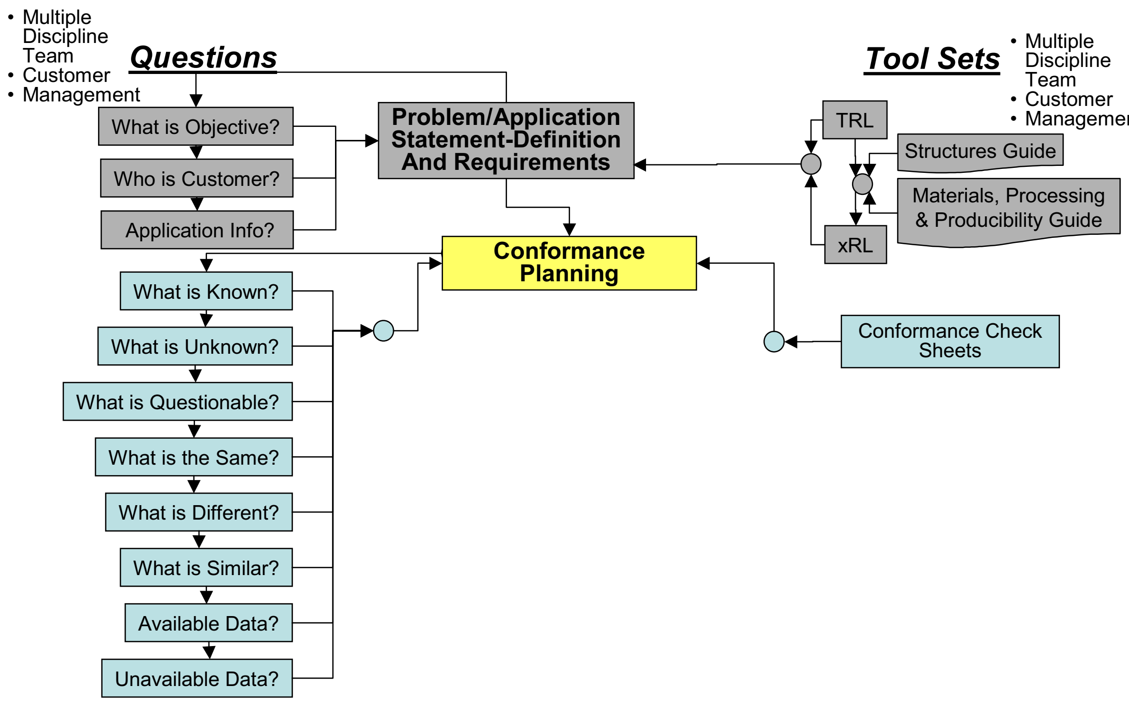



**Figure 3.1 Top Level Conformance Planning Activities**

Different questions are asked when starting the conformance planning activities. These questions establish what is known and what is unknown for conformance to the problem statement objectives and requirements. It is the first step in establishing what has to be conducted by multiple disciplines for qualification and certification of a new material and/or process. The answers form the nucleus of what existing information/data/ knowledge can be used and what has to be generated.

The process for conformance planning (Figure 3.2) includes asking questions about the detailed xRL exit criteria on how conformance will be met for materials, structures and producibility. A key item is that an Integrated Product Team (IPT) conducts this process with concurrence of results by the whole IPT and by customers. The outputs from these planning activities are a series of check sheets for materials, structures and producibility conformance activities listing what, when and how activities will be conducted.

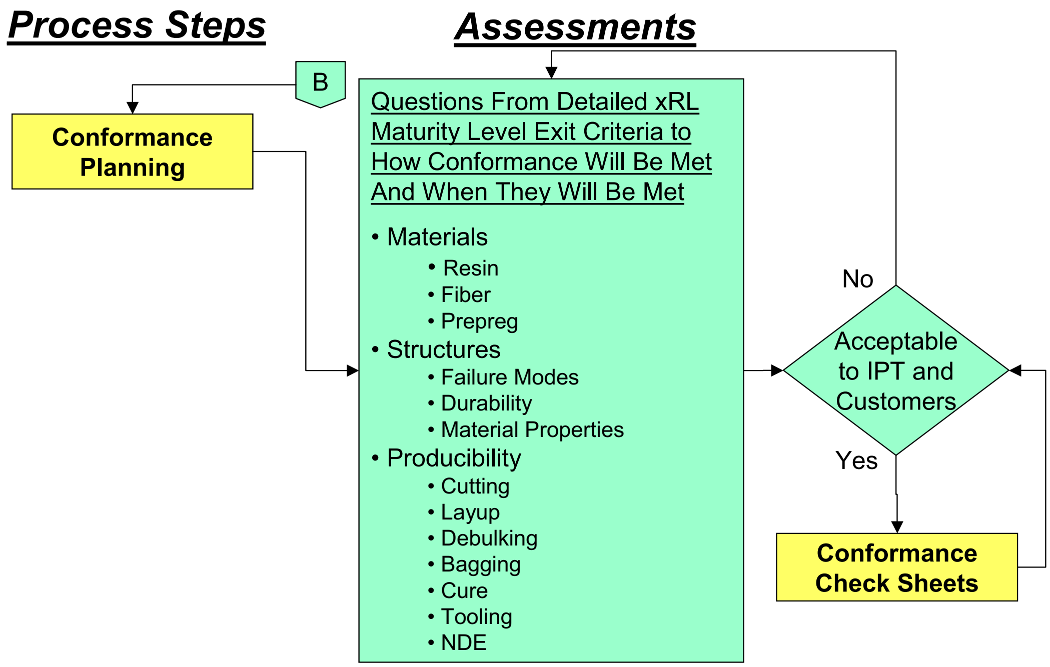



**Figure 3.2 Conformance Planning Process**

These are a series of steps in this question answering process. The following items outline these steps.

- Gather existing knowledge: heuristics, lessons learned, information on similar problems or applications, public literature, analyses, and test results.
- Address every question/requirement. Address functional/disciplinary issues. Address interdisciplinary issues/assumptions/decisions as an IPT with all stakeholders involved.
- Determine divergence risk on existing information.
- Assess the conformance of existing knowledge with requirements.
- Handle Error and Uncertainty (See Methodology Section 9). Determine additional knowledge needed based on knowledge gaps, unacceptable risk, etc.
  - Understand and Classify Potential Uncertainty Sources
  - Determine What Is Important
  - Limit Uncertainty/Variation by Design and /or Process
  - Quantify Variation (Monte Carlo Simulation or Test)
- Address long lead items.
- Perform prudent studies to flesh out the conformance plan – could include trials, test, analyses, and combinations thereof.
- Prepare the conformance plan. Initiate efforts as applicable, while studies are underway to address details of the next maturity level of the plan.
- Address cost, schedule, and technical risk.
- Set up criterion for committal gates – analytical tools, test methods, guidelines, specifications, knowledge committal, maturity assessment, etc.

- Secure commitment to the plan from all stakeholders.
- Address the business case as appropriate.

Conformance check sheets are generated by individual disciplines addressing the details of what needs to be conducted to achieve conformance to problem statement objectives and requirements. Figure 3. 3 shows a listing of the different types of conformance check sheets for three disciplines. Figure 3.4 shows a representative check sheet example for resin. Detailed check sheets for the same three disciplines given in Figure 3 are shown in Appendix D.

- **Structures**
  - Application Failure Modes
  - Material Properties
  - Durability
- **Materials**
  - Fiber
  - Resin
  - Prepreg
- **Producibility**
  - Cutting
  - Layup
  - Debulking
  - Cure
  - In-Process Quality
  - Final Part Quality

**Figure 3. 3 Conformance Check Sheet Areas**

| RESIN - THERMOSET | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | How Obtained, Test or Anlaysis | Test/Analysis Identification |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Uncured Resin** | | | | | | | | | | | | | | |
| Viscosity | ➢ | x | x | x | x | x | | | | | | | Test | ASTM D 4473 |
| Reaction Rate | ➢ | x | x | x | x | x | | | | | | | Test | DSC via ASTM D 3418 and ISO 11357 |
| Heat of Reaction | ➢ | x | x | x | x | x | | | | | | | Test | DSC via ASTM D 3418 and ISO 11357 |
| Volatile Content/evolution temperature | ➢ | x | x | x | x | x | | | | | | | Test | TGA |
| Volatile Type | ➢ | x | x | | | | | | | | | | Test/product knowledg | FTIR/Formula access |
| Volatile Vapor Pressure | | | x | | | | | | | | | | Test | |
| Resin Cost | | x | x | x | x | x | | | | | | | Specified Value | Based on vender input |
| Density | | | x | x | x | x | | | | | | | Analysis | Based on cured/uncured test data |
| Resin Cure Shrinkage | | | | x | | | | | | | | | Analysis | Based on volumetric test data |
| CTE | | | | | | | | | | | | | Analysis | based on TMA or linear dilatometer data |
| Thermal Conductivity | | | x | | | | | | | | | | Analysis | Assumed to be that of cured resin |
| Specific Heat | | | x | | | | | | | | | | Analysis | Assumed to be that of cured resin |
| Kinetics Model | | | x | x | | | | | | | | | Analysis | Based on Reaction Rate |
| Viscosity Model | | | x | x | | | | | | | | | Analysis | Based on Kinetics Model, Test Data |
| Intellectual Property Issues | | x | x | x | x | x | | | | | | | | |
| HPLC | ➢ | x | x | x | x | x | | | | | | | Test | |
| FTIR | ➢ | x | x | x | x | x | | | | | | | Test | |
| Health and Safety Information | | x | x | | | | | | | | | | MSDS | |
| Morphology | | | x | | | | | | | | | | | |
| Ingredient Suppliers | | | x | x | x | x | | | | | | | | |
| **Cured Resin** | | | | | | | | | | | | | | |
| Tensile Stress to Failure | | x | x | | | | | | | | | | Test | ASTM D638 |
| Young's Modulus, Tensile | | x | x | | | | | | | | | | Test | ASTM D638 |
| Tensile Strain to Failure | | x | x | | | | | | | | | | Test | ASTM D638 |
| Glass Transition Temperature | | x | x | | | | | | | | | | Test | ASTM D3418 |
| Volatile Content | ➢ | x | x | x | x | x | | | | | | | Test | ASTM D3530 |
| Density | ➢ | x | x | x | x | x | | | | | | | Test | ASTM D-792 |
| Modulus as a Function of Temp | | | | x | | | | | | | | | Test | Function of Temp and Degree of Cure |
| CTE | | | | x | | | | | | | | | Test | ASTM E831 or linear diletometry |
| Thermal Conductivity | | | | x | | | | | | | | | Test | ASTM C177 |
| Solvent Resistance | | | x | | | | | | | | | | Test | ASTM D543 |
| Specific Heat | | | | x | | | | | | | | | Test | ASTM E-1269 or Modulated DSC |
| Bulk Modulus | | | | x | | | | | | | | | Analysis | |
| Shear Modulus | | | | x | | | | | | | | | Test | ASTM E143 |
| Poisson's Ratio | | | x | | | | | | | | | | Test | ASTM E143 (Room Temp) |
| Coefficient of Moisture expansion | | | | x | | | | | | | | | Test | No Standard |
| Compression Strength | | | | x | | | | | | | | | Test | ASTM D695 |
| Compression Modulus | | | | x | | | | | | | | | Test | ASTM D695 |
| Mass Transfer Properties | | | | x | | | | | | | | | Test | /eight gain vs time, Ficks Law and modelir |
| Viscoelastic Properties | | | | | x | | | | | | | | Analysis | |
| Toughness Properties | | | | x | | | | | | | | | Test | |
| Tg, Wet | | x | x | | | | | | | | | | Test | ASTM D3418 |
| CME | | | | x | | | | | | | | | Test | |
| Solvent (Moisture) Diffusivity | | | | x | | | | | | | | | Test | |
| Solvent Resistance | | | x | | | | | | | | | | Test | |

**Figure 3.4 Example Conformance Check Sheet**

# 4. Knowledge Generation

This section is divided into discussion of (1) general information on knowledge generation for an overall design knowledge base, (2) dealing with knowledge from heuristics, lessons learned, etc., (3) analysis, (4) test, (5) combinations of knowledge, analysis, and test, and (6) combinations of any category mix from different sources or different stages of maturity.

## 4.1 General

It is very important to reveal concerns early – cost, schedule, and technical – so that unknowns can be addressed and risk mitigation plans can be exercised if necessary. As such, it is good to ask *and document*, the handling of questions which interrogate every aspect of the material, process, application, threat, and opportunity. Performing this type of assessment requires different perspectives – assembly personnel, business personnel, customers, designers, fabricators, manufacturing personnel, system maintainers, suppliers, technologists, etc.

The information in this methodology and in the AIM-C system is helpful to performing strength, weakness, opportunities, and threats (SWOT) analyses on the materials, processes, and applications considered.

Thorough documentation is a very necessary practice. Seldom are the developers and implementers available when a system is in production, or for that matter, headed toward decommissioning and disposal. Sometimes it is hardly weeks or months before obsolescence, change in environmental laws, or business instability in a key or sole supplier creates the need for re-evaluation or re-qualification of some aspect of the insertion case.

## 4.2 Knowledge

Existing knowledge includes customer and supplier references, related quality records, previous databases, and lessons learned. It is important when using existing knowledge in an insertion assessment to understand and document the source and the details surrounding the situation in which the knowledge was first generated or understood. It is also important to identify the difference between opinion and scientific observation.

As discussed in Section 1, it is important to illuminate understanding with the quantitative assessment of distance from experience, Figure 4-1.

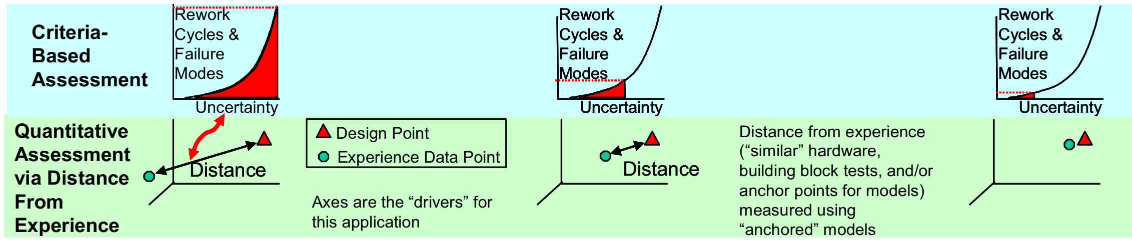



**Figure 4-1 Assessment of Distance from Experience and Its Impact in Planning for Technology Insertion**

## 4.3 Analysis

When using analysis to mature technology, one must understand the pedigree of the algorithms used, the assumptions made, the uncertainties introduced, the pedigree of the input files, and the validation performed to date. Similar to distance from experience expressed in Figure 1 for previous knowledge, is the assessment of the similarity of the analysis validation case to the particular application of the analysis method at the time of use for maturing technology/applications for insertion.

As with heuristic knowledge and with test data, it is imperative to document the input, the analytical method configuration control, the operating system used, and any validation planned or completed.

## 4.4 Test

When establishing the qualification test matrix, the plan should be sequenced to identify critical design and manufacturing properties early so that testing and analysis can be modified or discontinued if success criteria are not met. This will minimize qualification costs and risk by eliminating inadequate alternate materials and/or processes early in the test program before more expensive qualification tests are performed.

### 4.4.1 Specimen Traceability

When setting up the test program, the coordinator (typically the airframer) must decide how much traceability is desired and how easy is recovery of this information. In a typical test program, traceability information is generated by the resin and fiber manufacturers (batch numbers), the prepregger (batch and roll #), the part fabricator (panel # and autoclave cycle) and the specimen machining area (specimen identification or ID). Similar information must be included if using analysis.

Use the specimen ID to easily determine the location of the specimen in the as-fabricated panel and compare that location to the NDE data for the panel and the panel ply lay-up verification photomicrographs. For example, if two specimens produced low values in a test and they were cut from the same panel right next to one another it points to a possible problem in that area of the panel. The specimen ID should also be traceable to the actual autoclave cycle completed and any anomalies that occurred there as well as the roll of material used to make the panel and any variances that occurred in the lay-up or bagging of the panel. Traceability to the material batch number and the specific roll is important for problems that can be traced back to bad material as well as for calculation for equivalence.

### 4.4.2 Specimen Fabrication

With the move to outsource more testing and fabrication, control and documentation are becoming more important. For in-house fabrication a late change typically just impacts the number of hours used, whereas a late change for an out of house contractor may require modifications to the contract. More important is just agreeing to the work that is to be completed and the methods since it is unlikely you will be able to "stop by" the fabrication house to see if they are doing what you intend. All of the following items have become issues in at least one past material testing effort and should be defined prior to beginning fabrication.

- Are extra specimens required for testing/machine mistakes/investigate other environments?
- Is the fabricator responsible for verifying the panel lay-ups with photomicrographs or is a planning check off acceptable?
- Who is responsible for remaking substandard panels?
- Who supplies the material and remake material?
- Is the fabricator responsible for NDE?
- What is the inspection technique to be utilized and what are the criteria? Will it be tighter than the standard criteria? (dB loss for through-transmission ultrasonic inspection)
- How much edge trim is required?
- Is it acceptable to fabricate all of the specimens of a test type in a single panel or do you what them cured in two panels in different autoclave cure runs to create two fabrication "batches"?
- How many thermocouples are required?
- Do you want an actual cure cycle data submitted?
- Is the fabricator responsible for submitting the material batches used?
- Is it acceptable to use two rolls of material in a panel? Two batches?
- Is the cure cycle controlled with the free air temperature or the part/tool temperature?
- Is free air temperature overshoot permitted or required when approaching hold temperatures?
- What are tolerances on cure cycle hold time and temperatures as well as ramp rates?
- When is substitution in the bagging material sequence permitted?
- Is the part vacuum level taken from the active line or is a static port used?
- What number of vacuum ports is required per panel size?
- When the cycle calls out a vacuum only portion, is a minimal (10 psi) autoclave pressure permissible to improve heat transfer?
- Are autoclave abort and reprocessing procedures permissible?

- Is water jet cutting of specimens acceptable or must they be cut with a diamond wheel saw? Are cutting fluids permitted?
- Is a picture required of the specimen layout and reconstruction prior to panel cutting or is another method of specimen location in the panel required (angled lines draw on the panel for example)?
- What are the machining tolerances?

### 4.4.3 Specimen Testing

Specimen testing is moving away from the full service in-house test labs toward out-of-house entities that may or may not provide what you are expecting. The best way to limit the number of surprises and increase the usefulness of the data is to agree up front on what the testing house is to provide. The following is a partial list of issues that have come up in the past. This list assumes a test methods document or list of standard test methods have already been agreed to. Even standard methods often leave substantial room for interpretation.

- What methods will be used for moisturization? Water boil or humidity cabinet? Must the specimen be dried prior to moisturization?
- Are specimens to be conditioned until weight equilibrium?
- Is the moisture content at failure reported (as distinguished from the moisture content prior to test) Note that high temperature test specimens (especially those tested at 350 deg F or greater) can have significant desorption prior to failure.
- Are the room temperature specimens to be dried to the point of weight stabilization? This will typically take about three weeks.
- Are traveler specimens going to be used to monitor the moisture weight gain?
- Is the data to be supplied in MS Excel or is MS Word acceptable?
- Is a photo of each test set-up required?
- Are photos of each failed specimen required? A typical failure?
- Are plots of each specimen's load response required or just the failure levels? Strain gage response or loading head travel?
- Which strain reporting points are required to be loaded into a table format from the raw data? Load at 100, 1000, 3000 or 6000 microinches, for example.
- How is confirmation of acceptable failure modes handled? Test house judgment or a digital photo sent to requester of failed specimen?
- Must an acceptable failure mode/load be confirmed for the first specimen prior to testing the remaining specimens?
- If specimens are to be tested at two temperatures, are they to be sequentially taken from the specimens provided or alternated?
- Is there the ability to test an extra specimen within the contract if an odd failure occurs or is that a contract add-on?

- Is a summary of the data required? In what format? Average values, standard deviations, nominal thickness stress level calculations, thickness, lay-up or lay-up identifier? Is the material traceability information required to be part of the test report?
- Are notations of unusual failure modes required?
- Is there calibration information on the test equipment?

If an analysis approach is being used, the issues listed above must be addressed and all assumptions made in the analysis must be clearly stated.

### 4.4.4 Test Variability

All testing has variability. It is very useful to have a list of expected test results and typical coefficients of variability (COV) based on previous testing with similar materials. When doing a second-source qualification, the COV's are available for the existing material based on the quality control data and the original test matrix. When generating data by analysis (analogy, interpolation or extrapolation), the statistical approach to generating COV's must be clearly stated along with assumptions and a statement regarding the validity of that approach.

## 4.5 Combinations of Knowledge, Analysis, and Test

Methodologies for use of combinations of knowledge, analysis, and test are provided in Section 9 and its associated attachments.

# 5. Conformance Assessment and Committal

Review available knowledge: heuristics, lessons-learned, information on similar problems or applications, public literature, analyses, and test results.

Address every question/requirement. Address functional/disciplinary issues. Address interdisciplinary issues/assumptions/decisions as an IPT with all stakeholders involved.

Determine divergence risk on existing information.

Evaluate the handling of error and uncertainty.

Assess the conformance of existing knowledge with requirements.

Determine additional knowledge needed based on knowledge gaps, unacceptable risk, etc.

Audit documentation, marking, completeness of information, version controls, etc.

Secure agreement from all stakeholders. Note differences, concerns, assumptions, and highlight critical information to the committal gate at the next level of maturity.

Commit appropriate files to the master database.

Make a plan for corrective action on that data which did not meet committal criteria, marking, uncertainty management, etc.

Make the committals of maturity advancement in the readiness level files. Include all required documentation at the time of committal.

Address the business case as appropriate.

Make the decision to continue maturing on the problem statement or revise the problem statement as appropriate.

If the problem is not continued, prepare and commit the decision and rationale to the knowledge base for archival purposes and future lessons learned.

# 6. Qualification

Qualification of equipment, consumable materials, materials, and processes is usually required in addition to certification of specific structure. Following are some of the elements of qualification.

- Supplier audits, along with a jointly signed Process Control Documents (PCD), and verification of appropriate supplier documents
- Material specifications developed with appropriate requirements
- Process specifications developed with appropriate robustness
- Inspection plans - receiving, quality conformance - destructive and non-destructive
- Standard drawing notes
- Design guidelines
- Material call outs - preferred materials lists and criteria
- Fabrication call outs - preferred suppliers' list and criteria
- Material life information and technical impacts "outside the processing window"
- Standard disposition and repair information
- Tooling guidelines
- Consumables listings, specifications, and results of evaluations such as foreign object detection, contamination, and quality conformance evaluations
- Effects of defects determinations – detection and ramifications of defects
- Multi-site round robins and sensitivity studies and their documentation
- Common test method/standards - one time and basis of repeated use
- Environmental considerations of processing, the application, out-time, storage, re-qualification for life extension, chemical resistance, etc.
- Peripheral/accompanying materials qualified and specifications - barrier ply, multiple needed product forms for processes and applications, adhesives, sealants, repair materials, etc.
- Intellectual property understood and documents in place
- Safety and medical documents approved and personal protective equipment, training, etc. documented and in place
- Raw and cured disposal, fire and crash handling procedures, shipping procedures - raw and part, etc.
- World wide laws understood - use, disposal, personal protective equipment, etc.
- Life cycle costs understood and plan for capture of remaining factors
- Risk mitigation plans - multi sources, plan for licensing or related qualifications, etc. for material, suppliers, fabricators, and development/implementation information
- Joint design, methods, test results, parts/materials, etc.
- Paint, de-paint, special coatings

# Section 7. Certification Requirements for New Materials/Applications

The overall AIM-C methodology for inserting a new material into an application is a multidiscipline, multi-gated process to be performed by a multi-functional team, an integrated product development team (IPT) that includes technology developers and application designers in key functions. While it is difficult to assimilate the entire process for each function, it is relatively easy to provide an overview of the process and the steps to be taken by each discipline involved in the IPT. That summary is provided here. The role and process for each of the individual key disciplines is defined in subsequent sections of this document.

**7.1. Certification Readiness Guides the AIM Methodology** – The AIM methodology promotes the introduction of new materials by enabling the development of an integrated design knowledge base addressing all functional requirements and significant interactions. The methodology allows materials to be qualified and their applications certified rapidly for use in DoD products. The key to acceleration is the development by the joint application and technology development IPT of a key features fabrication and test article, Figure 7-1.

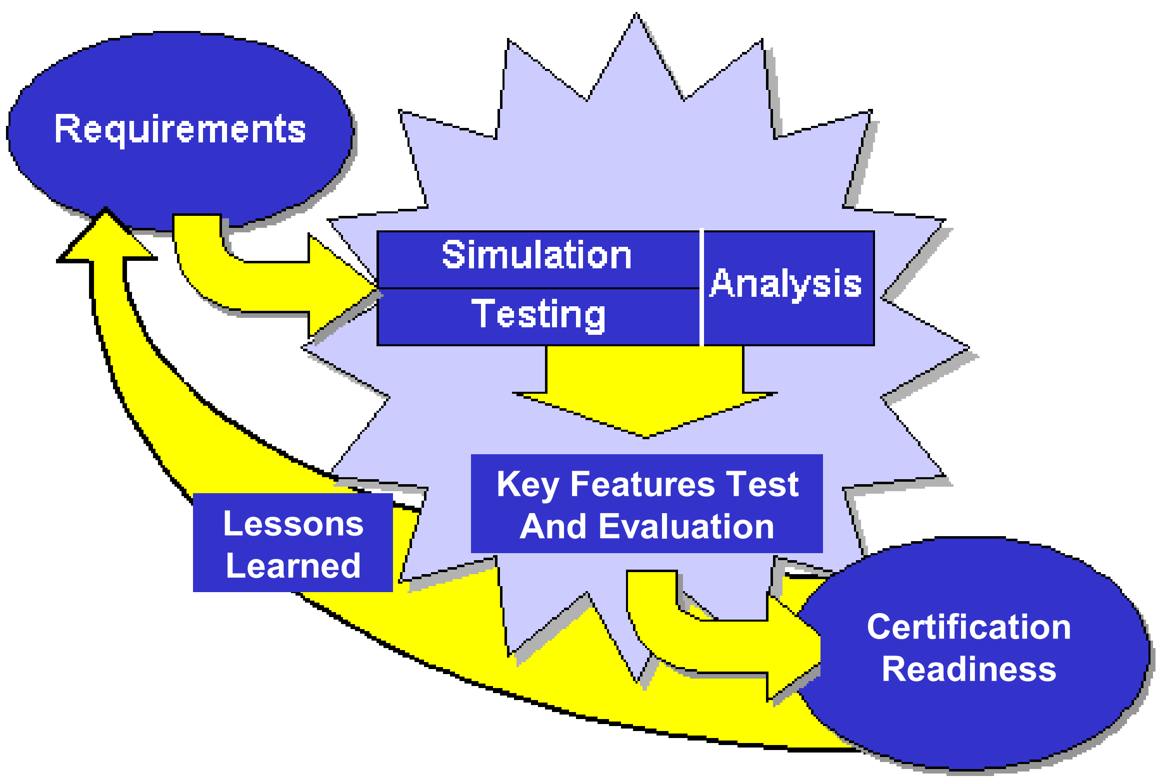



**Figure 7-1. The Early Focus of the AIM-C Methodology is the Key Features Fabrication and Test Article. It Focuses the Insertion Activity on Certification Readiness**

The key features article embodies those features considered potential showstoppers for each of the disciplines involved in the IPT. It focuses the materials and process development, as well as fabrication and assembly development prior to fabrication and it helps focus the risk reduction testing required to ensure successful certification after testing. It drives the IPT to answer every question regarding the application of the material to such a component and drives the development of the design knowledge base. For once the failure modes and loads have been determined by test for this complex, full-size structure, the tests required to develop the proper design values, or allowables, can be focused on those properties and designs that truly drive the integrity of the design.

**7.2 JSSG Formed the Basis of Our Approach** – In the AIM-C program, and in the software developed under AIM-C, we modeled our certification methodology after the one presented in the Joint Service Structural Guidelines Document. While we did divide the requirements up a little differently, to map them to their appropriate disciplines, we basically took the document and mapped it into the AIM-C software methodology by way of a series of Excel Spreadsheets that became our guide to certification. Figure 7-2 shows, in yellow boxes, the portions of the JSSG for Structures that were used in AIM-C Phase 1.

•***Loads and Criteria***: Consists of the development and evaluation of design criteria, external forces acting on the airframe, and repeated loads derived from aircraft design usage or usage obtained from operational data.

•**Flutter and Dynamics:** Evaluating the effect of unsteady aerodynamic forces acting on flexible structures and other dynamic loading conditions.

•**Vibroacoustics:** Dealing with developing the vibration and acoustics criteria used for design and installation of the aircraft structure and associated equipment items.

•***Strength***: Evaluating internal loads and stresses to determine whether adequate strength and safety margins exist under applied load and exposure to extreme environments.

•***Durability and Damage Tolerance***: Determining the service life of the airframe by evaluating accumulated damage (e.g. cracking) of components due to repeated load sources and exposure to operational environments.

•**Mass Properties:** Assessing the weights, centers of gravity, and mass moments of inertia to determine whether these are within allowable limits. Also, we manage the Automated Weight and Balance System, a flight essential tool for tracking individual aircraft mass properties in support of each mission of every USAF aircraft.

•***Manufacturing***: Including all the steps necessary to assemble a subsystem, component, or system. This process begins during product design with manufacturing and design engineers developing designs and production processes so the systems can be readily produced.

**Figure 7-2 Elements of JSSG Used in AIM-C**

We didn't use the JSSG alone. The FAA and NASA were doing some excellent work on aiding the private aircraft industry into methods for rapidly certifying materials using similitude with previously certified materials to decrease the number of tests required to ensure the use of existing allowables in their AGATE program. In the AIM-C program we followed this path and offer numerical and statistical analysis tools that allow the user to verify the confidence levels. In addition, the FAA was about to undertake a new National Program for Certification of Composite Structures that influenced some of the decisions made about the breadth of what we incorporated.

But A and B basis allowables are not the only requirements for certification of composite structures. Composites are unique in that their processesing methods and fabrication techniques impact the strength, durability, and stiffness of the structure much more than is true of more monolithic, isotropic metallic materials. And so the certification of a composite structure must include not just the material and its constituents, but the fabrication method, the processing methods, and in some cases, the assembly method in order to meet the requirements of knowing that one has the strength and durability required to meet the rigors of the flight environment into which the vehicle is to be deployed.

**7.3 Requirements Drive the Design Knowledge Base (DKB) Development** – But allowables and the impact of the material on structural properties are not the only elements of the design knowledge base. One of the primary objectives of the AIM-C program was to define the design knowledge base required to certify a vehicle for deployment. Figure 7-3 shows the summary of these elements of the design knowledge base as defined by the design team and the AIM-C team for the AIM-C Phase 1 program. While allowables and the effect of environment and defects are crucial parts of the knowledge base, there are many other aspects that have to be looked at and decisions made about how they will be handled.


**Figure 7-3 The Design Knowledge Base Definition for AIM-C**

**7.4 What Can Be Done by Existing Knowledge, What Cannot** – In general, material families can be qualified for use based on a rudimentary set of tests and extensive knowledge of the properties and characteristics of a composite material, if the design values are sufficiently below the test results obtained. If the designer is willing and able to use the properties and durability characteristics given, without excessive weight burden, then the use of generic allowables is feasible. This was determined, verified, and documented under the AGATE program.

However, it is rare that a design for flight has the weight margins required to accept certification by similitude. In general these vehicles are optimized and tailored to provide structural and material efficiencies that drive the design as close to the allowable limits as we can support with desired durability. Still, even in these cases, existing knowledge of fabrication methods, assembly techniques, and processing can play a pivotal role in reducing the fabrication and testing required to achieve confidence in the ability to deliver reproducible parts and assemblies for any particular application. By contrast, lessons learned from previous material systems give us some rather specific do's and don'ts that can spell the difference between successful insertion and insertions stopped without recourse.

Some of these lessons learned are identified and categorized in Figure 7-4. In that Figure, we have segregated the lessons into particular disciplines so that the lead for that

| Customer / Stakeholders | IPT | Design | Allowables |
|---|---|---|---|
| Regulatory agency understands and approves methods used to insert materials | Full time focus of development team | Design teams can make design decisions before design guidelines were established | Testing for allowables costs too much |
| Customers are ready for 1) price, 2) service level, 3) maintenance & Inspection reqs, and 4) repair requirements | Development maturity in one area that outstrips the general maturity can be detrimental to the overall process | Preliminary design values can be developed with very few tests in prototype. How do we move into this paradigm with reduced risk for operational vehicles? | Must establish the requirements for the material |
| Customer is part of IPT in good and bad times | If materials development lags product development, the product is at risk | Concept development is done without regard to materials - this imposes limitations on designs, concepts, and costs | Early specs did not address the variables which impacted the process downstream |
| When customer changes, the tolerance for risk, vision, and technical criteria change | Has the material been used on other products or is it currently in use on other products? | Multifunctional parts require different designs than we traditionally look at. | Must test durability, aging, and environmental effects |
| Identify stakeholders early | Is an industry database available? | Design criteria that are late in being developed or established can eliminate new materials from the design space. | Moisturization takes a long time |
| Need to resolve conflicting requirements | IPTs need to be much larger than is currently perceived. They must include more administrative disciplines. | When designers do not follow composite design guidelines, there will be problems manufacturing parts. | Must understand long term environmental exposure effects |
| Material decisions must be made with the head and not with the heart. | Must demonstrate the ability to manufacture parts as designed | Design capabilities for composite parts and tools are required. | The impact of proof testing on certification and risk reduction must be determined |
| Government programming - large scale demos instead of basic materials and structural data. These programs leave many unaddressed issues and uncertainties | Need an On-the-Floor support staff capable of identifying problems and resolving them. | Conceptual design tools impose load paths that make composites a tough sell. | Due to miscommunication, the entire materials qualification program was run with an incorrect postcure - autoclave cycles used in the lab were not validated. |
| | Material form not compatible with design requirements and manufacturing process (K-3 wing, tow vs slit tape, fabric types, large Ti castings) | Incorrect ply stacking design or lay-up sequence | Lower performance of the materials in design details |
| | Lack of interface between design, materials, and manufacturing | Product design requirements and objectives must be met | Coupon data doesn't translate into elements |

discipline can review and refresh the understandings that drive designs in particular directions (away from one fabrication method, toward another for example).

**Figure 7-4 A Portion of the Lessons Learned from the AIM-C Design Team**

**7.5 What Can be Done by Analysis, What Cannot** – Our ability to simulate and analyze structures and materials, including assembly, fabrication, and material processes has come a very long way in the last few years. The potential for similar strides in the next few is dramatic. In many cases these analyses have given us knowledge on a level we have not had before. A primary development of the AIM-C toolset has been to integrate the scientific toolset that allows us to determine the impact of a change made by one discipline on the parameters that affect other disciplines. Most noteworthy in this regard has been the interaction of design, structures, materials, and manufacturing to develop design solutions that are more robust than those produced in the past. We have the ability to "place" anomalies (tool mark off, area of less dimensional control, fiber waviness, etc) in regions in which they do not affect strength, stiffness, or the function/durability of the application.

However, there remain a number of elements of the design knowledge base that cannot be developed by analysis or test, but must be gathered from experience. The selected manufacturer need not have performed fabrication, processing, assembly, or test of the type of product being considered, but history shows that where experience is the driver, nothing but hands on experience can circumvent the perils in the early portion of the learning curve. That is why the AIM-C methodology leans so heavily on risk reduction leading to the key features fabrication and test article. This gives the fabrication house time to get familiar with what is being developed, the design requirements, and the hands on experience required to deliver reproducible parts with predictable failure modes for application to Department of Defense (DoD) systems. It is the demonstration of this capability that is a key to providing robust products for our customers.

**7.6 How Analysis, Test, and Existing Knowledge Accelerates Satisfaction of the Requirements** – It is pretty easy to see how existing knowledge leveraged against the requirements of the design knowledge base can accelerate the development of the design knowledge base for a material system. If the existing knowledge contains data for a similar system, whose behavior is known to mimic that for which the knowledge base is being developed, then that existing knowledge can be either accepted in part or in total and, when necessary, one can ratio the data to produce a knowledge base even closer to that expected for the new material.

However, one of the primary benefits of the AIM-C program was to provide in an easy to use format the best of the analysis tools available for prediction of the behavior of composite materials and structures. Tools for materials and processing, structural analysis and allowables development, and manufacturing simulation all exist in AIM-C. Moreover, these analysis tools are tied into templates that guide the user toward integrated solutions – solutions that span materials, processing, and structures. This is very important because while any structure is made up of the materials, processes, fabrication methods, and design, it is the integration of these disciplines that create a reproducible product.

The AIM-C system offers producibility tools that minimize variability and its impact. The ability to predict the as-manufactured part capability is another tool that AIM-C brings to the insertion of composite materials. No longer are models run independently, verified independently for material properties, structural properties, and manufacturing capabilities, but all data is generated to satisfy and verify the as-manufactured part properties and their variations. This means that the certification database for the application is the sum of the data used to predict the performance and variability of the as-manufactured part. While the same methodologies and analytical capabilities could be applied to metallic parts, the payoff is not generally as great because the ability to change the material system by processing or handling is not as great as it is in composites.

One element that does pay dividend to both the metallic and composite structure predictions through AIM is the statistical and probabilistic analysis capability available to ensure the robustness of the allowables and design values produced. The power of these tools is that they tie the material constituents through the processing to the application and allow a common set of tests to generate allowables for the as-manufactured structure. No longer are we simply pooling materials data to get approximate allowables, but we are pooling data from the materials, processes, and design to develop allowables that are unique to a component and its failure modes and loading conditions.

The AIM-C approach also provides guidelines for effective use of knowledge, test, and analysis – a recommended approach for each element of the AIM-C methodology. But we know that as the experience with these materials grows, and the knowledge base increases, these guidelines will need to be revised and so provision is made for that as well. For now, these guidelines, shown as a limited set in Figure 7-5, become the baseline against which cost, schedule, and performance are evaluated.

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (Uni and Cloth, ie 5hs or plain or 8hs etc.) | | x | x | | | | | | | | | |
| 2.1.1 | ➢ | Tensile Strength | x | x | x | x | x | | | | | | | Test-Analysis |
| 2.1.2 | ➢ | Tensile Modulus E11 (longitudinal) | x | x | x | x | x | | | | | | | Test-Analysis |
| 2.1.3 | ➢ | Tensile Strain to Failure | x | x | x | x | x | | | | | | | Test-Analysis |
| 2.1.19 | | Compressive Strength | | | | o | | | | | | | | Analysis |
| 2.1.20 | | Cost | x | x | x | x | x | | | | | | | Specified Value |
| 2.1.21 | | T(g) | | x | | | | | | | | | | Test |
| 2.1.22 | | wet T(g) | | x | | | | | | | | | | Test |
| 2.1.23 | | Health and Safety | | x | | | | | | | | | | MSDS |
| 2.1.10 | | CTE - Radial | | | o | | | | | | | | | Analysis |
| 2.1.11 | | Filament Diameter | x | | x | | x | | | | | | | Test |
| 2.1.12 | | Filament Count | x | | x | | x | | | | | | | Test |
| 2.1.13 | | Transverse Bulk Modulus | | | o | | | | | | | | | Analysis |
| 2.1.14 | | Youngs Modulus, E22 Transverse | | | o | | | | | | | | | Test |
| 2.1.15 | | Shear Modulus, G12 | | | o | | | | | | | | | Analysis |
| 2.1.16 | | Shear Modulus, G23 | | | o | | | | | | | | | Analysis |
| 2.1.17 | | Poissons Ratio, 12 | | | o | | | | | | | | | Analysis |
| 2.1.18 | | Poissons Ratio, 23 | | | o | | | | | | | | | Analysis |
| 2.1.4 | ➢ | Yield (MUL) | x | x | x | x | x | | | | | | | Analysis |
| 2.1.5 | ➢ | Density | x | x | x | x | x | | | | | | | Test |
| 2.1.6 | | Heat Capacity (Cp) | | | x | | | | | | | | | Test |
| 2.1.7 | | Thermal Conductivity Longitudinal | | | x-o | | | | | | | | | Analysis |
| 2.1.8 | | Thermal Conductivity Transverse | | | x-o | | | | | | | | | Analysis |

**Figure 7-5 Guidelines for Meeting Qualification/Certification Requirements Are Part of the Conformance Planning Activity**

**7.7 Metrics for Acceleration** – As the IPT begins to develop its conformance plan to demonstrate that the as-manufactured part meets its requirements and the requirements for certification, it must decide to what level of risk reduction (confidence building, if you will) it will seek given the time/cost constraints under which it operates. The metrics for insertion are cost, schedule, and technical performance. Any one of these can always be sacrificed to achieve an acceptable result for another, however, the goal of the AIM-C program was to allow the IPT to weight these metrics as necessary to meet their insertion needs in the most rapid, cost effective, and least risk manner possible. The AIM-C team developed a means for tracking progress according to a schedule, cost, and technical performance according to the level of confidence developed for each as part of the maturation plan.

Figure 7-6 graphically represents the maturation tracking system in the AIM-C methodology. This tracking device is a summary of conformance, for each discipline on the IPT, required to meet the goal of certifiable insertion of a new material into a DoD system. This particular version assumes that validated analytical and experimental capabilities defined in the AIM methodology are available to meet those goals. From the design, fabrication, and test durations associated with each of these test plans, an overall summary schedule can be produced that is tailored to the application that is being examined. From these same definitions, the costs for design, analysis, fabrication, and test can be determined and used to project the total cost to reach readiness for certification.

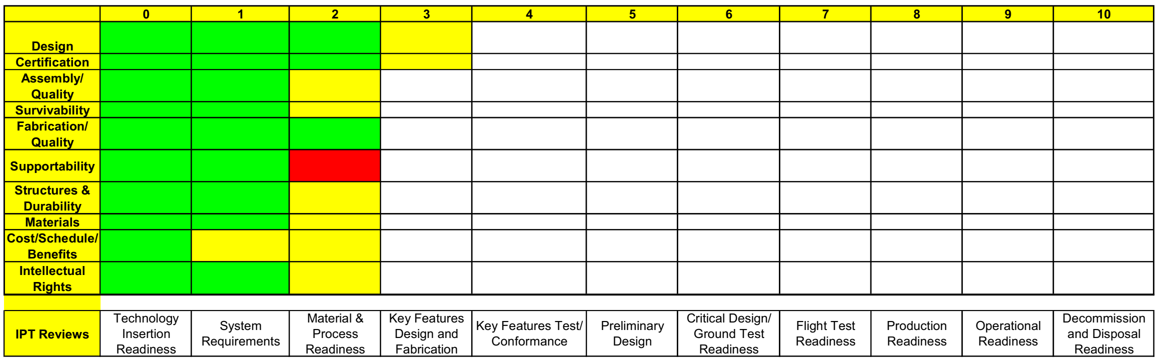



**Figure 7-6 AIM-C Maturation Tracking System**

But certification plans, costs, time, and risks are all negotiable between the IPT and their customer. If the team and its customer agree to take a higher risk approach in order to achieve certification readiness in a shorter time, then the tracking device will never show every thing green (for example), but will show those element s whose risks were considered acceptable as yellow and the cost and schedule modules can be used to develop the projected cost of the plan and the projected schedule. The reduction in the cost or schedule versus the guideline plan can be metrics against which the team can select between alternative plans to meet their specific goals. One method to track cost and schedule is shown in Figure 7-7 and for risk in Figure 7-8 as examples of how these metrics can be tracked for a given application.

**AIM Methodology: Hat Stiffened Models and Approach (Template 14)**

| | Labor (Hrs.) | Flow (Wks) | Risk Factors Probability | Risk Factors Impact |
|---|---|---|---|---|
| Problem Definition and Collection of Data | 37 | | 20 | 2 |
| Load, Validate, Verify HSP Global Model. Collect Data. | 53 | | 15 | 2 |
| Determine load cases, document 5 most significant, for example. | 53 | | 75 | 0.5 |
| Configure structure w/ aid of RDCS. Design scan/uncertainty analysis. | 106 | | 5 | 2 |
| Exercise local models to compliment analysis | 106 | | 10 | 4.5 |
| Add functionality to model(s) because of need identified in initial analysis | 160 | | | |
| Re-check load cases. Determine new significant cases, if any | 37 | | 5 | 4.5 |
| If new load cases, then repeat above steps. | 106 | | | |
| Summarize and Report Design | 27 | | 5 | 3.5 |
| Totals | 686 | 14-wk effort | | |
| Cost at $100 per labor hour | $ 68,628 | | | |

**Conventional Methodology: Blade, J, or I Stiffener**

| | Labor (Hrs.) | Flow (wks) | Risk Factors Probability | Risk Factors Impact |
|---|---|---|---|---|
| Problem Definition and Collection of Data | 37 | | 20 | 2 |
| Create deterministic FEM model of stiffener, Collect Data | 80 | | 30 | 3 |
| Determine load cases, document 5 most significant, for example. | 53 | | 90 | 0.5 |
| Configure structure, evaluating layup and materials choices (no geometric effects) | 64 | | 50 | 2 |
| Develop local FEM models to compliment analysis | 80 | | 30 | 3 |
| Iterate on geometry to configure structure -- dependant on allotted time | 399 | | 40 | 2.5 |
| Iterate on local FEM models compliment analysis | 346 | | | |
| Re-check load cases. Determine new significant cases, if any | 37 | | 35 | 4.5 |
| If new load cases, then report above steps. | 160 | | | |
| Summarize and Report Design | 27 | | 5 | 3.5 |
| Totals | 1282 | 30-wk effort | | |
| Cost at $100 per labor hour | $ 128,212 | | | |

**Figure 7-7 Cost and Schedule Metrics for a Given Application**

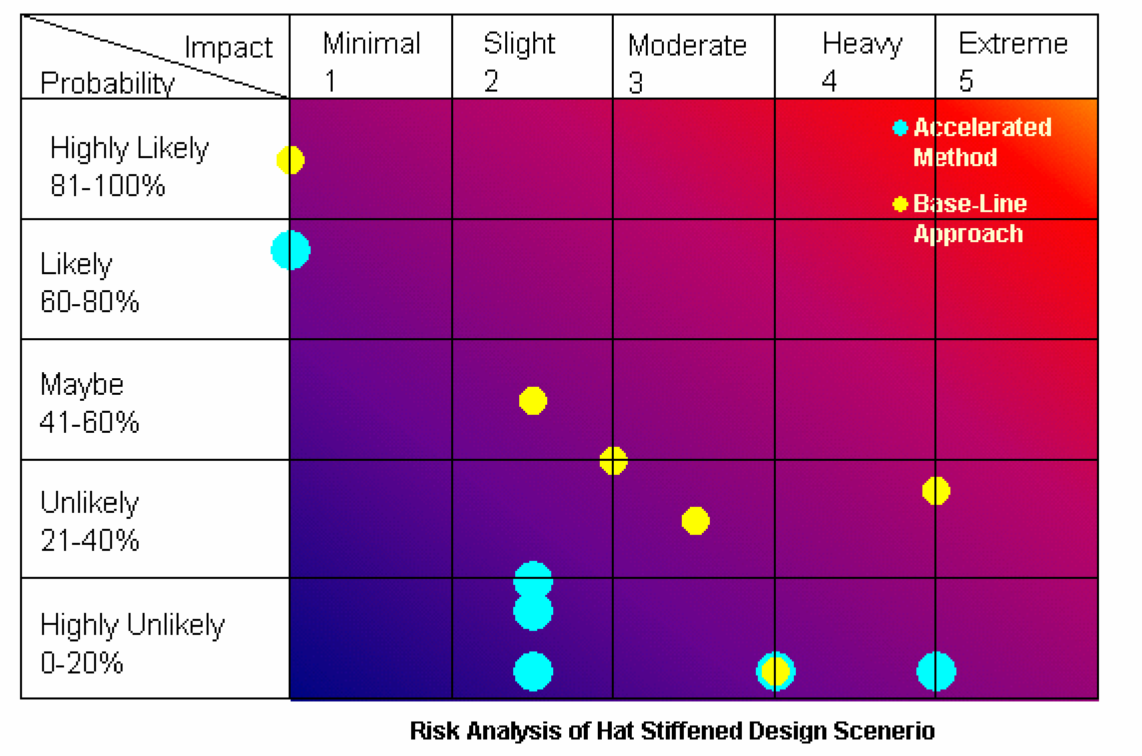



**Figure 7-8 Risk Assessment for a Given Application**

## 7.8 Joint Service Specification Guide

This guide, jointly developed by the Air Force, Navy, and Army, establishes the structural performance and verification requirements for the airframe. These requirements are derived from operational and maintenance needs and apply to the airframe structure which is required to function, sustain loads, resist damage and minimize adverse operational and readiness impacts during usage for the entire service life. This usage pertains to both land and ship based operations including take-off, catapult, flight, landing, arrestment, ground handling, maintenance, and flight and laboratory tests. This guide also provide for trade studies and analyses to identify and establish certain structural design parameters and criteria which, as a minimum, are necessary to enable the airframe to meet these structural performance requirements, consistent with the program acquisition plan for force level inventory and life cycle cost. These guidelines are provided in detail in US Department of Defense Publication JSSG-2006.

**7.8.1 Brief Summary of the Joint Service Specifications Guide –** The Joint Service Specifications Guide includes definitions of the type of information required to provide certification agents with the confidence levels required to certify aircraft airframes. Moreover, it covers the following topics: airframe configurations, equipment, payloads, weight distributions, weights, center of gravity, speeds, altitudes, flight load factors, land-based and ship-based aircraft ground loading parameters, limit loads, ultimate loads, deformations, service life and usage, atmosphere, chemical, thermal, and climatic environments, power or thrust loads, flight control and stability augmentation devices, materilas and processes, finishes, non-structural coatings, films, and layers, system failures, lightning strikes and electrostatic charges, foreign object damage (FOD), producibility, maintainability, and supportability. Where standard values exist they are provided, but the product definition always supercedes this document in defining requirements for the aircraft and its airframe. This guide not only defines the values that are required, but also helps define the testing required to demonstrate satisfaction of the requirements. The user will recognize at once that a number of different disciplines are involved in defining and satisfying these guidelines. The need for an integrated product team to perform these activities and integrate the means toward their satisfaction is key to removing duplicative effort, testing, and disconnected requirements from the plan to achieve conformance with these guidelines – which is one of the key focal points for the AIM-C acceleration effort.

**7.8.2 Summaries of the Guidelines for Design, Systems, Structures, Manufacturing, Materials** – With only a little modification, we can divide the areas addressed in the JSSG Document into the subject divisions. This will help us organize and segregate what each discipline in the IPT is responsible for answering. However, if the IPT is performing as it ought to do, the entire team is involved in and responsible delivering the best solution for all competing requirements throughout the guide. In this vein, then design would lead the team in addressing: airframe configurations, equipment, payloads, weight distributions, weights, center of gravity, speeds, and altitudes. Systems would lead the team in defining solutions for the power or thrust load requirements, flight control and stability augmentation devices, as well as system reliability in service, after lightning strikes, and after electrostatic discharges. Structures and Loads would lead definition of flight load factors, land-based and ship-based aircraft ground loading parameters, limit loads, ultimate loads, deformations, service life and usage, as well as foreign object damage. Manufacturing would lead the team to define producibility and maintainability. And Materials and processes would address the areas of atmospheric, chemical, thermal, and climatic environments, materials and processes, finishes, non-structural coatings, films, and layers. All members of the team would be responsible for determining the requirements for inspection and supportability, although in many companies these elements are led by a supportability discipline specialist.

**7.8.3 Benefit of Addressing the Guidelines as an Integrated Team –** With so many potentially conflicting requirements to be faced and with a mandate to accelerate the insertion of productive, high payoff materials, the most rational solution was to address these guidelines with an integrated team of specialists in each of these disciplines so that the insertion had maximum potential for successfully meeting the various criteria. And, in those cases in which all the criteria could not be met, the team was charged to deliver a choice between criteria in order to best meet the objectives of the airframe application. The team then could review the requirements, select those best suited to the application, modify those applicable to best fit the system requirements to fit the application in question, develop a plan to meet these requirements, develop the database/knowledge base required to fill in what was not already known, and to provide a test plan and oversight to ensure that only the most necessary data is delivered to satisfy the requirements. The integrated Product team was also assigned the tasks of assessing the conformance of the knowledge base developed with that required and to approve the pedigree of the information used to feed the knowledge base and satisfy the program and certification agents.

The integrated product team also includes the certification agent, the cost, and schedule leads so that there is constant review and approval of the conformance plan, data development, and knowledge assessment by the team members that determined the metrics for both acceptance and need by the program. It is cost, performance, and risk that are the metrics used to measure acceleration of materials, or technology, insertion.

Sections 7.9 through 7.11 provide an interpretation or example of the use of AIM-C from the perspectives of Structures, Manufacturing, and Materials Engineering Viewpoints.

## 7.9 Use of AIM-C for Structures

For all disciplines involved in the integrated Product Team, the AIM-C methodology carries the same steps: Problem and Requirements Definition, Conformance Planning, Knowledge Generation, Conformance Assessment, Acceptance and Committal to the Design Knowledge Base, and Documentation of Lessons Learned. The next few sections address these steps as they apply to three primary disciplines involved in the insertion of a new material system, but they apply equally well to other disciplines, other technologies, and other applications. Structures Technology is one the disciplines that is closer to the application than many of the disciplines involved in the IPT, perhaps closest except for Design. However the steps of the AIM-C methodology apply to them just as they do to the others as will be demonstrated in the discussion.

**7.9.1 Problem Statement and Requirements Generation** – Structural design requirements come from three primary sources: the Joint Service Specification Guidelines that we've been discussing already, the specific requirements called out by the customer, and requirements imposed by other disciplines in order for them to meet their requirements. It is the third of these sources that requires the application of the IPT to design integration and ensures that all disciplinary requirements have been either accommodated or looked at and determined to be secondary to the other requirements imposed on the system.

In the past, Military Service Specifications were the primary source for structural design requirements for any system, but as systems became more sophisticated and the interaction of disciplines became more pronounced, Mil-Specs have been replaced by the JSS Guidelines and requirements defined by the funding customers. Whether general specifications will be developed for structures in the future remains a continuing question. But no matter where the requirements come from the AIM-C Process is capable of handling them.

**7.9.2 Conformance Planning** – There is a hierarchy to conformance planning that is related to the testing performed to support it. Strength and stiffness come first because the analytical tools require this data early on to develop models for the structural analysts and design community. Non-linear failure modes: buckling, crippling, collapse come next as compression and shear loadings are defined from the finite element model built based on the stiffness data and strength data provided in the first steps. Finally, durability and damage tolerance assessments are performed to develop the data required for life prediction and damage progression are developed. Strength and durability of the attachments (be they bolted or bonded) are a major effort in this knowledge generation task and is so reflected in the conformance planning.

The improved analytical procedures incorporated into the AIM-C toolset allow some reduction in these tests, but these reductions are largely offset by the need for variational analyses of the materials, processes, and geometries involved in the application.

1. Obtain preliminary lamina properties (modulus, etc) so that finite element models of the structure can be built for preliminary analysis. Lamina properties are also needed to predict laminate allowables. Traditionally, lamina properties are obtained from test. However, AIM-C Tools are available to generate these properties given resin and fiber properties. Tasks include: enter known data into AIM-C System; get material info from Materials (fiber & resin) module; check airframe requirements (temperature range, environment, etc); run Lamina module to get predicted lamina properties; pass lamina properties to IPT's and other AIM-C modules; identify additional resin, fiber and prepreg data needed to increase confidence level in predictions for next cycle of allowables predictions (Item 5)
2. Generate preliminary Laminate allowables (UNT, UNC, FHT, FHC, OHC, BRG, CSAI) based on nominal parameters. These preliminary allowables will be used to size the structure. Need to include the effects of environment and design features (open vs filled, countersink, hole size, edge distance, etc). Again, this data would all come structural testing. However, AIM-C Tools are available to generate some of these properties. Specifically unnotched and open hole tension and compression data (UNT, UNC, OHC, OHT) may be generated for a range of laminates using the AIMC tool. Some test data is required. At a minimum lamina testing at 10 and 90 degree fiber orientations are required in order to obtain data for the Strain Invariant Method (Template 10). In addition, the point stress method used to generate strength data using Template 7 requires lamina strength data obtained from testing at 0 degree and 90 degree fiber orientations and requires testing of an open hole laminate. The laminate lay up may be common lay up desired for the application but it is best to not use one strongly dominated by +/- 45 degree plies. Tasks include: enter known data into AIM-C System; get needed info from lamina module; run Laminate module or Templates 7 or 10 to get predicted laminate carpet plot data.
3. Preliminary size the part using data generated in previous steps. AIM-C tools exist for a specific class of structural problems that deal with the sizing of a hat stiffened panel (Templates 14,16 and 17). These provide additional insight into the properties needed for conformance.
4. Predict in-plane laminate allowables (UNT, UNC, FHT, FHC, OHC, BRG, CSAI). Include Environmental impacts. (This task is completed at the beginning of the ALO phase to minimize the amount of redesign because of allowables changes downstream. Need to refine the design allowables based on proposed processing, tooling, effects of defects, etc.) Tasks include: run structures module to update design allowables based on MP2 input; run durability module to determine impact of fatigue

(based on preliminary spectrum); run materials module to determine impact of fluid resistance, etc.; release updated allowables to IPT's.

**7.9.3 Knowledge Generation –** Conformance planning leads to the initial development of design properties for initial sizing and trade studies. These elements include:

5. Pilot batch of material available - First batch of material fabricated using proposed nominal production parameters but on a pilot line.
6. Lamina and Laminate tests, including environment, of Pilot Batch. Number of tests are variable. The objective of these tests is to determine batch variability. This data will be used for extensive structural configuration and sizing exercises by structural designers and engineers.
7. EMD Go ahead - Official start of the Engineering Manufacturing Develop phase. Product teams launch into intense design phase.

**7.9.4 Conformance Assessment –** Conformance assessment requires a disciplinary review of the data obtained by analysis, test, or previous data; an IPT review of the same data so that problems for any discipline can be addressed, and finally, a review by both IPT and certification agent is performed. Once good rapport between the IPT and the certification agent has been developed, then normally, we would expect to see the certification agent in the IPT final review of the material system.

8. Determine impact of selected materials (components variability, etc.), processes (cure cycle window, etc.), and producibility features (i.e. tooling, part configuration, etc.) on design allowables. Design allowables may need to be refined based on proposed processing, tooling, effects of defects, etc.
9. Update preliminary allowables with pilot batch data - update previously estimated allowables based on pilot batch data. These allowables will now be available for Concept Lay out (CLO). Again, this data will be used for extensive structural configuration and sizing exercises by structural designers and engineers

**7.9.5 Committing the Knowledge to the Design Knowledge Base –** Knowledge is committed to the design knowledge base when the IPT, including the certification agent agrees that the knowledge is being used for the design of the application. In this case, this knowledge includes the pedigree and data associated with the material, its processing, and the design that was tested.

10. Production qualification material batches. - The number of batches and testing must be coordinated with Certifying Agency. The batch qualification data and the elements, coupons, and components made from it should be accessible to the IPT.
11. CLO – Concept Layout - Product team task – here the knowledge base and the design are linked together and bookkept electronically so that all the knowledge supporting this phase of the design are housed or can be referenced from the design knowledge base. The IPT and certification agent document their agreement with these elements of knowledge prior to the placing of the knowledge into the knowledge base.

**7.9.6 Capturing Lessons Learned –** Even after the design values, the configuration, and the manufacturing and materials specifications have been documented, the AIM-C methodology requires that lessons learned from the process be captured. These are captured within the AIM-C System so that future users are able to see and learn from the lessons learned by those who had gone before. This is crucial because it can avoid costly learning experiences from being repeated.

12. Allowables modifications, as dictated by tests - Continuously evaluate predicted allowables versus test data. Update the allowables when differences are identified between prediction and test. Complete this phase before BTP phase is complete.

**7.9.7 Application To Further Design Cycles** - As described herein, the phases of this effort are just the first cycle of the design-build-test process. The cycle is repeated for ALO including:

13. Allowables validation tests (coupon tests) - Validate predicted design allowables from the AIM-CAT tool. Need to do theses tests with the production qualification material – including: Select critical tests to perform first based on risks (cost, schedule, technical) identified by what we know; tests coupons should be fabricated by the shop that will fabricate the production parts; use the selected production processes to build in the predicted MP2 parts; choose proper test methods, test labs, etc.
14. ALO – Assembly Layout - Product team task

Finally, the same process is applied to the design before the Build-To packages are released to the manufacturing shops. These steps include:

15. Effects of defects (coupon/element tests) - Based on identified expected defects, determine via tests impact on design allowables. Performed earlier enough in program that design changes can be made to increase robustness and minimize cost.
16. Element Tests, including fatigue - Test critical joints and splices, including fatigue tests. Include defects as required.
17. BTP – Build To Patches and normal Redesign effort based on coordination with manufacturing
18. Allowables modifications, as dictated by tests - Continuously evaluate predicted allowables vs test data. Update the allowables when differences are identified between prediction and test. Complete this phase before BTP phase is complete.

## 7.10 Use of AIM-C from Manufacturing Perspective

This section provides an overview of the producibility methodology for new material qualification and certification. Several new and unique areas are associated with the AIM-C producibility methodology. First and foremost is the aspect of feature based producibility assessments where standard producibility components with increasing complexity are fabricated and evaluated in stages associated with increasing maturity levels. As the knowledge base for different materials is established, this will allow better material-to-material comparisons of producibility. Second, the approach addresses both producibility operations and quality technical areas and production readiness. The approach structure enables early identification of any show stopper issues to minimize rework or redoing of activities because of problems.

Composite producibility operations/processes include cutting, layup, debulking, bagging, cure, tooling and non-destructive evaluations (NDE). Quality includes in-process and final part. For aircraft applications, the integrated product team (IPT) disciplines involved in producibility activities include manufacturing, material and processing, tooling, and quality.

The overall AIM-C methodology process flow is requirements, conformance to requirements, knowledge gathering, conformance assessment, and knowledge committal activities. A unique aspect of the methodology process flow for producibility requirements is the addition of production readiness as part of the requirement package. This requirement package is addressed by conformance to requirements and conformance activities.

**7.10.1 Problem Statement and Requirements Generation** – Component requirements flow down to specific exit criteria according to categories of disciplines or areas. Producibility/Fabrication exit criteria are primarily based on successful part fabrication through a phased approach from producibility development through producibility readiness for the application. For new material insertion, the primary goal is that producibility stability has been demonstrated with multiple parts and that final process specifications exist. The intent for this stability is to enable generation of design allowables, subcomponents and components for certification. Previous experience has shown that stability for applications that has not been achieved with scale up has required significant rework because of a show stoppers that only surface when full scale parts are attempted. For this reason, the exit criteria address application features from elements, through subcomponents, to full scale components to minimize risk at the time of actual application to component fabrication.

The feature based part fabrication approach is for knowledge generation and is compatible with the exit criteria for the application itself and with the producibility maturation process. Three issues arose when establishing the producibility methodology/process.

1. There is a different perspective of readiness levels when looking at maturity from a producibility perspective.
2. Producibility subdivides into the manufacturing operations/processes of cutting, layup, debulking, bagging, cure, tooling, and NDE where each could be at a different maturity level and not be captured correctly at the TRL level.
3. Production readiness for each of the operations/processes in producibility is not captured.

The technology readiness level (TRL) approach for measurement of maturity is driven by certification requirements. It looks at maturity from the application or system point of view for design and test items or steps. This qualification readiness level concept then leads to the question of how can production readiness be incorporated into requirements for qualification. Production readiness has a series of generic evaluation categories that have to be addressed, regardless of the technology (materials, processing, producibility, etc.).

By combining the production readiness categories with XRL maturity step numbering, a matrix can be established where individual blocks can be filled in for exit criteria for production readiness and technology readiness requirements that is applicable for composite materials, processing and producibility. The categories include technical requirements and ones associated with production readiness. Being generic, it covers all assessment areas. It should be noted that not all areas or maturity level exit criteria may be specifically applicable to qualification and certification of materials, processing, producibility or answering of the problem statement.

**7.10.2 Conformance Planning -** The approach for producibility requirement conformance is comprised of two steps. First is to generate the producibility knowledge and information at an item level for each item to satisfy qualification and certification requirements. Second is to summarize information from each item as to its impact on either in-process quality or final part quality.

The in-process quality information goes into material and processing guidelines/specification for controls and tolerances. Final part quality information is used for comparisons of capabilities to application requirements as a means of assessing whether the application parts can be made with the materials and producibility operations.

**7.10.3 Knowledge Generation -** The feature based producibility approach is a key aspect of producibility methodology. This approach is based on manufacturing a series of increased complexity parts starting with flat, constant thickness panels going up to full scale generic components based on the application. Parameters for producibility areas and items are established using flat and ramped panels. These parameters are then either validated or modified when making multiple thickness flat panels, application elements, and generic full scale components. One of the unique aspects of this approach is that mechanical and physical properties can be obtained during producibility development and utilized for the design knowledge base properties and effects of defects very early in qualification and certification activities.

Initial fabrication trials are representative of the applications being considered and evaluation results are used to establish producibility parameters. Later parts are generic components that are based on the application being certified. These parts would contain key features of the application for early producibility evaluations and assessments.

These feature based producibility parts are fabricated at different stages or maturity levels and are a metric of producibility maturity. Flat and ramped panels are the basic parts for producibility assessments and comparisons at all maturity levels to ensure that any specific changes to parameters do not impact overall parameter impact on quality.

**7.10.4 Conformance Assessment –** Conformance assessment fall into two categories for producibility. In-process quality addresses item variability that is measured/controlled during individual item or operation execution. For composites producibility, in-process quality variability covers: indirect/support materials, ply angle, ply lap/gap, out time, freezer time, cure time, temp, pressure, heat up rates, cure abort conditions, debulk time, temp, pressure, methods, bagging gaps, breathers, bleeders, and NDE standards.

The investigations and assessments of in-process variability impact is conducted on each individual item during quick look assessments initially and detailed assessments for IPT review. Final part quality addresses accept/reject criteria commonly used for composite parts: geometric dimensions, thickness, voids, porosity, inclusions, surface waviness, surface finish, fiber volume/resin content, in plane fiber distortion, out of plane fiber distortion. These evaluations yield capabilities for material and producibility which is then compared to application requirements to see whether these requirements can be met with the capabilities. This information is also used during part producibility assessments.

Producibility part assessments are conducted when answering questions about manufacturing application components. It is a way of using the knowledge base information from producibility item assessments, final part quality and other knowledge to answer manufacturing questions in an IPT environment. The size of this is huge relative to application diversity and the needed amount of information is therefore very large.

As a step in conducting part producibility assessments, an evaluation was conducted to address producibility information needed at the time of part trade studies on a hat stiffened panel. A review of IPT activities was conducted from a producibility standpoint and results are listed as seven activities: ID defects to be minimized, ID surface(s) that need to be maintained, ID acceptable tolerances, define assembly/manufacturing method, define tooling approach, define producibility, quality steps, and make parts. The first three items are from part requirements. Items 4 and 5 are a trade off of manufacturing (final part quality from producibility item assessments) and tooling capabilities (from previous knowledge other than what is generated in the AIM-C process) is compared to requirements. Items 6 and 7 are the producibility operations, in-process quality and final part fabrication.

The information or knowledge for assessment steps 2, 3, and 4 comes from previous knowledge or history. Information or knowledge for assessment steps 5 and 6 comes from producibility item assessment results and from previous knowledge or history. One information and history void area is dimensional quantification of defects relative to tooling, producibility and materials. Consequently, results from this part assessment process are very subjective and vary from person to person and company to company according to previous experience and opinion.

**7.10.5 Committing the Knowledge to the Design Knowledge Base –** The most consistent way to capture the manufacturing or producibility knowledge base is to document the specifications and fabrication processes as part of the product definition package (the build-to package as Boeing refers to it). The couples all design, producibility, and certification knowledge in a single design knowledge base for use by any fabrication house or shop so that they know how this component is to be manufactured and why it looks and is fabricated the way its is defined. The mechanism for this documentation exists and it is being used for much of the knowledge base as defined by AIM-C currently. We are talking about a significant, but not unwieldy expansion to include the manufacturing pedigree of the component.

**7.10.6 Capturing Lessons Learned –** As noted before, the AIM-C methodology requires that lessons learned from the process be captured. These are captured within the AIM-C system, by discipline, so that future users are able to see and learn from the lessons learned by those who had gone before. This is crucial because it can avoid costly learning experiences from being repeated.

## 7.11 Use of AIM-C from Materials Engineering Perspective

Up-front consideration and thorough planning for a program's combined material and process needs over the life of the program can significantly reduce both costs and risks. Qualification evaluations typically exhibit progressive cost escalations from coupon tests, to elements, to components, to parts, and eventually to aircraft. This progression is commonly known as the "building block" approach to qualification. It is important, therefore, to conduct initial planning to properly align and coordinate multiple sources, product forms, and processes early in the qualification effort. This planning allows better utilization of the existing expensive large scale tests by incorporating various considerations in left hand/right hand or upper/lower portions of the test items.

Materials can be evaluated for specific applications, which may allow for a partial replacement of the baseline material. It should be noted that if a partial replacement is considered, the cost of multiple drawing changes required maintaining a distinction between two materials must be considered. In addition, some cost must be allocated for analysis review to determine which application can withstand material properties that are not equivalent or are better than the baseline properties.

When a material or process-related change is identified or a material or process-related problem is defined remediation, the stakeholders may use the steps here to develop a solution.

**7.11.1 <u>Problem Statement -</u>** The problem statement bounds the qualification program by providing a clear statement of the desired outcome and success criteria. It delineates responsibilities and requirements for the aspects of the program to the material supplier, processor, prime contractor, test house, or Navy customer. It becomes the cornerstone for other decisions and serves as the basis of the business case as well as divergence and risk analyses on which the technical acceptability test matrix is built. When the problem statement is found (1) to be lacking specificity, (2) to be so specific as to limit approaches, or (3) to have a clear technical error; modifications may be made with the agreement of the qualification participants and stakeholders.

**7.11.2. <u>Conformance Planning –</u>** Conformance planning involves developing the business case for development of the knowledge base required to satisfy the requirements identified in the problem statement definition.

**7.11.2.1. Business Case** - Following development of the problem statement, a business case is developed (1) to clarify responsibilities, (2) to show the clear benefit of the qualification to all participants and stakeholders, and (3) to obtain and allocate resources for the qualification effort.

**7.11.2.2. Divergence and Risk -** Divergence and risk analyses are conducted to provide the most affordable, streamlined qualification program while addressing risks associated with using related data, point design qualifications, and so forth. The divergence analysis assists the qualification participants in determining how similar or how different the new material or process is from the known and understood materials or processes. Risk analysis is performed to determine the consequence of reduced testing, sequencing testing and so forth.

**7.11.2.3. Technical Acceptability -** Technical acceptability is achieved by fulfilling the objectives included in the problem statement, answering technical questions based on historic knowledge and practices, and by showing through test, analysis, and the results of the divergence/risk analyses that the material or process system is understood. Its strengths and weaknesses are then identified and communicated through design and analysis guidelines.

**7.11.3. <u>Knowledge Base Development</u>** – Knowledge base development includes data mining, data development, and analytical prediction of material and structural behaviors. The IPT uses these knowledge pools to determine whether or not the design they have developed will meet the desired, primary certification requirements. The allowables development and equivalency validation focuses on the quantitative aspects of the qualification. It provides methodologies for meeting the qualification and certification criteria. .

**7.11.4. <u>Conformance Assessment and Commitment of Knowledge -</u>** In the past, qualification programs have often fallen short because they ended with the quantitative aspects of design databases. However, a successful qualification program must include the conformance assessment needed to assure production readiness. Production readiness includes raw material suppliers, formulators, fiber suppliers, preformers, processors, quality conformance testing, adequate documentation, and other areas. Again, this protocol methodology does not provide all the answers for specific qualifications. Instead, it provides discussion to stimulate thought by the qualification participants and prompts appropriate planning based on the problem statement, business case, divergence or risk analyses, and technical acceptability testing established for the particular case by knowledgeable stakeholders. And the system documents this conformance and the pedigree of the knowledge used to attain that conformance.

**7.11.5. <u>Lessons Learned -</u>** Finally, the methodology admits that no qualification is perfect. Lessons learned from the past should be incorporated into the plan as soon as the tie is identified in the divergence or risk analyses. In addition, lessons learned from the current qualification should be documented and acted upon throughout the qualification.

Developing a qualification plan should provide a total system performance validation with a complete database.

### 7.12 How the AIM-C Methodology Reveals Unknowns and Risks

The conventional Building Block Methodology works to establish as much knowledge about a material system as can be generated in element and coupon level tests in order to reduce the risk for development and testing of the risk reduction articles that thereby reduce the risk for full scale articles. The AIM approach seeks to reduce the testing of the expensive and often misleading risk reduction article by replacing them with a very early development, fabrication, and test of what is called a Key Features Fabrication and Test Article.

The Key Features Article ensures that all disciplines of the IPT have addressed their greatest concerns with an article to be fabricated early enough in the program that, should redirection be required, there is still time to accomplish it. It ensures readiness for scale-up to full size components, since the article is the scale of the largest component to be fabricated. It ensures that data mining, knowledge gathering and test development is focused on only that data required to ensure the success of the Key Features Article. And, by virtue of the lessons learned from the testing, it focuses the certification testing that follows it toward those parameters that truly control the design of the component, its failure modes and loads. This alone can reduce the certification test cost by more than 50% (See Sections on Cost and Schedule).

**7.12.1 How the Key Features Build and Test Feeds Conformance –** In the AIM-C Methodology, Figure 7-9, the Key Features Build and Test Article is the focal point for the development of knowledge leading up to its build and test. As that focal point, it guides and directs all of the knowledge gathering processes to focus on those features predicted to control the design of the parts to be built using the prescribed material(s).

Conformance plans and test requirements are built around the development of the manufacturing processes and material qualifications required to ensure that a reproducible part can be delivered and tested. The IPT works hard to make sure that tests performed to satisfy materials requirements work to fulfill as many design, manufacturing, and engineering test requirements as they possibly can. Similarly, manufacturing tests are used to their maximum benefit for the team. No test is performed that cannot meet multiple needs within the IPT until those needs have been predominantly satisfied. As manufacturing approaches readiness for the key features fabrication, the processes are pretty nearly locked in for the production of the airframe hardware. This means that toward the end of this cycle, we can begin to develop allowables that reflect the manufacturing approach. And once the Key Features Article has been tested, assuming a successful outcome, the allowables development can begin in earnest knowing that the manufacturing processes have been validated and that critical design details have performed as predicted.

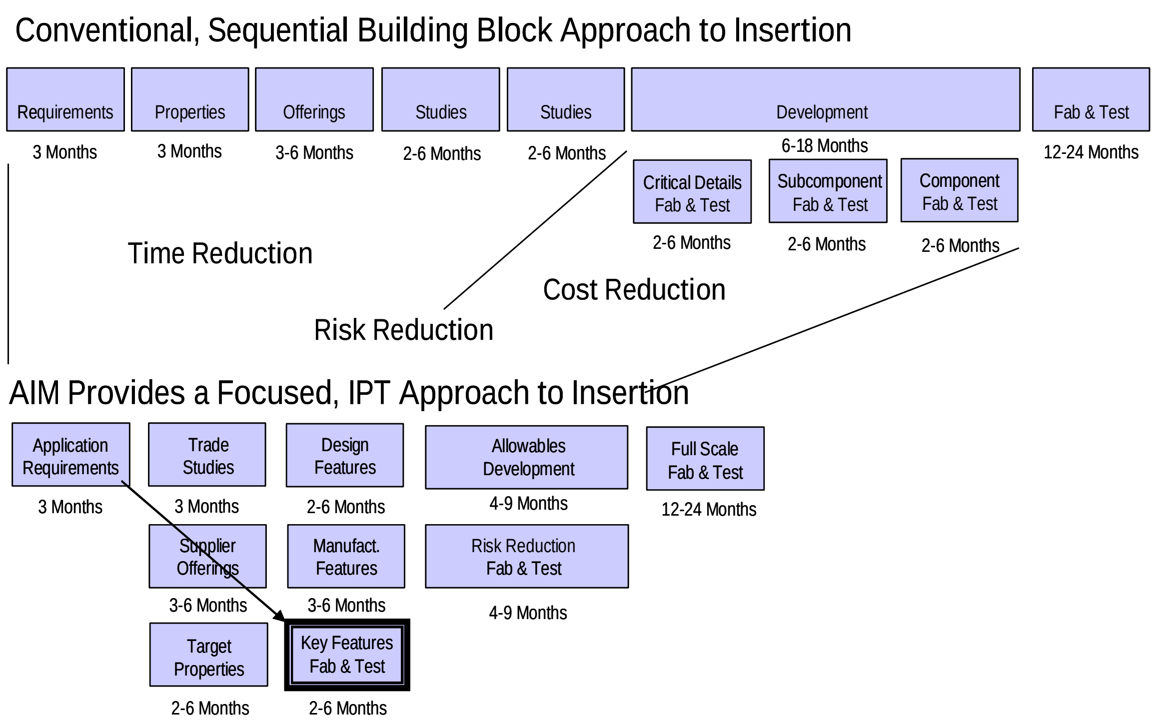



**Figure 7-9 The Key Features Fabrication and Test Article is a Key to Acceleration**

**7.12.2 How the Results of the Key Features Test Focuses the Certification Plan** – In addition to the role of the Key Features Fabrication and Test Article to focus the efforts prior to its testing, the results of that testing drives and focuses the development of allowables for design. For once the Key Features Article has been fabricated and tested, repaired and retested, we know what strength and stiffness parameters drive the design of the component. Thus we can begin to restrict the allowables to those failure modes and loads that control the design of the component. This allows us to focus our testing and knowledge mining on those parameters that control the design.

### 7.13 Summary

Figure 7-10 provides an example of how selected testing, validated analysis tools, and understanding of variability, and uncertainty management can be utilized for allowables determination. This approach is promising for further application in joints and other increasingly complex structural certification situations.

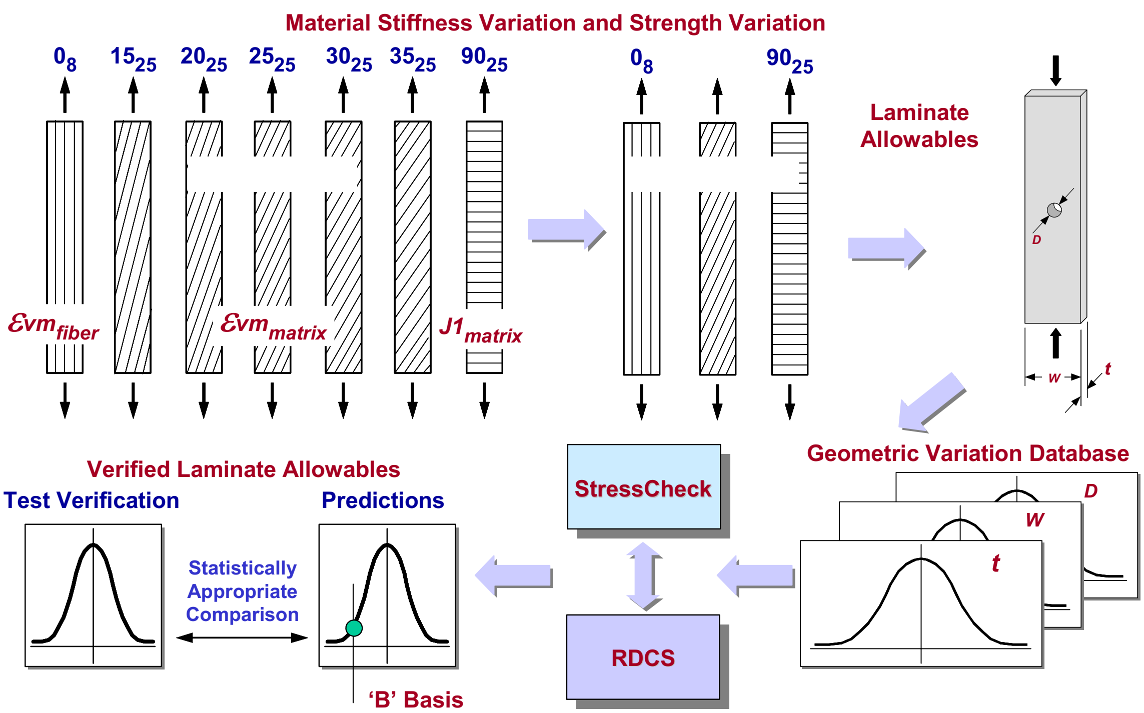



**Figure 7-10 Traditional Allowables Using the Strain Invariant Failure Theory (SIFT) Based Approach**

# 8. Legal Considerations

Regulations or legal considerations are of the highest priority when considered in development of the problem statement and requirements before conformance planning can begin. Most requirements are negotiated; some of these, however, are not negotiable and could pose to be show-stoppers.

- Safety and Medical – Evaluate the Material Safety Data Sheet to get approval for use and assess the cost of personal protection equipment for materials handling, needed facility or material handling changes, and other product liabilities such as toxicity, teratigen, carcinogen, etc. Check by-products during heat up, cure, dust, and leaching which could occur over the product life cycle in manufacturing, fabrication, assembly, support, use, and disposal.

- Check legislation, case law, and other regulations. These include environmental issues, international laws (if the use is a world wide application), safety and medical (as mentioned earlier), etc. Are there legal issues such as substance control, ozone depleting substance, etc? Are there Federal Acquisition Regulations (FARS) or Defense Federal Acquisition Regulations (DFARS) regarding the material or application, sources of the material or process, etc?

- Check program requirements/contract and those of your particular qualification/certification agency. Is first article testing required, live fire testing, etc? Are there milestone deadlines that are none-negotiable or critical path items? Are there restrictions on sources of supply for information or goods exchange?

- Check Intellectual Property status. Which items are protected? Which are not? Which should be? Are there hidden costs from licensing, sole source conditions, etc? Are the issues delineated and plans in place to cover licensing, copyrights, publications, etc?

- Are there existing proprietary information agreements or similar arrangements that must be addressed?

- Are there export restrictions?

- Are appropriate policies, marking guidelines, and authentication procedures in place to address all the issues uncovered?

Some of the obstacles that have been identified from these types of studies include:

- Conflicting requirements
- Prohibitive disposal costs
- Raw material source was not available/scalable for growth

- Personal protection equipment was available to deal with the hazard (carcinogen or mutagen), but the company did not want the risk or press of having the hazard in the working process or community.
- Material did not pass toxic characteristics leaching procedure so the cost of curing it before disposal was added to the consideration of its use.
- Dermatitis was a bigger issue than was anticipated.
- The odor of a material was obnoxious to workers.
- Volatiles could not be deal with economically in scale up.
- There were hidden costs to use of the material.
- The end product could not be used world wide, so the material selection was changed.
- Competing materials were clearly identified and a strategy for judgment was defined.
- A key resin toughener was not available for the product on a production basis.
- A critical analysis technique could not be used because of pending litigation.  The schedule and cost profile had to be changed to accommodate additional testing.

# 9. Managing Error and Uncertainty

**Part I. A Structured Approach for Managing Uncertainty**

One key part of the AIM-C approach for accelerating material insertion is using a structured methodology for dealing with potential error sources and uncertainties. This section gives a brief description of the approach developed and used during the AIM-C hat-stiffened panel design selection process.

The basic AIM-C approach for addressing uncertainty consists of the following four steps:

–Understand and Classify Potential Uncertainty Sources
–Determine What Is Important
–Limit Uncertainty/Variation by Design and/or Process
–Quantify Variation (Monte Carlo Simulation or Test)

**Step 1. Identifying and Understanding potential uncertainty and error sources**

–Maintains Visibility of potential errors
–Forces step-by-step breakdown of the analysis/test process
–Forces agreement on responses of interest

Classifying them allows the team to determine appropriate strategies for addressing them. Figure 9.1 provides an example.

| | Inherent variations associated with physical system or the environment (Aleatory uncertainty) | Uncertainty due to lack of knowledge (Epistemic uncertainty) inadequate physics models | Known Errors (acknowledged) e.g. round-off errors from machine | Mistakes (unacknowledged errors) human errors e.g error in input/outp |
|---|---|---|---|---|
| **Lamina Stiffness/ Thermal Properties** | Variation in all fiber and resin moduli, Poisson's ratio, and CTE | Unmeasurable Constituent Properties (transverse fiber modulus, etc.) | CCA: Use of model outside of bounds.(e.g., woven 3D preform) | CCA: I/O errors, code bugs<br><br>Empirical:Testing machine not |
| **Laminate Stiffness Calculation** | Variations in ply-thickness, ply angles, etc. | Assumes thin plate with no shear | Use of model outside bounds for items listed | I/O errors (ply thickness, material, layup |
| **Stress-Free Temps/ Residual Curing Strain Input** | Many parameters can affect residual stress: local fiber volume fraction, | Micro-stresses are considered to be independent of meso-stresses; there are few | The formulation is believed to be most accurate when the cure cycle temperature | Errors in material property definition, errors in coding, errors in integrating |
| **Coupon Geometry and Load/BC Input** | Cured ply thickness variations, specimen | | | Errors in Coupon Geometry Definition or Improper |

**Figure 9.1 Example of Identifying and Classifying Uncertainties**

•Types:
–Aleatory Uncertainty (Variability, Stochastic Uncertainty)
–Epistemic Uncertainty (Lack of Knowledge, e.g., unknown geometry)
–Known Errors (e.g., mesh convergence, round-off error)
–Unknown Errors (Mistakes, e.g. wrong material inputs used)

**Step 2. Determining which variables are important.**
Complex problems have hundreds of potential uncertainties. Since it is time-prohibitive to spend equal effort investigating each one, effort must focus on the most important uncertainty sources – those which are likely to occur, and/or those which have a large influence on the response(s) of interest.

It is interesting to note that this evaluation is similar to simple Risk Analyses, assessing both Probability of occurrence and consequences of failure.

Prior knowledge is useful in determining likelihood of occurrence. One good example of this is illustrated in Figure 9.2. In developing the analysis approach for predicting the performance of the hat-stiffened panel, it was necessary to account for the potential presence of structural defects. There are a near-infinite variety of potential defect types – over 100 are listed in Boeing quality documents for composite structures. Given our limited schedule and budget, there was no possibility to develop approaches to address all possible occurrences. Using data from past programs, the most frequent defects were determined for cocured and cobonded stiffened panels. These defects, comprising almost 75% of all defects, were determined to be Delaminations, Cure Cycle Inconformities, Ply wrinkles, and Voids/Porosity.

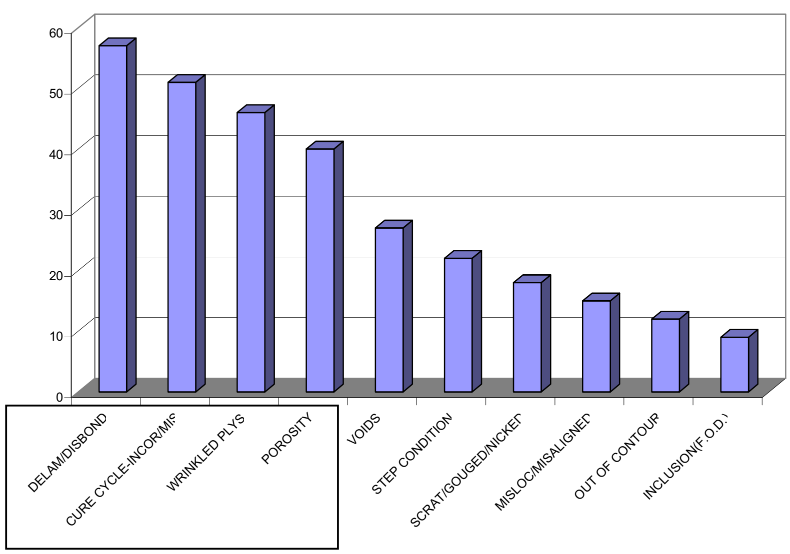



*Figure 9.2 Pareto of Defects for Cocured Stiffened Panels*

Tools such as Design Scans, analytical Design of Experiments (DOE), Analysis of Variance (ANOVA) Taguchi methods, and Sensitivity Analysis are useful in quantifying a variable's influence on the result. The Robust Design Computational System (RDCS) provides this tool suite, Figure 9.3.

**A Domain Independent Comprehensive Tool Set to Analyze the Design Space**

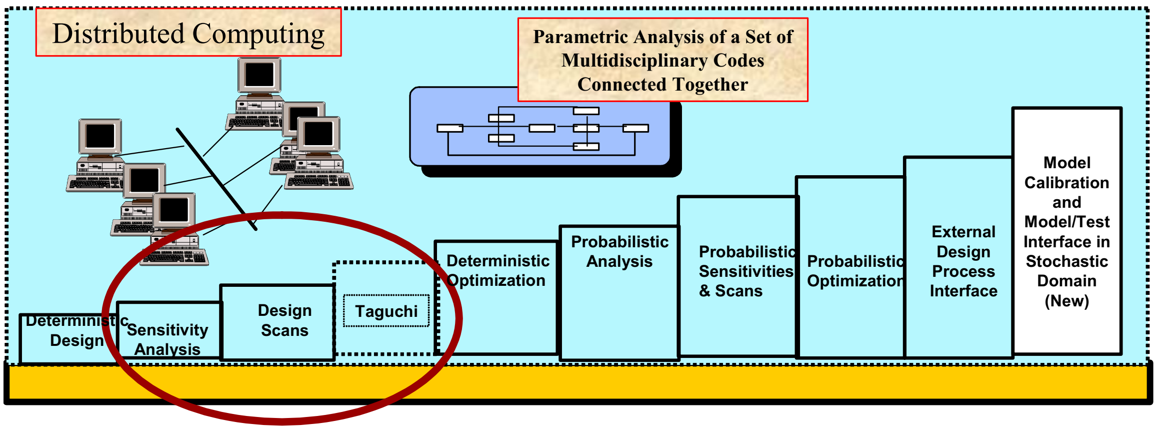



*Figure 9.3 Robust Design Computational System Tools for Assessing Importance*

The use of these tools has occurred frequently on the AIM program. One example from the AIM-C program is the investigation of fiber transverse modulus effect on composite laminate performance. The transverse modulus of the fiber is a very difficult property to accurately measure. This raised a very serious concern that any inaccuracy in this transverse fiber modulus estimated may lead to excessive error in laminate strength and modulus. Using RDCS Design Scan tools and ANOVA showed that, as expected, Fiber Volume and Fiber $E_{11}$ had significant effects on laminate modulus, but Transverse Fiber Modulus ($E_{22}$) had very little effect on either laminate stiffness (Figure 9.4, left side). Using RDCS sensitivity analysis tools, data was produced (right side of Figure 9.4) showing that large ±20% variations in fiber $E_{22}$ also had very little effect (about ±1%) on laminate strength.

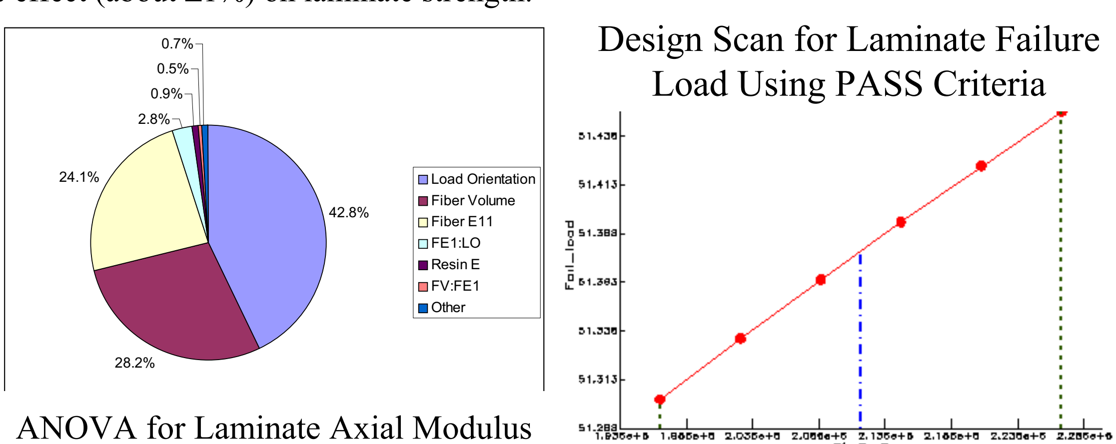



*Figure 9.4 Effect of Transverse Fiber Modulus on Laminate Stiffness and Strength*

Other examples from AIM-C include the effect of Stress Free Temperature on laminate performance and the effect of various geometric variables on Stiffener Pull-off load. In the first example, it was found that there was very little variation in stress free temperature for flat laminates over a wide range of cure cycles. This small variation had an insignificant effect on thermal stresses in the laminate, which, in turn, had almost no influence on laminate failure. In the second example, results showed that some geometric variables, such as stiffener cap width, had almost no effect on structural performance.

**Step 3. Limiting Variation by Design (Robust Design)**

Where possible, many uncertainties may be eliminated or reduced by design choices. The idea is simple – Pick the material and design to play to your strengths! One major advantage of this step is that the process produces data early in the design cycle, allowing negotiation between competing response variables (e.g., Structural Performance and Producibility)

This is a major philosophical shift for Structures (as well as many in other organizations). In the rush to obtain adequate functional materials and designs which meet all the requirements, making designs robust to variation and other uncertainties is typically thought of as a luxury that the program cannot afford. On the contrary, data suggests that the current approach, which ignores design robustness issues, may in fact result in an increased insertion schedule and increased costs. The left side of Figure 9.5 shows data from an actual program which illustrates that design rework to address unanticipated performance problems results in significant time and money expenditure. The right half shows an ideal situation, where the tools and procedures are available to address these issues in the initial design.

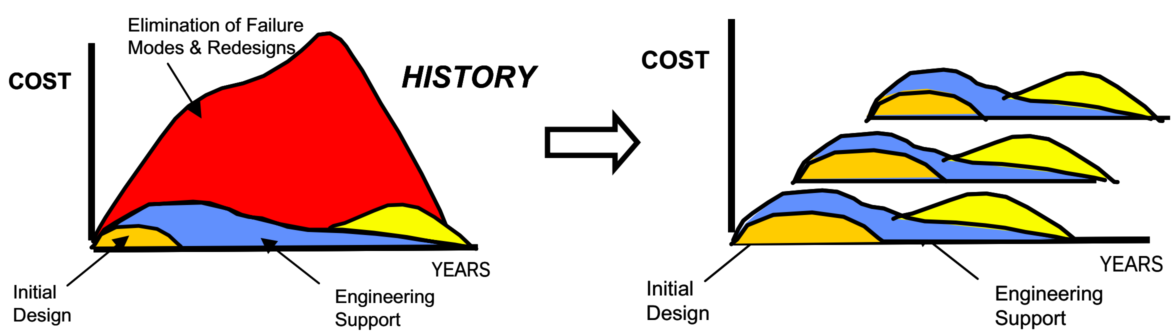



*Figure 9.5 Effect of Better Design Selection on Insertion Time and Cost*

Figure 9.6 shows the cost information of various phases of an actual material insertion into a stiffened panel design. The rework effort due to redesign activities exceeds the constituent, coupon, element, subcomponent and component tests combined! The only larger expense is the cost of the full-scale airplane testing.

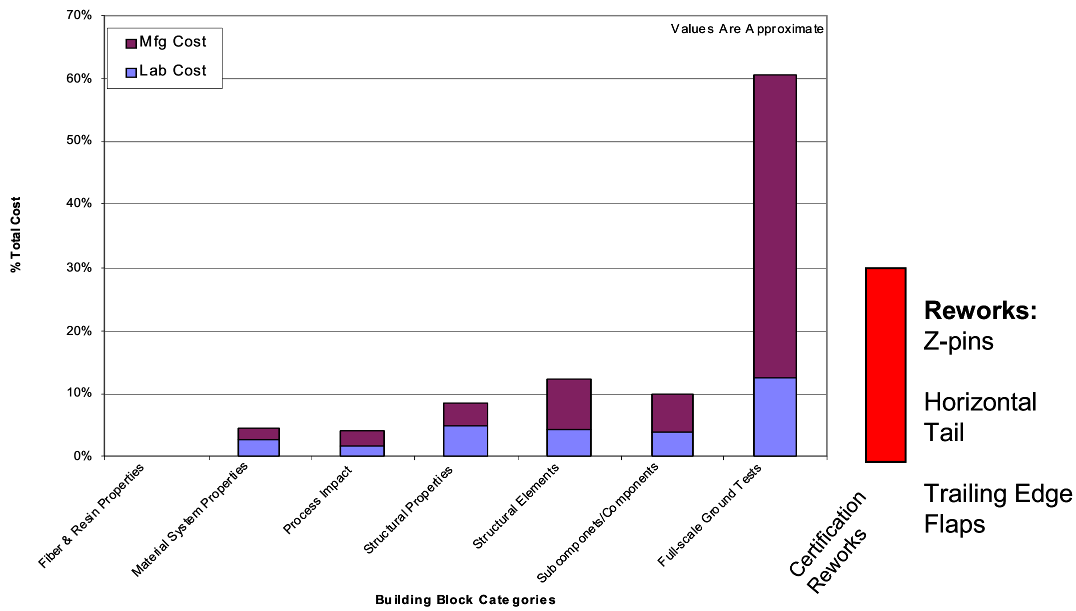



*Figure 9.6 The Effect of Redesign Activities on Total Hat Stiffened Panel Development Costs*

On AIM-C, we undertook a similar hat-stiffened-panel (HSP) insertion problem. With a goal of avoiding this time-consuming and expensive redesign activity and thus accelerating this insertion activity, we applied the latest emerging analysis tools and a robust design philosophy. The benefits were threefold. First, by applying simple versions of the tools to quickly perform design studies, we put data on the table early. This helped the integrated product team develop reasonable compromises that were based on data. Second, by combining these analysis tools with statistical techniques (such as DOE/ANOVA and Sensitivity Analysis), we were able to perform studies that allowed us to achieve a more robust design. Finally, we were able to both (a) build a configuration which was very close to the "as drawn" and (b) predict the performance of the as built configuration. In Structures, we expect that our enhanced focus on Design Robustness (rather than Absolute Mean Performance) will likely yield a better "allowable" failure load.

Problem 1:
• Bondline delaminations are commonly occurring defects
• They occur at structurally-critical locations
• The failure load can be very sensitive to bondline delaminations
Question: Can we formulate a design that is much less sensitive to delaminations?
Using a parametric SUBLAM model, we can focus on several geometric variables and their effect on propagation of small bondline defects (delaminations) in three areas where they commonly occur – at the edge of the flange, and two locations adjacent to the noodle (nugget). The goal of the study is to find reasonable values of the geometric parameters (attach flange length, lower radius, and angle of the hat sidewall/web which minimize the likelihood that these defects will grow. Using a parametric model (shown in Figure 9.7) and the distributed computing and ANOVA analysis capabilities of RDCS makes this study quick and easy.

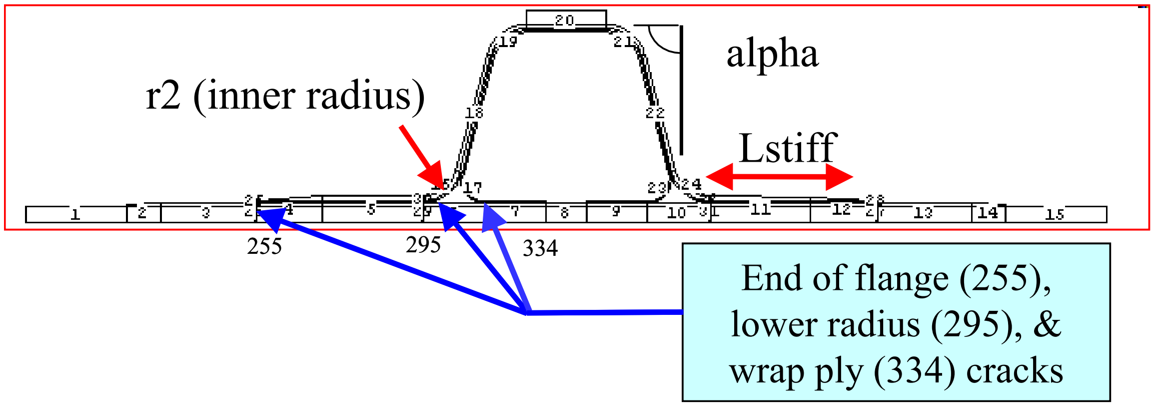



*Figure 9.7 SUBLAM Pull-off Model for Hat-Stiffened Panel*

Figure 9.8 shows initial results for the influence of the lower radius and the stiffener length on the Strain Energy Release Rate (SERR) at the delamination tips. In this figure, the web angle is fixed at 30°. The initial design point (web angle = 30°, radius = 0.25", and attach flange length = 0.75") is shown as a red dot. The data shows that this design is critical for Mode I growth of the delamination at the edge of flange (the red plane) and has a SERR of about 1.0. The green dot represents a new potential design point which minimizes the SERR. This new design with web angle = 30°, radius = 0.20", and attach flange length = 1.25" is simultaneously critical for Mode I growth of the flange edge delamination and mixed mode growth of the radius delamination. The SERR of this design is about 0.5. This means it has half the sensitivity to these defects (i.e., it takes double the pull-off load to cause defect growth).

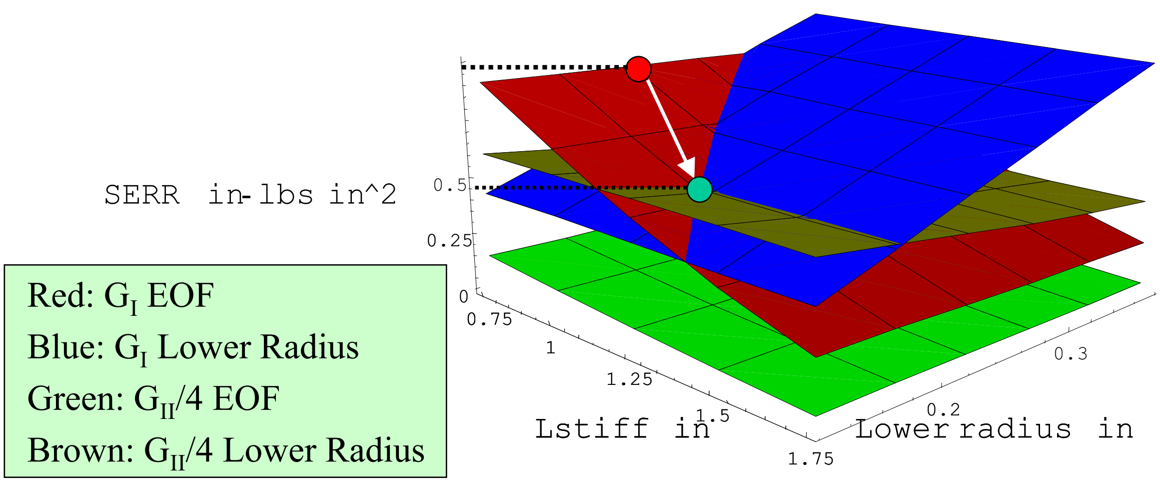



*Figure 9.8 Effect of Stiffener Leg Length and Lower Radius on Delamination Defect Sensitivity*

Figure 9.9 illustrates taking the study one step further. By reducing the stiffener spacing, adding wrap plies, and reducing the web angle to 20, the design is now critical for Mode I failure at the lower radius flaw and the SERR is again halved to less than 0.25. This design is now only one-fourth as sensitive to bondline flaws as the original design!

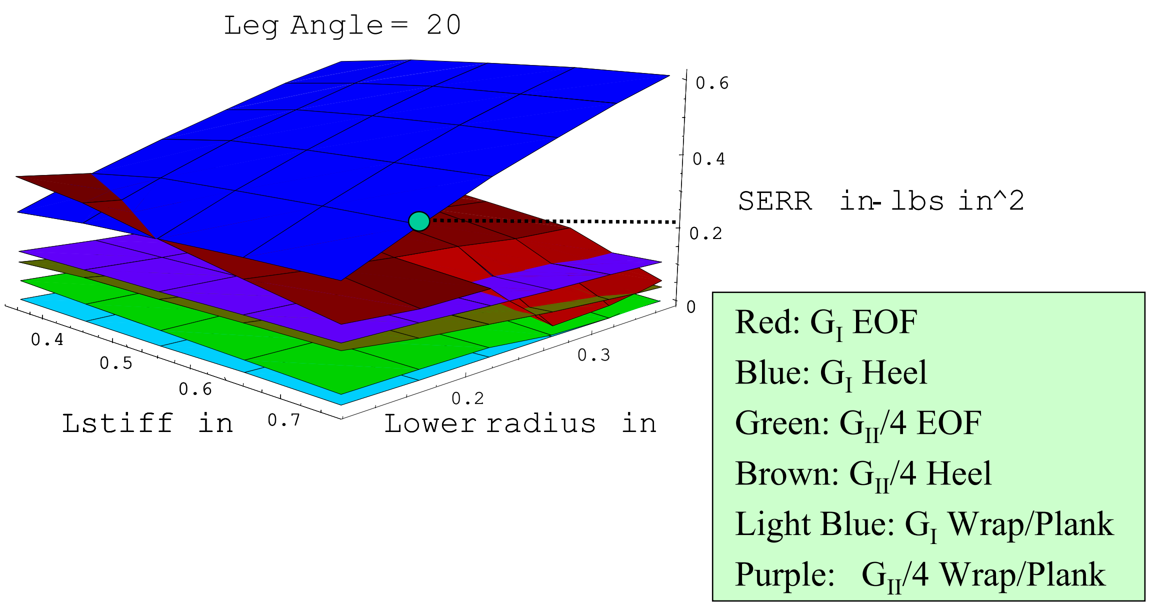



*Figure 9.9 Delamination Defect Sensitivity after Design Iteration*

Note that in the final design, we decided to use a "corrugated design' which has no edge of flange. This effectively eliminates the "edge-of-flange" defect location. This is another way to reduce the sensitivity of defect by design – instead of making the design robust to the presence of the defect, the IPT may choose designs which minimize or eliminate the possibility of defect occurring.

Problem Statement 2: A second example involves sensitivity to geometric manufacturing tolerances. Can we minimize the effect of off-nominal dimensions on the failure load? Basic strength and stability and weight considerations suggest the hat should be tall (say 1.91-cm, 0.75-inches or above). For tall geometries, the above results suggest that a gentle run-out angle (less than 45°) is required to "get on the flat area of the curve" (i.e., to reduce the sensitivity of the failure to the angle tolerance of the run-out), Figure 9.10.

For this study, a relatively simple parametric 3D shell model of the stiffened panel is used. Instead of using a Fracture Mechanics approach and seeking to reduce the SERR near known flaws, this study uses the Strain Invariant Failure Theory (SIFT) and seeks to find geometry combinations that reduce the dilatational and distortional strains ($J_1$ and $\varepsilon_{vm}$). The results are shown in Figure 9.10.

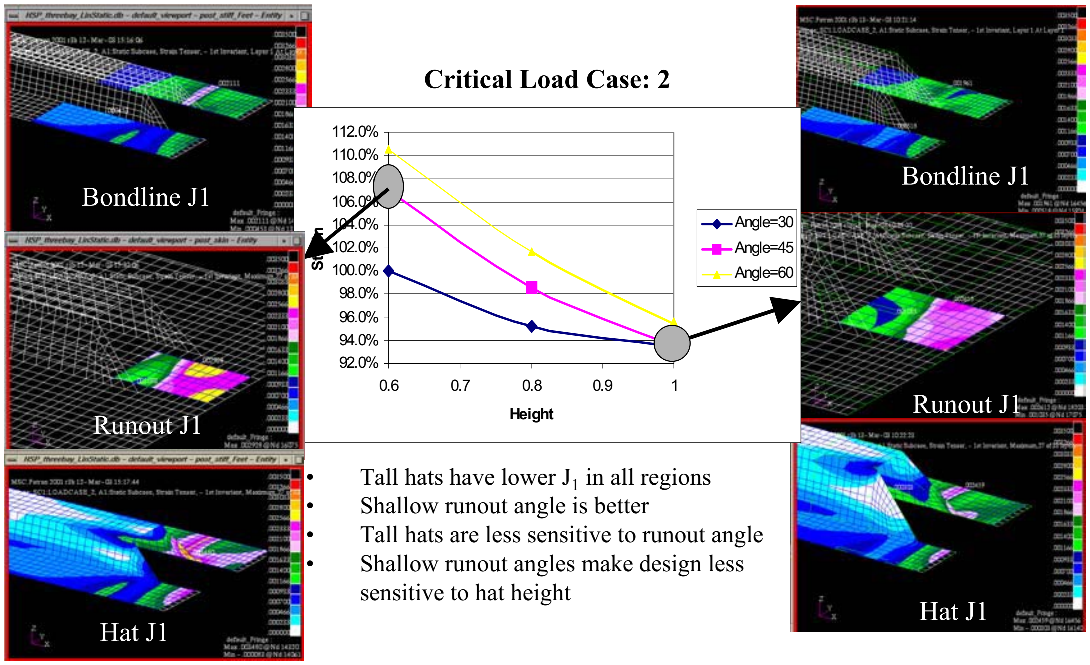



*Figure 9.10 Effect of Stiffener Termination Geometry on Peak $J_1$ and $\varepsilon_{eqv}$ Strains*

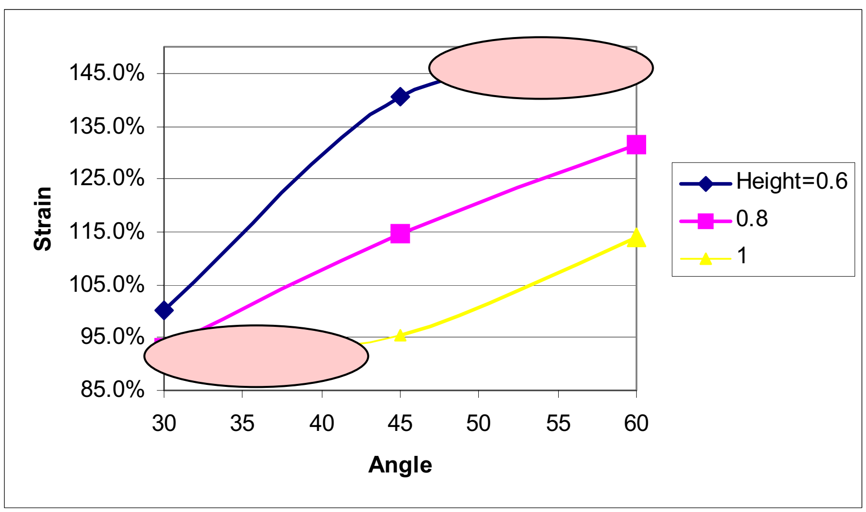



*Figure 9.11 Effect of Runout Geometry on Peak Runout J1*

Basic strength and stability and weight considerations suggest the hat should be tall (say 0.75" or above). For tall geometries, the above results suggest that a gentle runout angle (less than 45°) is required to "get on the flat area of the curve" (i.e., to reduce the sensitivity of the failure to runout angle tolerance. Figure 9.12 shows the sensitivity of some designs to the typical ±3° drawing tolerance.

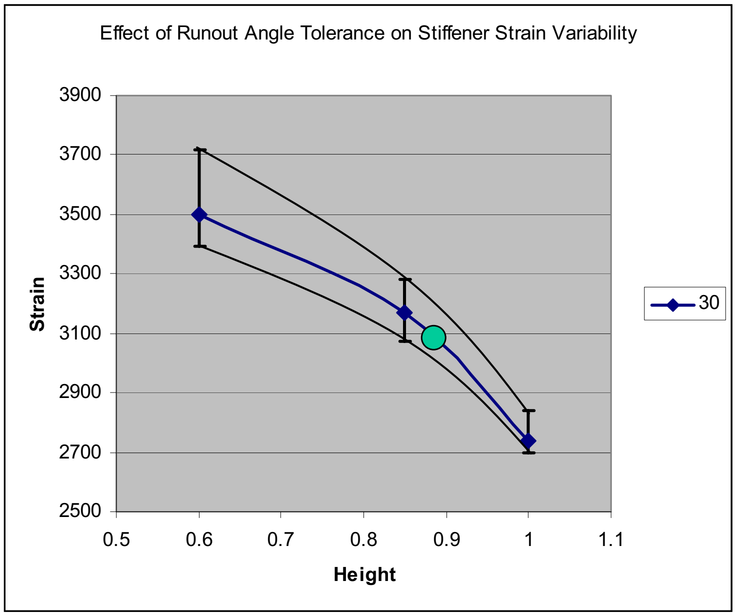



*Figure 9.12 Sensitivity of Peak Runout J1 to Runout Angular Tolerance*

The selected design, shown with a green dot, would exhibit 3% higher strains if the runout angle were cut too steep (but still within drawing tolerance). This would result in a failure load which is about 3% low. If this were unacceptable, the hat could be made taller, trading a bit of weight for additional robustness. The data suggests that very short (0.6”) hat designs would fail about 6% low under the same off-nominal condition.

**Step 4. Quantifying Variation**

The final step, after error sources have been identified and classified, impotant variations have been determined, and the design has been made as robust as possible, is to quantify the remaining important variations. To perform this step, Testing or Probabilistic Analysis Tools (Figure 9.13) are applied.

This is another change from current Structures and Materials philosophy, which currently only quantify certain uncertainties, such as material variability associated with coupon allowables. Many other variations are considered covered in “material scatter”, covered by factors, by or worst-case assumptions.

Major challenges exist to ensure widespread adoption of detailed uncertainty analysis. These include reducing the cost and schedule associated with testing, and developing tools and approaches which make analytical statistical studies fast, accurate, easy to use, and produce understandable results. The emergence of new physically-based analysis methods and the continued enhancement of RDCS have made great inroads toward this goal, but the determination of appropriate approaches and procedures for differing applications is still underway.

Recent RDCS improvements, Figure 9.13, have been made which greatly expand the operating space of uncertainty analysis. These improvements include:

- Continuous, discrete and enumerated variable types
- Sensitivity analysis on mixed space and constrained design space exploration
- Integration of external uncertainty analysis plug-ins with RDCS
  - Advanced design of experiments – Design Explorer
- Probabilistic (Robust) Optimization
  - A capability to define statistical parameters as design variables

**A Domain Independent Comprehensive Tool Set to Analyze the Design Space**

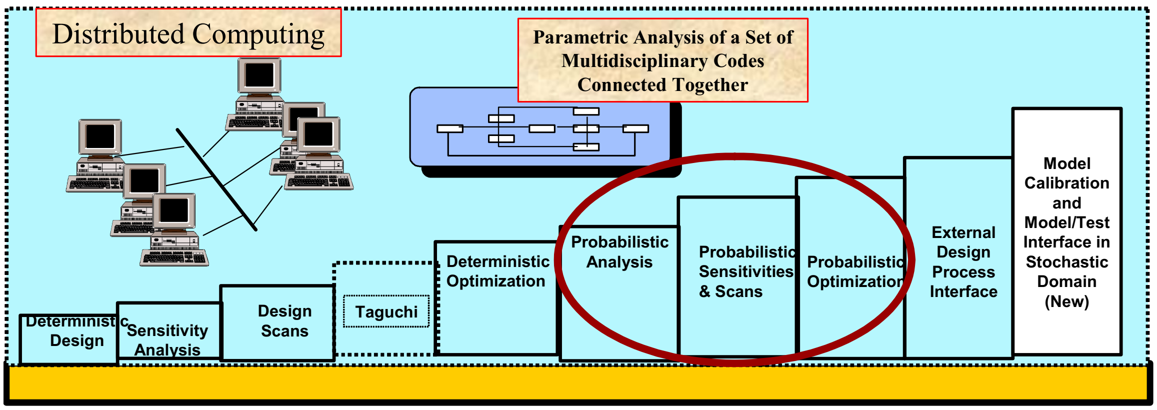



*Figure 9.13 Robust Design Computational System Tools for Quantifying Variation*

One simple example on AIM-C is the use of RDCS Probabilistic Analysis to assess the effect of constituent properties, prepreg properties, and geometric variables on the strength of open hole tension (OHT) coupons. The results of this Monte-Carlo Simulation are shown in Figure 9.14.

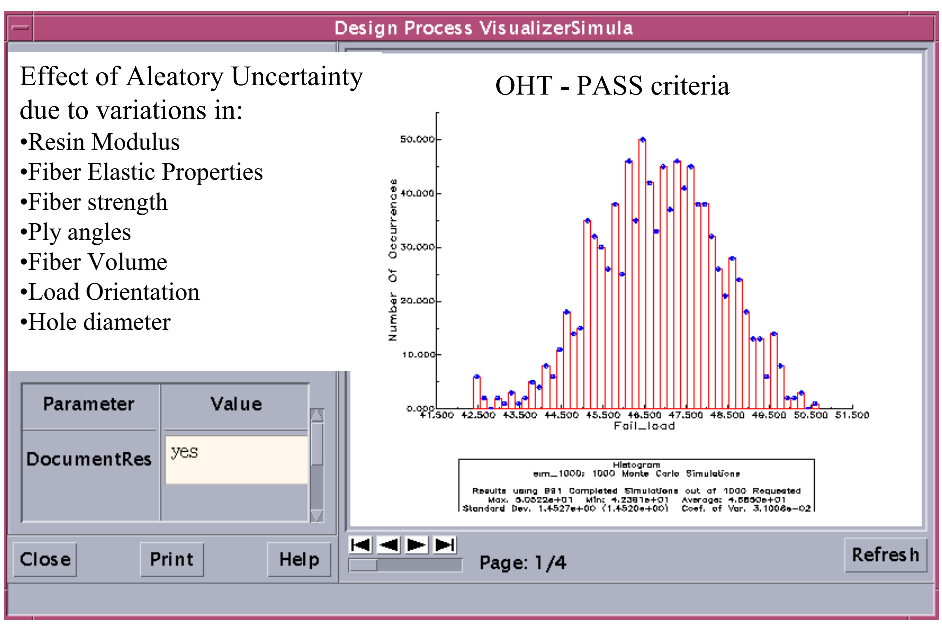



*Figure 9.14 Monte Carlo Simulation Result for Open Hole Tension Strength*

Figure 9.15 shows a summary of the results produced using various simple composite failure criteria. Note that the Maximum Strain Criteria failed to produce reasonable predictions for the mean and also significantly overestimated the variation of the test data. This result was expected, since the laminate was not fiber dominated. These results illustrate an important lesson – statistical analysis is not a substitute for physically meaningful domain analysis (in this case, an appropriate failure criteria).

| | Test | 1. Max.Strain | 2. Hashin | 3. Phase Avg. |
|---|---|---|---|---|
| Mean | 37.274 | ~~57.585~~ | 34.231 | 42.39 |
| Std.Deviation | 1.683 | ~~3.1091~~ | 1.0371 | 1.4527 |
| Coefficient of Variation | .04517 | ~~.06316~~ | .02801 | .031 |

*Figure 9.15 Summary of Monte Carlo Simulation Results for Various Failure Criteria*

Figure 9.16 shows additional information that may be obtained from the probabilistic analysis. On the left is a plot showing the effect of each input variable on the variation (rather than the mean). On the right is a cumulative distribution function of failure load. The 10th percentile value (an estimate of the B-basis allowable with undefined confidence level) is noted in this plot.

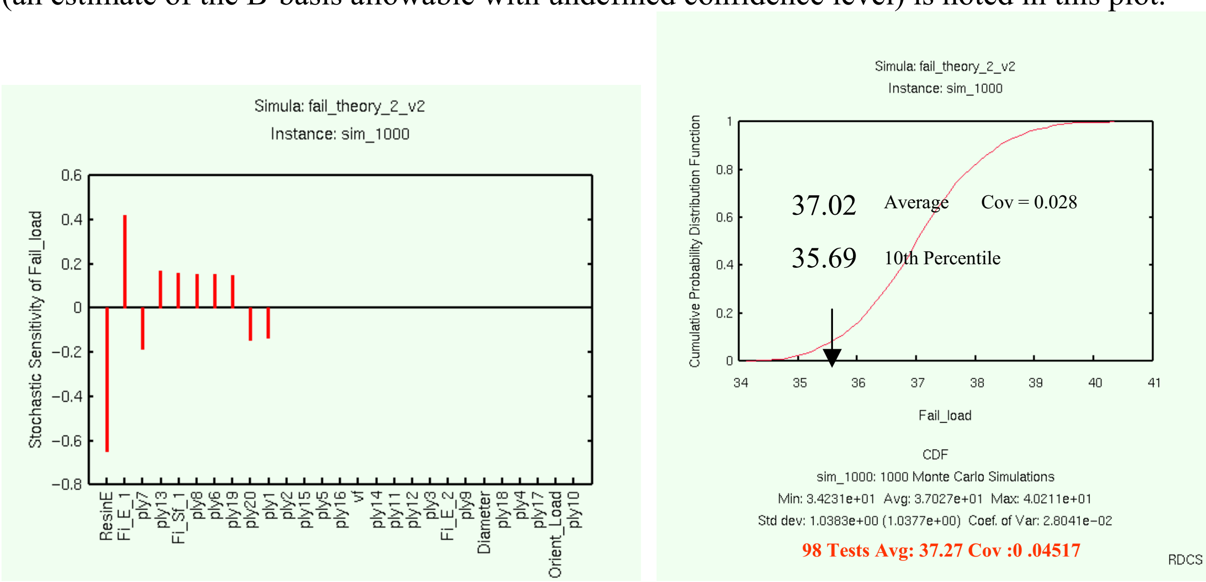



*Figure 9.16 Additional Information Obtained from Probabilistic Analysis*

A more complex example of quantifying variation is a study to predict hat stiffened panel pull-off strength incorporating effects of bondline delaminations, geometric variation, constituent stiffness variation, and critical failure property variation (from test). For this Monte Carlo Simulation, SUBLAM Fracture model similar to the one shown previously in Figure 7. The following parameters are considered random variables and assigned distribution information based on data and allowable tolerances:

–Length of stiffener flange (Mean = 1.25”, SD = 0.015”)
–Leg angle (Mean = 20º, SD = 1.5º)
–Lower radius (Mean = 0.2”, SD = 0.015”)
–Fiber volume (5% COV)

–Fiber modulus (5% COV)
–Resin modulus (5% COV)

The Robust Design Computational System (RDCS) math model shown in Figure 9.17 ties together the Resin, Fiber, Prepreg, and Lamina Modules and the HSP SUBLAM Fracture model to produce results.

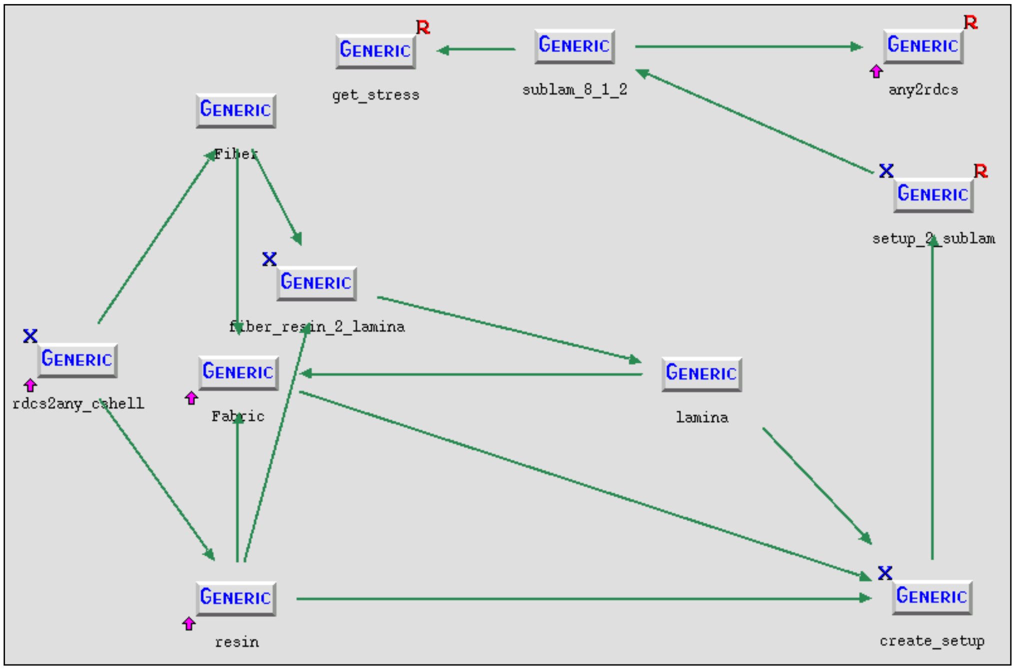



**Figure 9.17 Robust Design Computational System Math Model**

Numerical values of Mode I and II Strain Energy Release Rates (SERR) are reported for a 90 lb/in pull off load. For this geometry, Mode I and II SERR at the end of flange drive the failure results.

Variations in crack driving force due to geometry variation are significant ($SD_{GI}$ = 0.036, $SD_{GII}$ = 0.026). Adding the effect of variability in material elastic constants increases the SERRs to $SD_{GI}$ = 0.068 and $SD_{GII}$ = 0.041. The Mode I variation is shown on the left of Figure 9.18. The Mode II variation is shown on the right.

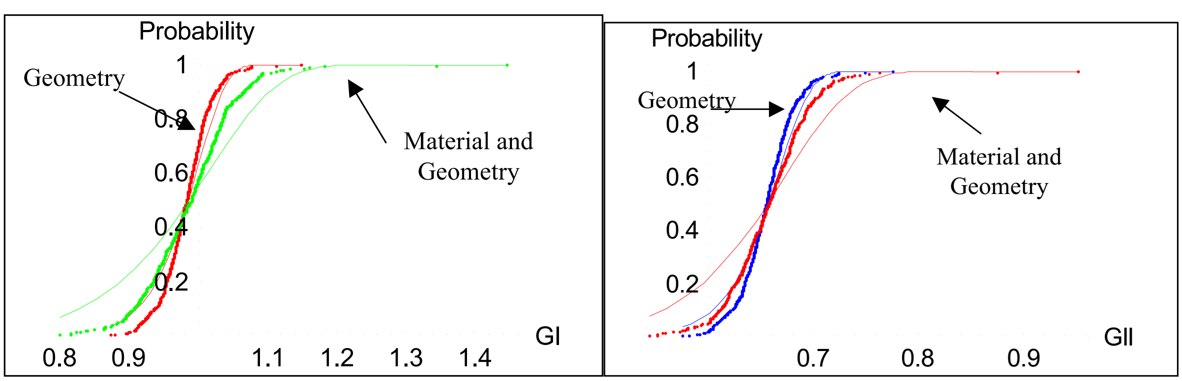



*Figure 9.18 CDFs for Mode I and Mode II SERR Due to Geometry and Material Variation*

Variations in critical failure properties, obtained by test coupon (DCB and ENF) experimental results, are shown in Figure 9.19. Comparing Figures 9.18 and 9.19, it is apparent that the materials measured resistance to crack growth (Critical SERR) is much more variable than computed variations in crack driving force due to other material/geometry variation. These large variations in coupon measured fracture strengths will increase the scatter in the failure load, thus complicating test prediction.

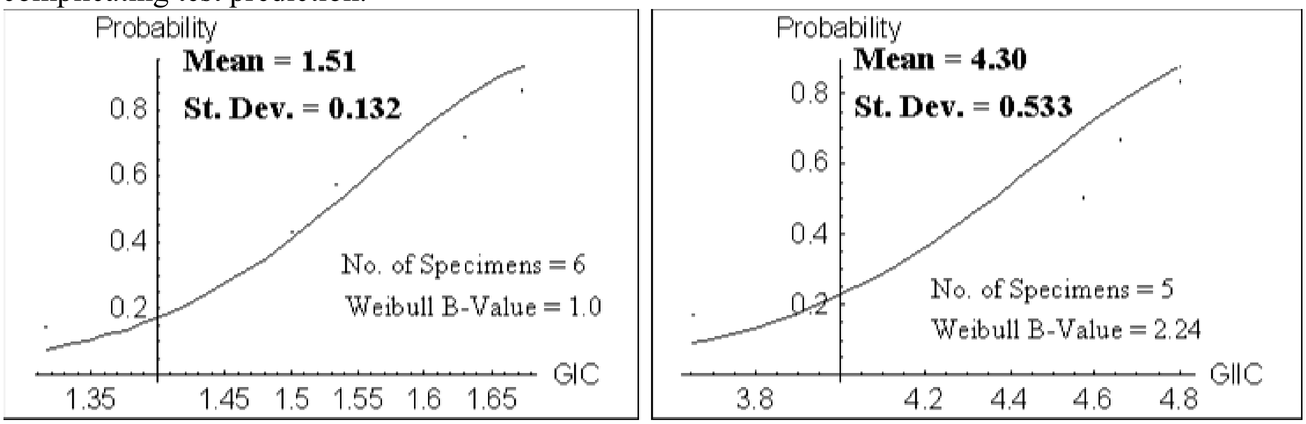
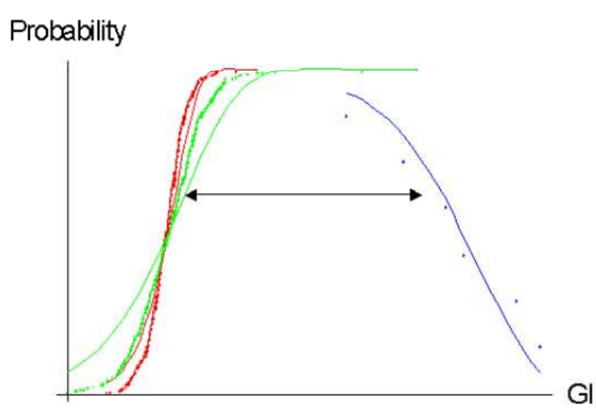



*Figure 9.19 Variation in Critical Mode I and Mode 2 SERR from Coupon Test (DCB and ENF)*

The failure probability, for a given load level is obtained as shown in Figure 9.20, by comparing the cumulative distribution functions (CDFs) of the SERR at the crack tip (the green curve on the left, determined by analysis) with the critical SERR (the blue curve on the right, determined by coupon test).




For continuous distributions, the probability of failure is:

$$p_f = \int_0^\infty F_{G,sublam}(G_{max}) f_{G,exper}(G_{max}) dG_c$$

$F_{G,SUBLAM}$ is the CDF of expected SERRs for the HSP system

$f_{G,exper}$ is the PDF of the experimental data.

*Figure 9.20 Procedure for Determining Failure Load Distribution*

The results of this analysis are shown in Figure 9.21. The two results columns represent another error source associated with the analysis method – the selection of the proper interaction criteria between the Mode I and Mode II fracture modes. The data shown for Criteria 1 assumes a quadratic interaction, while Criteria 2 assumes a more conservative linear interaction. Both assumptions are widely used in practice. For both criteria, the mean values, standard deviations, and B-basis values (90% of the population is above this value with a 95% confidence level) are predicted. Regardless of criteria, the data shows that the B-value prediction strongly depends on the confidence in the input data.

| | | Criteria 1 | Criteria 2 |
|---|---|---|---|
| Mean (lbs/in) | | 110 | 100 |
| Standard Deviation | | 5.82 | 4.90 |
| B-Values (lbs/in) | n = 6 (current number of experimental data) | 77.5 | 72.6 |
| | n = 10 (typical number of experimental data ) | 80.5 | 75.1 |
| Weibull Distribution | n = 500 (simulation results) | 99.8 | 91.6 |

*Figure 9.21 Pull-off Failure Statistics*

Following these four steps will help any IPT to better understand the effects of all uncertainties, and to maximize the likelihood of a successful material insertion into any design application.

**Part II. Using and Combining Data from Knowledge, Analysis, and Test**

As with any engineering endeavor, the "Designer" attempts to bring to bear information from all available sources. This may include data obtained from many sources, including:

–Previous Knowledge and Divergence Risk
–Analysis
–Test

To make proper use of this data, the design build team must understand the peculiarities associated with each source of data, as well as having appropriate methods for combining it into a rational, complete picture.

**Data Obtained from Previous Knowledge and Divergence Risk**

This may include information and conclusions from previous testing, analysis, and fabrication/service experience of similar materials and/or the same material used in a different structural concept or service environment.

The data may take the form of documented data or lessons learned, or may be in the form of "expert opinion". An example of such data is shown in Figure 9.22, which summarizes previous experiences of several experienced manufacturing engineering experts on the effect of tooling on part quality for stiffened panels.

| Issue | Rigid Tooling | Soft Tooling Approach |
|---|---|---|
| Stiffener Spacing | Excellent control (+/- .03" possible) | Poor control. Expect movement of up to .13". Difficult to pin details that have limited rigidity. |
| Stiffener Straightness | Excellent control (< .09" out of plane over 36") | Decent control (< .13" over 36") |
| Edge Ramp Definition (ply drops) | Potential consolidation issues. The tooling forces the part shape. If plies are mislocated, fiber/resin movement is required to achieve consolidation. One ply (<7% thickness) mislocated is typically OK. Greter amounts cause problems. Misplaced ply ramps cause problems. | Excellent consolidation. Should be well consolidated even if plies are significanly out of place. (Does not address ply waviness at stiffener termination) |
| Traditional Composite Panel Defects (delaminations, porosity, inclusions, etc) | Possible Porosity due to long Volatile Escape Paths | No Unique Issues |
| Top Radii Thinning | Top radii expected to be slightly thicker than nominal (10-15%) (Rubber mandrels will produce less pressure in the corners | Top radii likely to be thin. Up to 40% thinnout will sufficient numbers of uni tape plies. Up to 20% with all cloth plies. |
| Crowning (Top & Sides) | No Unique Issues | Crowning Expected (~0.050) |
| Crowning-Skin (Thin skin under hat) | **10% Thinning Expected** | **10% Thinning Expected** |
| Bottom Radii Thickening | **5 to 10% Thickening Expected** | **15 to 30% Thickening Expected** |
| Thick/Thin Flanges | Flange thickness controlled by the full surface tooling. Not typically a noticable problem. | Flange edge thickness more variable. Flanges typically 15% thin due to tooling pressure. (Fiber volume change in flanges and skins under the flanges. Resin flowed out toward midbay and noodle area.) |
| Noodle Voids, Porosity, Delaminations | Dependant on proper amount of noodle material. Preforming adhesive helps as well as overstuffing by ~10%. (Overstuffing dependant on radii and surrounding material.) | Tooling/part variability makes the proper amount of overstuffing harder to predict. Therefore typically overstuffed by 20% which reduces voids and porosity issues but exacerbates radii thickening issues. |
| Noodle Fiber Waviness (plies around radii near noodle) | Typically not significant | Due to additional noodle overstuffing described above, this condition may result. |

*Figure 9.22 Expert Knowledge of Likely Defects Resulting from Various Tooling Concepts*

Data obtained from previous experience is particularly prone to Epistemic error and mistakes. When documenting results, it is practically impossible to foresee all the potential future uses for the data. Also, engineering documentation is often not written with this purpose in mind. As a result, written reports and databases often omit key data required to completely assess the applicability of the analysis or test data. Sometimes, if the data was generated recently, it may be possible to find key individuals who can fill in the details and share undocumented data and conclusions. Unfortunately, human memory also can be faulty. Even if the events are remembered as they occurred, each individual tends to put them in a context based on the whole of their previous experiences. After witnessing a test, for example, most people walk away with a slightly different perspective of what occurred and what conclusions can be drawn.

All previous data requires interpretation and extrapolation to be applied to the current application. This brings up the question of Divergence Risk – What constitutes similarity and How do you characterize or quantify any differences from the current application?

–We do this all the time (Engineering Judgment)
–Example coupon COV from similar systems
–Mathematical or other structured approaches

Obviously, if the previous data was developed last week (little time for technology to progress) and is for exactly the same material, design, and application, there is no significant divergence risk. If it is from 20 years ago, using a different material, design, and application, it will likely provide much less applicable information and will require a great deal of engineering judgement to apply. In almost all cases, the reality is between these two extremes. In almost all cases, new empirical knowledge from analysis and testing will be required to “bridge the gap”.

**Data Obtained by Analysis**

Data from analysis has a number of advantages. If appropriate analysis methods are available, it is relatively fast and inexpensive to develop analytical data. It is also the easiest method for dealing with most aleatory variations, even allowing assessment of variations which would be very difficult to vary and measure by test. Along with these advantages, there are some limitations. First, all analysis methods require some input data obtained from test. In the materials and structures realm, true material scatter must be obtained from tests. Using analysis, the influence of this scatter on failure load can then be assessed by analysis. Also, to provide accurate results with just material data, an accurate physics-based method must be available. Many analysis methods are semi-empirical, requiring additional test data for calibration and limiting the variables which can be analytically assessed.

Analytical data is naturally prone to Epistemic uncertainty.
–Is something missing in the Physics or Idealization?
–More difficult as complexity of shape or loading increases
–Surface Finish Example, Fillet Example
Examples of data obtained from analysis include the structural failure studies for Laminate Strength Analysis and Hat Stiffened Panel pull-off load discussed earlier.

**Data Obtained from Physical Tests**Test data is currently considered to be the “Gold Standard” of data because it accurately assesses the Physics…but only of the test specimen (with its associated boundary conditions, loads, environment, etc.). Physical testing cannot possibly duplicate the actual service conditions of the real application (aircraft, missile, etc.).

Small coupons and simple materials tests

Simple coupon tests often have more variation and error sources than is generally recognized. They are prone to excessive aleatory uncertainty that is often inadvertently lumped with “material scatter”. Figure 9.23 demonstrates this effect. Filled Hole Compression (FHC) specimens have a typical manufacturing tolerance for both the hole and the fastener. Analysis shows that this tolerance has a significant effect on the failure load, which is generally considered part of the “material scatter” for this property. These phenomena must be recognized and accounted for in the specimen preparation and test procedures, otherwise a dull drill could bias the results, or the use of two different fastener lots could increase the scatter.

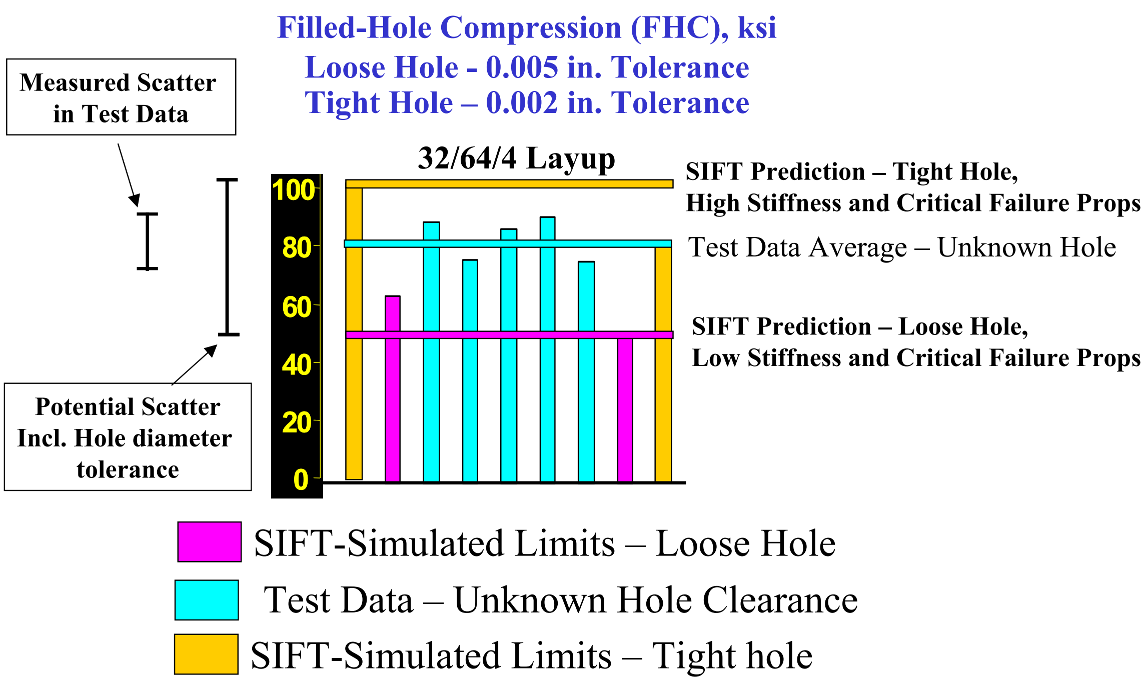



*Figure 9.23 Specimen Hole Fit Tolerance Affects "Material Scatter"*

Small coupon tests often also have specimen preparation and test setup variation which does not exist on the real aircraft. This is often inadvertently included in the "material scatter". One example is shown in Figure 9.24. In this example, the fixturing method for the open hole compression specimen influences the failure load. If not accounted for, this effect may show up as a bias in the mean, or (if combining data from multiple sources) added test variation.

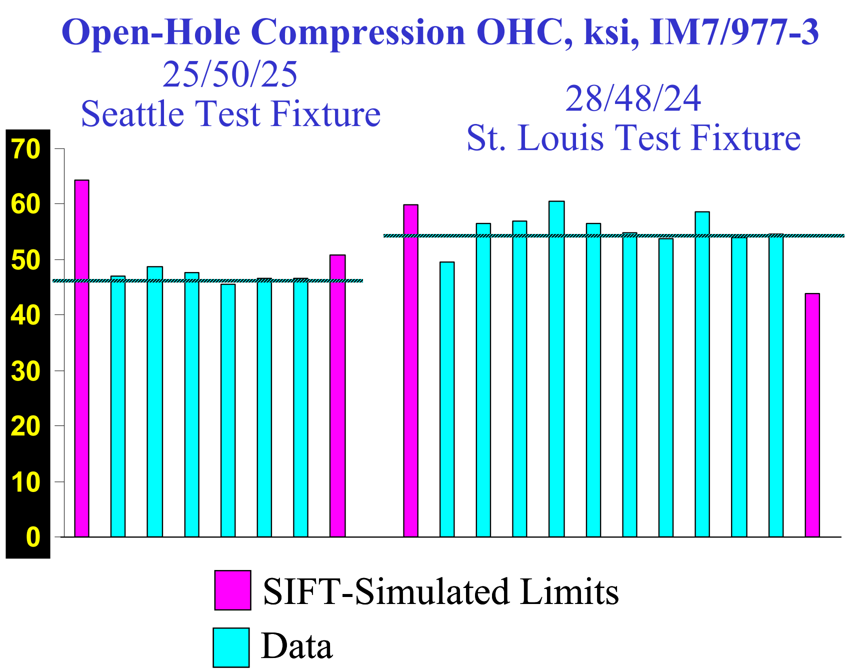



*Figure 9.24 Test Fixturing Affects "Material Scatter"*

In addition to effects such as those shown above, coupons and elements may not be representative of the actual structure unless excised from larger panels

***Large-Scale Testing and Complex System tests***

Large-scale system testing has the advantage of capturing scale-up effects (such as real manufacturing process effects, size effects, and interactions between the various elements of the system). In addition, big tests are very convincing – they look quite real – but, as with analysis, it is prone to idealization errors. For example, getting consistent known Boundary Conditions and Loading is often difficult. An excellent example of this difficulty is the full-scale thermomechanical fatigue test of the Concorde airframe, which was so complex that the results were very difficult to interpret. Large system tests can provide very useful validation data, such as verifying that the analysis correctly predicted the correct critical failure mode and location, and the correct load distribution, but they are very expensive and insufficient if used alone.

Due to the expense, few (if any) replicates can be tested. This means that it becomes very difficult to *quantify* aleatory uncertainty since you can only obtain limited quantitative failure data (e.g., selected environments, and only a single critical failure mode). This type of testing relies on smaller building block element testing and analysis to provide supporting data and to adjust the results to other relevant environments. It is generally only used to provide a final validation that the analysis and data from the small-scale testing is correct.

**Combining data from multiple sources (Heterogeneous Data):** From the previous discussions, the need for a coherent methodology for integrating various sources of information with their own uncertainty pedigree is clear.  In the most general sense, the various elements of the developed data pooling methodology can be graphically represented as in Figure 9.25.

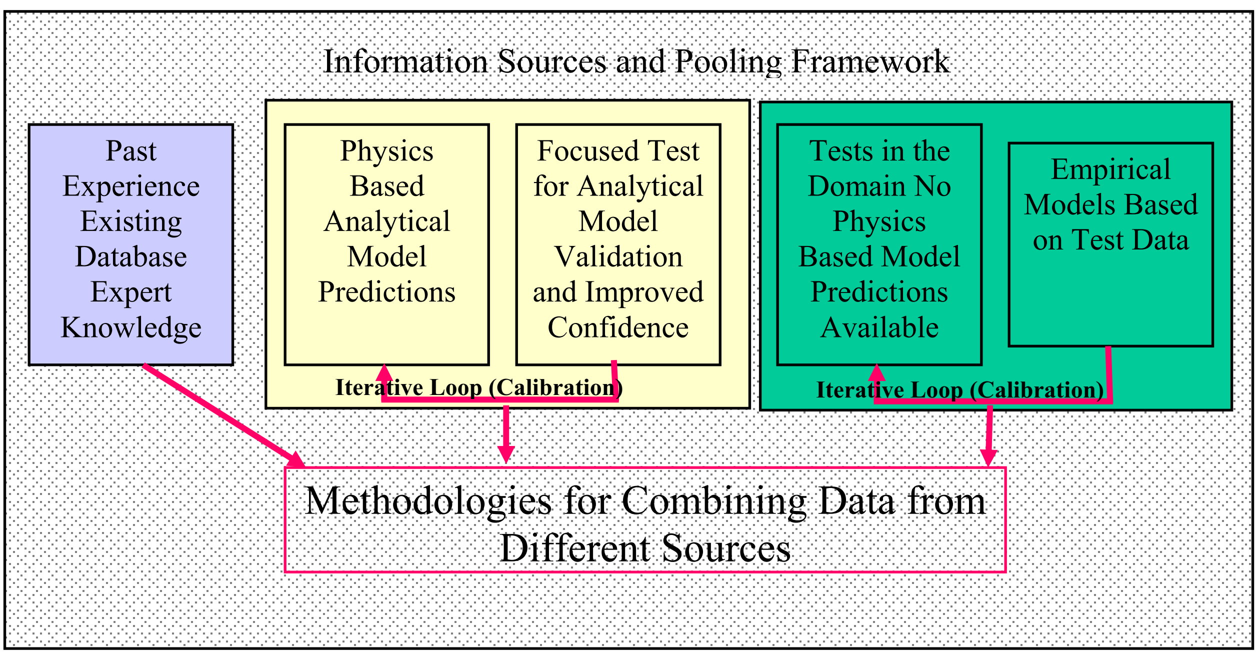



*Figure 9.25 Identification of Information Sources and Sub-iterations within Each*

The various elements of the above methodology are acknowledging the following:

- Domain expert opinions and past database of similar materials are valuable but their applicability to a specific design problem is uncertain
- The physics models generally need to be calibrated since some of the inputs that go in to test conditions that are compared against are unknown or the model parameters themselves need to calibrated for the particular condition
- The current state of the art is such that there is domain space where adequate physics based model are not yet available. In this case empirical models are developed based on tests.
- From a practical design point of view, judicious combination of all the information sources needs to be made to make design decisions with least risk using a quantitative basis (not a subjective decision)

Considering the above and more specific to material allowable development, a more quantitative framework attributes can be stated as:

- Ability to make prediction of new materials/conditions leveraging from known past history that has test and analytical model predicted data. The predictive capability should include percentile values as the case of arriving at a B-basis or A-Basis allowable.
- Ability to produce an error metric associated with predictions. The algorithm for the error metric must reflect changes due to any new information consistent with the quality of new information (actual or based on “what if” scenarios).
- Ability to make predictions in the presence of small amount of test data with very few replications (5 to 100 samples). As a corollary, the methodology should be able to pool test data from different conditions but judged similar (e.g. different laminate lay ups from the same basic material) to form a sizable pool of data to improve the quality of predictions
- Ability of the methodology to address a potentially needed calibration step for the parameters of physics based models or parameters of the data fusion methodology model itself
- There are refined physics based models that demand severe computational resources and there are less accurate models but provide quick answers. The methodology should be able to provide the engineer with ability to trade off uncertainty and fidelity based on design stage (e.g. conceptual, preliminary and detailed).
- Ability to provide additional quantitative measures that can be used to improved decision making using mathematical optimization approaches.
- Ability to handle different types of uncertainty information in a mathematically consistent format. For example, aleatory uncertainty is normally quantified in a probabilistic format and epistemic uncertainty (lack of knowledge) is frequently portrayed as interval or discrete information or other forms with no probabilistic metric associated with it.
- All of the above needs to be wrapped in a rigorous mathematically sound approach

**Pooling Model and Test Results:**

Two potential approaches for pooling of model and test data were evaluated. They are a) the Hierarchical Bayesian Approach and b) Factor Models Using Percentile Regression Approach.

**Hierarchical Bayesian Approach:**

The primary benefit of hierarchical-modeling is it forces the user to think about how information should be sensibly combined because it requires the user to formulate a model that captures the "similarity" opinion about data sources being integrated. The hierarchical model approach was applied to open hole tension data with and without countersink for laminates with 4 different laminate stacking sequence. Predictions based on analytical models were also performed for the four laminates and for another laminate for which there was no experimental data. The predictions were very reasonable. The conclusions were somewhat limited due to the fact that at the time of this study, a limited number of computer runs were available to integrate with the test data. However, since then more numerical studies have been completed. This approach could be further studied now that we have adequate number of numerical and corresponding test data.

**Phase-1 Factor Model Study:**

Considerably more work compared to Bayesian, was performed on the Factor Model approach. The many mathematical details of this approach are described in detailed reports which are attached as appendices along with references. Attachment 1 summarized the Phase 1 and Phase 2 efforts.

The Factor model study was performed in two phases. The phase 1 study can be considered as an exploratory study of the methodology to material allowable application. The objective of the study was to consider the Factor model as a basis for development of a coherent methodology for integrating various sources of information in order to predict accurately the percentiles of failure load distributions. The key issue is that, it is highly desirable, that the methodology deal with percentiles in a direct manner that can be associated with traditional A-Basis and B-Basis material allowable. The approach involves the linear combination of factors that are associated with failure load, into a statistical factor model. This model directly estimates percentiles of failure load distribution (rather than mean values as in ordinary least square regression). A regression framework with CVaR deviation as the measure of optimality is used in constructing estimates. The CVaR deviation (is mathematically defined the enclosed reports) is the average measure of some fraction of the lowest percentiles. Estimates of confidence intervals for the estimates of percentiles were considered, and the most promising of these were adopted to compute A-Basis and B-Basis values. Numerical experiments with available test and model results dataset showed that the approach is quite robust, and can lead to significant savings in number of physical tests to qualify a material. The approach showed a capability to pool information from experiments and model runs, with newer experiments and model predictions, resulting in accurate inferences even in the presence of relatively small datasets. The model dataset that was used in this study was limited to two predicted data points for each stacking sequence and/or test condition.

**Phase-2 Factor Model Study:**

The Phase-2 study of the factor model application, expanded the Phase-1 effort to look at many other facets of the problems. The main conclusions were as follows:

- The accuracy of CVaR regression is relatively insensitive to the number of batches present, but fairly sensitive to number of test points per batch
- There are diminishing benefits in using more than 10 batches, or more than 10 points per batch, in any one application of CVaR regression
- The estimates of A-Basis and B-Basis are fairly robust, in the sense that they are not severely affected by miscalculation (biases or errors) in the analytical methods.

A brief overview of the studies, devoid of mathematical equations is as follows. One of the important studies was to better understand the error associated with the computed CVaR deviation metric. In order to compute the true error, a simulated scenario is necessary. The use of actual datasets from experiments cannot be used to compute absolute error as the true complete information from tests is an unknown in the statistical sense. However, one of the notable features of the study was to create the numerical test conditions to be as close as possible to the material allowable generation as practiced today with relevance to composites. That is, there are very limited *samples from test as well as from model analysis results*. Thus an understanding of the sampling error both in model and test and its relation to CVaR was considered valuable and critical. This was achieved in many steps as described below.

Since Weibull distribution is most commonly used to characterize composite material variation, a statistical model fitting study was conducted on the available test data for several stacking sequences such as open hole tension, open hole compression, un-notched tension and un-notched compression. From this study, the range of Weibull parameters (two parameters) that could be used in Monte Carlo simulation study was obtained. The ranges were then used as the basis for generating samples for the controlled statistical experiments study. From the parameter ranges, the study randomly generated parameters of the Weibull distribution in addition to samples from within a randomly generated distribution.

On the model prediction side, a Weibull distribution was used to predict the error due to error/biases in the analytical model data.

With the above information, absolute errors associated with CVaR while predicting percentiles with limited data was possible. Many realistic combinations of limited number of datasets on the CVaR deviation were studied. It included the effect of limiting the number of stacking sequence tests, the number of tests with in a stacking sequence and sensitivity studies.

The second part of the study considered the scenario of availability of model results from two or three models with varying predictive accuracy and with varying number of test results. The goal was compare the CVaR deviation measure when information from various sources was pooled. The analytical model results for one model contained only nominal, a predicted high and low values for failure loads. The other two model results contained estimated mean and standard deviation of failure loads.  Since test results with more than five samples (replications) were available for a number of stacking sequences, the predictive capability of the factor model was studied more extensively by eliminating one of the actual test results while generating the factor model and comparing the predictive results with the data set that was not used in factor model generation. This was done in a round robin manner.  A representative set of obtained results is discussed below.

A subset of data totaling twenty two from all stacking sequence with at least 5 replicates was chosen for this study.  Considering pooling of information from models only is depicted in Figure 9.26. The details of what represent M1, M2 and M3 are in enclosed report.

| Setup | regression coefficients | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | mean | st.dev | mean | st.dev | mean | st.dev | Mean | st.dev | CVaR |
| M1 | | | 1.098 | -4.303 | | | | | 16.86 |
| M2 | | | | | 0.571 | 0.005 | | | 24.656 |
| M3 | | | | | | | 0.594 | - 0.314 | 27.161 |
| M123 | | | 0.510 | -6.005 | 0.660 | -1.243 | 0.0409 | 0.040 | 13.822 |
| T5 | 1.000 | -1.435 | | | | | | | 10.287 |

*Figure 9.26 Predicting 10th Percentile from Model Results Only*

The regression coefficients for each model give a qualitative picture of the influence of individual elements in predicting the $10^{th}$ percentile failure load predictions. The CVaR error is metric on quality of predictions using the Factor Model. It can be seen for this particular case of model results, the predictive error in model 3 is the highest. It is also seen that perditions using Model 1 by itself is better that the other two. However, when information is pooled with other models, the predictions are better than predictions based on individual models, highlighting the complementary nature of model predictions and the final results are comparable to predictions using tests with 5 replicates.

Next, considering next pooling of model results with test results, various studies were conducted in which test data was introduced in incremental manner to the pooling methodology (Figure 9.27).

| Setup | regression coefficients | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Test mean | Test st.dev | Model 1 mean | Model 1 st.dev | Model 2 mean | Model 2 st.dev | Model 3 mean | Model 3 st.dev | CVaR |
| M123,T1 | 0.303 | | 0.105 | -5.131 | 0.825 | -1.058 | -0.081 | 0.072 | 12.609 |
| M123,T2 | 0.437 | 0.215 | -0.264 | -5.714 | 1.161 | -1.029 | -0.179 | 0.091 | 12.365 |
| M123,T3 | 0.624 | -0.268 | -0.136 | -3.881 | 0.713 | -0.718 | -0.088 | 0.046 | 11.821 |
| M123,T4 | 0.875 | -0.876 | -0.101 | -1.640 | 0.333 | -0.371 | -0.059 | 0.032 | 10.786 |
| M123,T5 | 0.966 | -1.428 | 0.155 | 0.163 | -0.110 | -0.178 | -0.002 | 0.039 | 9.725 |
| T5 | 1.000 | -1.435 | | | | | | | 10.287 |

*Figure 9.27 Combining Three Models and 1 to 5 Actual Measurements*

The uncertainty trade off between increased cost and the performing additional tests can be made using the last column CVaR measure.

A note regarding the results form Model -3 is needed. Because of the schedule constraints, the model-3 that was used in prior studies was sub-optimal with respect to its predictive capability. Had the Model-3 parameters have been calibrated before its use with the factor model (as identified in methodology in Figure 9.25), its influence on reducing the CVaR error measure would have been significant. The calibration of Model-3 was done except that it was not on time to be incorporated into the above factor model study. The model calibration studies that were performed are described below.

**Calibration of Models:**

The Probabilistic (Stochastic) Optimization Methodologies used to calibrate the input parameters for Model-3 is one of possible many applications of this technology. This technology provides a capability to define statistical parameters as design variables in a probabilistic optimization process. The technology allows the use of mathematical optimization techniques to operate in a probabilistic space by the ability to define probabilistic objective functions and constraints. This infrastructure can be potentially combined or independently used with other technologies described above.

The various steps in the model calibration are be summarized as

Step 1 - Identify and incorporate in the model all the potential uncertainty parameters
Step 2 - Perform probabilistic sensitivity analysis to determine the major drivers for the probabilistic response quantities (e.g. mean, standard deviation, 10th percentile etc) for each laminate
Step 3 - Reduce the dimension of the problem to major drivers for which the statistical parameters are most uncertain considering all laminates
Step 4 - Calibrate the unknown statistical parameters using probabilistic optimization for minimum violations considering all laminates. It is possible to use weighting functions which represent number of test data points is possible
Step 5 - Verify the approach using round robin out of sample approach
Step 6 - Use the calibrated model to predict response for new conditions
Step 7 - Recalibrate as new information becomes available

The probabilistic optimization process that was used is graphically represented in Figure 9.28. Considering the specific AIM-C application, the methodology can simultaneously consider the observed failure loads of six stacking sequences in four test conditions: open hole tension, open hole compression, un-notched tension and un-notched compression. The notations are TNX, CNX, TUX and CUX, wherein X represents a specific stacking sequence. The results of probabilistic sensitivity analysis in step 2 for this application are shown in Figure 9.29. The common top drivers that affect failure load scatter were selected from this list which are volume fraction, fiber elastic modulus –direction 1, fiber elastic modulus direction 2, fiber failure stress – direction 1, resin elastic modulus, resin shear strength and resin ultimate tensile strength. The resin tensile yield strength, resin compressive yield strength, and compressive ultimate strengths were assumed to be fully correlated to resin ultimate tensile strength by fixed factors provided by domain experts. In the probabilistic optimization process the statistical parameters of these identified random variables were treated as design variables as shown in Figure 9.30. The objective function was mean square values of the differences between analysis and test that included differences in mean as well as differences in standard deviation. The reduction in errors before and after model calibration is shown in Figure 9.31 and the new calibrated modified parameters are shown in Figure 9.32. The accuracy of the final results was verified using Monte Carlo simulation using the revised statistical parameter values.

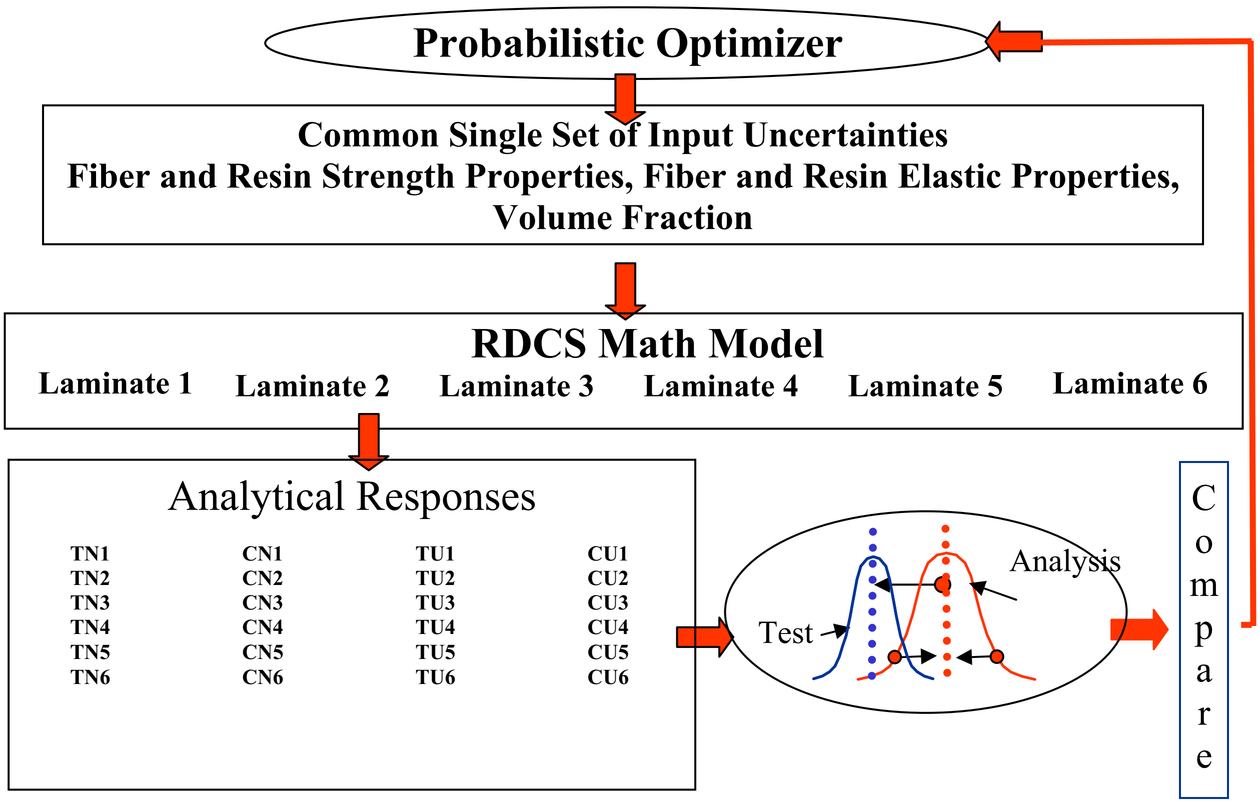
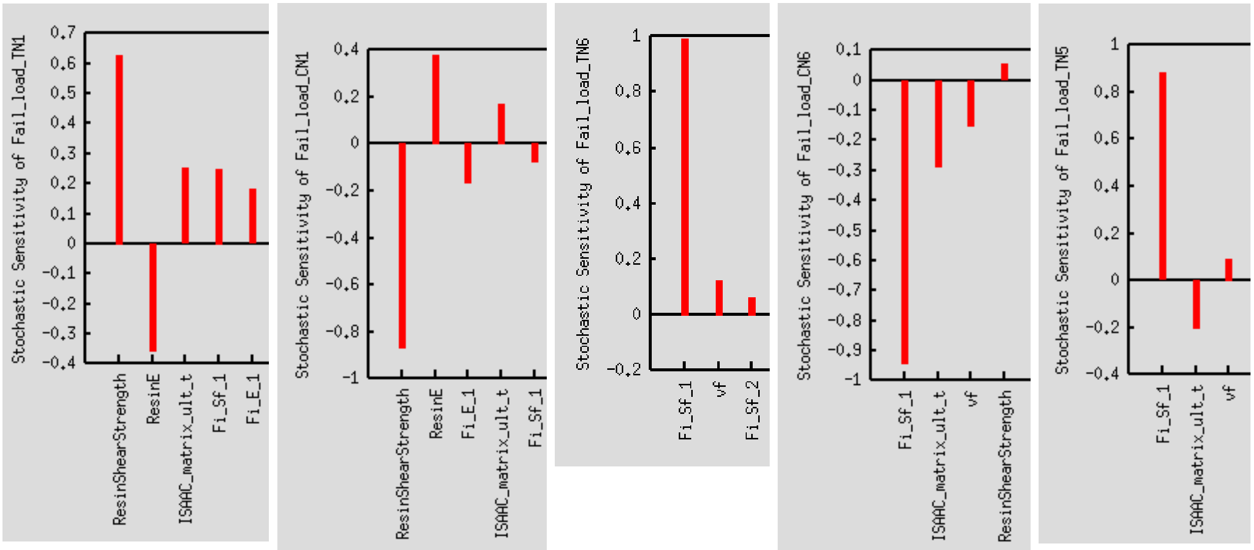



*Figure 9.28 Probabilistic Optimization Process Employed in the Model Calibration Process*




6/82/12 Tension | 6/82/12 Comp | 60/32/8 Tension | 60/32/8 Comp | 48/48/4 Tension

*Figure 9.29 Probabilistic Sensitivity Analyses to Identify the Top Drivers*

| Input Variable | Minimum | Nominal | Maximum | Initial | Scale Factor |
|---|---|---|---|---|---|
| vf.m_mean | 0.5 | 0.6028 | 0.7 | 0.6028 | 1.0 |
| vf.m_stddev | 0.003 | 0.006 | 0.012 | 0.006 | 1.0 |
| Fi_E_1.m_mean | 38000000 | 40100000 | 42000000 | 40100000 | 1.0 |
| Fi_E_1.m_stddev | 450000.0 | 950000.01000( | 1500000 | 950000.010 | 1.0 |
| Fi_E_2.m_mean | 2000000 | 2110000 | 2300000 | 2110000 | 1.0 |
| Fi_E_2.m_stddev | 10000.0 | 20000.0 | 30000.0 | 20000.0 | 1.0 |
| Fi_Sf_1.m_mean | 575000.0 | 610000.0 | 775000.0 | 610000.0 | 1.0 |
| Fi_Sf_1.m_stddev | 30000.0 | 61000.0 | 120000.0 | 61000.0 | 1.0 |
| ResinE.m_mean | 420000.0 | 516440.0 | 630000.0 | 516440.0 | 1.0 |
| ResinE.m_stddev | 15000.0 | 25000.0 | 45000.0 | 25000.0 | 1.0 |
| ResinShearStrength.m_mean | 4000.0 | 4616.0 | 5300.0 | 4616.0 | 1.0 |
| ResinShearStrength.m_stddev | 150.0 | 230.0 | 400.0 | 230.0 | 1.0 |
| ISAAC_matrix_ult_t.m_mean | 10000.0 | 15000.0 | 20000.0 | 15000.0 | 1.0 |
| ISAAC_matrix_ult_t.m_stddev | 500.0 | 1500.0 | 3000.0 | 1500.0 | 1.0 |

*Figure 9.30 Statistical Parameters That Were Treated as Design Variables in the Probabilistic Optimization Process*

| *Number* | *Layup* | *OHC* | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | *Test* | | *Before Calib.* | | *After Calib.* | |
| | | *# Tests* | *Average* | *Std.Dev* | *Average* | *Std.Dev* | *Average* | *Std.Dev* |
| *1* | *6/82/12* | *333* | *35.26* | *1.60* | *34.99* | *2.15* | *34.46* | *1.749* |
| *2* | *12/48/40* | *10* | *38.75* | *1.34* | *41.03* | *2.02* | *40.27* | *1.708* |
| *3* | *28/48/24* | *13* | *56.92* | *3.95* | *48.65* | *4.79* | *52.32* | *4.657* |
| *4* | *32/64/4* | *13* | *59.57* | *3.96* | *44.93* | *3.99* | *48* | *3.871* |
| *5* | *48/48/4* | *10* | *68.12* | *5.20* | *62.73* | *5.58* | *66.75* | *5.376* |
| *6* | *60/32/8* | *N/A* | *N/A* | *N/A* | *80.97* | *7.5* | *86.25* | *7.185* |
| | | | | | *Error* | *0.5188* | | *0.1646* |

*Figure 9.31 Optimization Process Reduced the Mean Square Error for Probabilistic Results from Analysis and Test*

| *Item* | *Before Calib.* | | *After Calib.* | |
|---|---|---|---|---|
| | *Mean* | *Std.Dev* | *Mean* | *Std.Dev* |
| *Vf* | *0.6028* | *0.006* | *0.6179* | *0.006* |
| *Fi_E1* | *4E+07* | *950000* | *4E+07* | *927284* |
| *Fi_E2* | *2110000* | *20000* | *2E+06* | *19995* |
| *Fi_Sf1* | *610000* | *61000* | *633568* | *56773* |
| *Resin_E* | *516440* | *25000* | *548256* | *23856* |
| *Resin_shear* | *4616* | *230* | *4746* | *186* |
| *Resin_Ult_t* | *15000* | *1500* | *14946* | *1461* |

*Figure 9.32 Modified Statistical Input Parameters that Provide a Better Match between Analysis and Test.*

The probabilistic optimization methodology that was applied for model calibration has a much wider application than the specific case illustrated above. For example the percentile values could be used in the optimization process as opposed to the higher statistical moments that was used in this application. An example of this will be the optimization of the process variables that can provide the maximum B-Basis allowable. Further, the optimization problem definition could include probabilistic constraints. A practical application of this in a new material introduction scenario can be arriving at processing allowable variations specifications for assured minimum B-Basis allowable.

The developed tools can handle complex probabilistic events in the objective as well as in the constraint functions. An example of such an application not exercised above is a system reliability problem wherein probabilistic constraints in the form of percentile values for multiple probabilistic events in the form “and/or” conditions could have been stated. A scenario of this application could be satisfying strength, fatigue, and fracture allowable based on percentile values. It is of value that the factor models along with probabilistic optimization process should further be applied to AIM-C methodologies to further validate their application.

# 10. Cost, Schedule and Technical Risk Assessment

Cost, schedule, and risk are the primary metrics for the AIM-C Program. Integrated Product Team (IPT) leaders will measure their performance and success using the parameters and the AIM Program needs a way to objectively develop these parameters, clearly, concisely, and consistently. With that end in mind, these parameters and the means for their determination are presented in this section. Not only are these parameters developed within the AIM toolset, they were also used by the Design Knowledge Base DKB re-creation teams, during the AIM-C Phase 1 program, to assess the capability of the system. It was the acceleration demonstrated by these DKB re-creation teams that gave credence to the potential for acceleration shown by the AIM-C process, examples of which are used herein to demonstrate the use of these parameters by IPTs.

**10.1 Cost** – Cost is not the primary metric used to assess the capability of the AIM methodology, but it is the one that is often the most difficult for IPTs to deal with and some of the better tools generated in the AIM-C program were focused on cost. The primary goal of the cost metric development activity was to provide to the IPT a tool to both assess the life cycle cost benefit of one materials system (or one application) versus another, but also to provide a means to determine if one method for achieving certification was more cost effective than another. To do that required that we assemble a tool that could develop realistic cost comparisons between systems from the non-recurring costs, through recurring costs, to operations and support costs. We were aided in this endeavor by the work previously performed under the Air Force Composites Affordability Program (CAI) and some work done internally by the Air Force on operations and support costs. The next few sections outline the non-recurring, recurring, and operations and support costs that make up the life-cycle cost models developed for AIM-C.

**10.1.1 Non-Recurring Costs** – Non-recurring costs are all those costs associated with the risk reduction efforts leading to authority to proceed with production of a product. These costs include the gathering of existing knowledge, testing from coupons to certification tests, and the cost of the analyses performed to support those tests. In the methodology the costs can be developed easily by examining the exit criteria for each Technology Readiness Level. Since each readiness level has a gate review associated with it that defines the knowledge required to exit the TRL, one can define and quantify the costs required to mature the technology through certification. This method is shown in Figure 10-1 that shows the elements of cost by TRL level and the source of money as it transitions from the development team to the applications team. The costs for the full scale test articles and their tests are assumed to be outside of this cost modeling effort and part of a project certification plan.

| Cost Allocation | Technology Development Costs | | | Shared Costs | | | | | Non-Recurring Costs | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Development Cycle | Technology Development | | | Concept Defintion | | | Risk Reduction | | RDT&E | | |
| TRL | 0.25 | 0.5 | 0.75 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Application Cycle Definition | Technology Discovery | Technology Verification | Technology Ready to Offer | Assembly Concept | Assembly Plan Definition | Key Assembly Detail Definitions | Key Assembly Details Tested | Sub-components Assembled & Tested | Components Assembled & Tested | Airframe Assembled & Tested | Vehicles Assembled & Flight Tested |
| | | | | | | | | | | | |
| Materials Development | 2 Panels | 20 Tests | 200 Tests | Req. Def. | Mat'ls for KFA | Sup Mat'ls | | | | | |
| Manufacturing & Tooling Development | | 3 Panels | 30 Panels | Req. Def. | Tool Con KFA | Tool Fab | Fab KF Article | Fab Subcomp | | | |
| Assembly Simulation and Planning | | | | Analyses | Plan Def. | Assembl. Def. | KF Article | Assemb Sub | | | |
| Certification Testing | | | | Req. Def. | | | Crit. Details | Allowables | Full Scale | Static | Fatigue |
| Structural Concept & Sizing | | | 5 Tests | 30 Tests | KFA Init Size | KFA Final Size | KFA Test | Design Values | | | |
| Design Engineering | | | | Concept Def. | Def. KFA | Assem. Def. | Redes. If Nec. | Sizing | | | |
| Supportability | | | | Req. Def. | Repair Conc | Repair Plan | | KFA Repair | Subc Repairs | Comp Repairs | A/F Repairs |
| Durability | | | | Init. Screening | | | KFA Test | Details Tests | Full Scale | Prep for A/F | Repair Dur |
| Survivability | | | | Req. def. | | | Eval | | | | |
| Cost Benefit Analysis | | | | Req,. Def. | Rom Costs | Plan Costs | Act. Costs | | | | |
| Intellectual Property Rights | | | | PIA etc. | Purchasing | | Downselect | | | | |
| Management, Scheduling and Planning | | Info | Pre Eval | SRR | PPR | PDR | CDR | IDR | A/F PDR | A/F CDR | APR |
| Man Level | 1 | 2 | 3 | 5 | 7 | 7 | 7 | 6 | 4 | 3.5 | 3 |
| Development Costs | 150 | 450 | 900 | 1350 | 1640 | 1190 | 640 | 300 | | | |
| Application Costs | | | | 150 | 450 | 900 | 1450 | 1450 | 900 | 675 | 600 |
| Total Costs | 150 | 450 | 900 | 1500 | 2090 | 2090 | 2090 | 1750 | 900 | 675 | 600 |

**Figure 10-1 AIM-C Cost Model for Estimating Non-Recurring Costs**

After the IPT has developed their plan for meeting the certification requirements, the testing and analyses and knowledge gathering efforts required can be quantified right down to the costs of individual tests, their numbers, and their complexity to determine costs. The same can be done for analytical and knowledge gathering efforts. The total non-recurring costs are then a simple roll up. Charts like that shown in Figure 10-2 allow the IPT to determine whether they will meet exit criteria by existing knowledge, analysis, or test. Once that plan has been determined and the number of tests at each level is defined, it is a pretty easy matter to roll up the costs for the non-recurring portion of the plan. This represents a significant risk reduction for the cost portion of the analysis as well.

| 2.1 | | TEST TYPE/PROPERTIES - FIBER | 0.25 | 0.5 | 0.75 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Fiber Form and Type<br>(Uni and Cloth, ie 5hs or plain or 8hs etc.) | | | | x | x | | | | | | | | | |
| 2.1.1 | ➢ | Tensile Strength | | | x | x | x | x | x | | | | | | | Analysis |
| 2.1.2 | ➢ | Tensile Modulus E11 (longitudinal) | | | x | x | x | x | x | | | | | | | Analysis |
| 2.1.3 | ➢ | Tensile Strain to Failure | | | x | x | x | x | x | | | | | | | Analysis |
| 2.1.19 | | Compressive Strength | | | | | | x | | | | | | | | Analysis |
| 2.1.20 | | Cost | | | x | x | x | x | x | | | | | | | Specified Value |
| 2.1.21 | | T(g) | | | | x | | | | | | | | | | Test |
| 2.1.22 | | wet T(g) | | | | x | | | | | | | | | | Test |
| 2.1.23 | | Health and Safety | | | | x | | | | | | | | | | MSDS |
| 2.1.10 | | CTE - Radial | | | | | x | | | | | | | | | Analysis |
| 2.1.11 | ➢ | Filament Diameter | | | x | x | x | x | x | | | | | | | Test |
| 2.1.12 | ➢ | Filament Count | | | x | x | x | x | x | | | | | | | Test |
| 2.1.13 | | Transverse Bulk Modulus | | | | | x | | | | | | | | | Analysis |
| 2.1.14 | | Youngs Modulus, E22 Transverse | | | | | x | | | | | | | | | Test |
| 2.1.15 | | Shear Modulus, G12 | | | | | x | | | | | | | | | Analysis |
| 2.1.16 | | Shear Modulus, G23 | | | | | x | | | | | | | | | Analysis |
| 2.1.17 | | Poissons Ratio, 12 | | | | | x | | | | | | | | | Analysis |
| 2.1.18 | | Poissons Ratio, 23 | | | | | x | | | | | | | | | Analysis |
| 2.1.4 | ➢ | Yield (MUL) | | | x | x | x | x | x | | | | | | | Analysis |
| 2.1.5 | ➢ | Density | | | x | x | x | x | x | | | | | | | Test |
| 2.1.6 | | Heat Capacity (Cp) | | | | | x | | | | | | | | | Test |
| 2.1.7 | | Thermal Conductivity Longitudinal | | | | | x | | | | | | | | | Analysis |
| 2.1.8 | | Thermal Conductivity Transverse | | | | | x | | | | | | | | | Analysis |
| 2.1.9 | | CTE - Axial | | | | x | | | | | | | | | | Analysis |
| 2.2.1 | ➢ | Sizing Type | | | x | x | x | x | x | | | | | | | Specified Value |
| 2.2.2 | | Fiber Surface Roughness | | | | x | | | | | | | | | | Test |
| 2.2.3 | | Surface Chemistry | | | | x | | | | | | | | | | Specified Value |
| | | Defect Identification | | | | x | | | | | | | | | | |
| | | Defect Limits | | | | | x | | | | | | | | | |
| 2.2.4 | | Fiber CME beta1 (Longitudinal) | | | | | x | | | | | | | | | Test |
| 2.2.5 | | Fiber CME beta2 (transverse) | | | | | x | | | | | | | | | Test |

**Figure 10-2 The IPT Conformance Plan Identifies Test, Analysis, and Existing Knowledge That Can Be Used to Define the Costs to Mature the Technology**

There are other portions of non-recurring costs that go beyond the qualification and certification plan. Tooling costs are a portion of the costs included in non-recurring costs. Re-qualification costs for materials are also computed in the non-recurring portion of the cost model because of the nature of the testing and analysis involved. One might consider re-qualification costs due to material changes during the course of production to be any of the three types of cost elements: non-recurring, because it is not a regular event in production or operation; recurring, because it does happen often during production; or, operations and support because it really done to verify that a new material formulation is equivalent to that used in the production of the vehicle as parts get replaced due to wear or damage, and operation and support (O&S) cost. However, the test types used for re-qualification are most closely associated with non-recurring costs and that's what is used to develop these costs and that's why they are booked there.

Non-recurring costs are those costs most impacted by the AIM-C process and so this is where one can develop the greatest visibility into the benefits of AIM-C.

**10.1.2 Recurring Costs –** Recurring costs are those costs incurred while fabricating, assembling, and producing the product. These costs include materials, processing, fabrication, joining and assembly, and any testing done to qualify a particular part for delivery. The summary cost model for recurring costs is shown in Figure 10-3.

| Cost Allocation | Recurring Costs | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Development Cycle | Production | | | | | | | |
| TRL | 9 | | | | | | | |
| Application Cycle Definition | Long Lead Item Purchases | Part Purchases | Fabrication of Parts | Tooling Replacement / Repair | Assembly | Quality Assurance | Pre-Flight Qualificaiton | Delivery |
| | | | | | | | | |
| Materials Development | | | | | | | | |
| Manufacturing & Tooling Development | | | | | | | | |
| Assembly Simulation and Planning | | | | | | | | |
| Structural Concept & Sizing | | | | | | | | |
| Design Engineering | | | | | | | | |
| Supportability | | | | | | | | |
| Durability | | | | | | | | |
| Survivability | | | | | | | | |
| Cost Benefit Analysis | | | | | | | | |
| Intellectual Property Rights | | | | | | | | |
| Management, Scheduling and Planning | | | | | | | | |

**Figure 10-3 AIM-C Recurring Cost Estimation Model**

A large effort was expended under the Air Force funded Composites Affordability Initiative (CAI) to develop recurring cost models for composite products and these have simply been incorporated into the cost models used in the AIM-C program. No effort was expended in this program to expand, validate, or verify these models. They were simply extracted from the work done on CAI and incorporated into the process used by AIM-C. The model shown in Figure 10-3 can be used to estimate recurring costs rapidly, but a more robust analysis like SEER-DFM should be used to determine costs for articles like the Key Features Article or subcomponent and component articles. However, under CAI funding these models were shown to be very accurate for those processes for which data exists, Figure 10-4. In this validation effort performed under CAI funding, the costs estimated from SEER-DFM for over 200 component and subcomponent parts were compared with actual costs. Results for all were within 3.5% and 95% were within 2% of the actual costs.

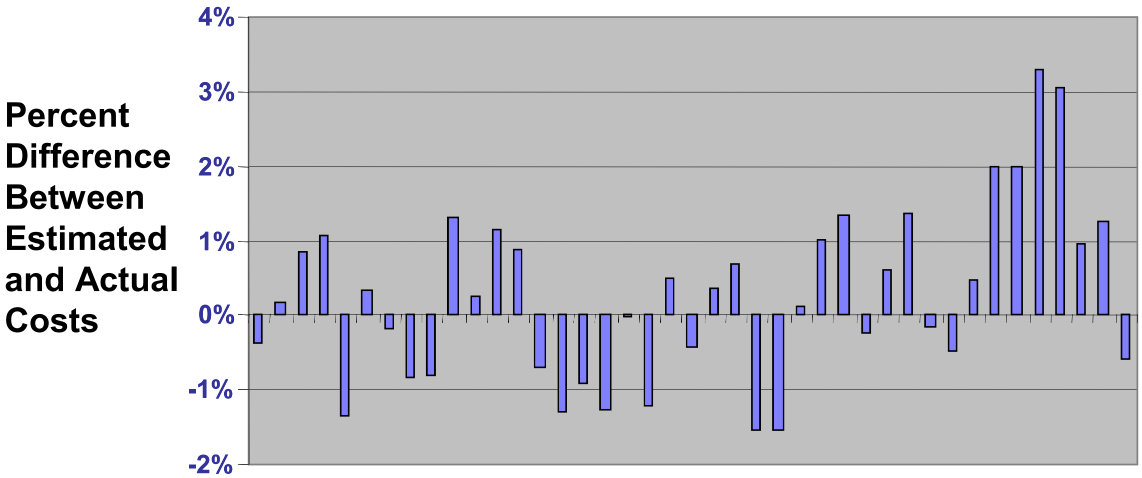



**Figure 10-4 Comparison of Costs Estimated Used SEER-DFM and CAICAT Cost Model with Actual Costs Collected Shows Accuracy**

The decisions made during the development of process limits, design values, and the key features fabrication and test article can make a great difference in the costs required to produce the product. The recurring cost module can be used to evaluate the impact of these decisions on the recurring costs of the product.

**10.1.3 Operations and Support Costs** – In some cases, operations and support costs can be drivers for the use of new materials in a system, especially when the material system provides a significant reduction in replacement costs. While the AIM-C methodology has little impact on the operations and support part of the costs for a given system, it has the disciplines that know those costs and they can be computed using the O&S cost model.

The biggest impacts that AIM-C has on O&S costs is the ability to select a material that minimizes O&S costs and the ability of AIM-C to potentially minimize the certification test costs required to implement the material, manufacturing, or structural change into the system. These costs are often major inhibitors to the introduction of new materials into existing systems or products.

The operations and support cost model developed for AIM-C came from Air Force data on such costs, but allows for modification based on the knowledge gained during the maturation process of AIM-C. The basic model is shown in Figure 10-5.

| Cost Allocation | Operations and Support Costs | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Development Cycle | Operation through Disposal | | | | | | | | | |
| TRL | 10 | | | | | | | | | |
| Application Cycle Definition | Vehicle Operations | Mission Personnel | Consumable Materials | Maintenance Personnel | Depot Level Repairables | Depot Maintenance | Vehicle & Pollution Control | Replacment Parts | Installation Support | Part Disposal |
| | | | | | | | | | | |
| Materials Development | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Manufacturing & Tooling Development | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | |
| Assembly Simulation and Planning | | | 1 | 1 | 1 | | | | 1 | |
| Structural Concept & Sizing | | | 1 | 1 | 1 | | | | 1 | |
| Design Engineering | | 1 | 1 | 1 | 1 | | | | 1 | |
| Supportability | 7 | 1 | | 14 | 9 | 5 | 5 | 1 | 3 | 1 |
| Durability | | 1 | | 1 | 1 | | | | | |
| Survivability | | 1 | | 1 | 1 | | | | | |
| Cost Benefit Analysis | 1 | 1 | | 1 | 1 | 1 | | 1 | 1 | 1 |
| Intellectual Property Rights | | 1 | | 1 | 1 | | | | | |
| Management, Scheduling and Planning | 1 | 1 | | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 9% | 7% | 5% | 24% | 19% | 9% | 8% | 5% | 10% | 4% |

**Figure 10-5 Operation and Support Model Follows Air Force Data to Define Ratio of Effort in Each Category.**

The overall AIM-C Cost model is defined most effectively in Figures 10-1, 3, 5. These figures show the relationship of each cost element to the technology readiness levels (TRL) where they are most often incurred. These Elements of Cost are rolled up to a higher summary level as shown in Figure 10-6.

| **AIM-C Cost Model** | | | | | |
|---|---|---|---|---|---|
| | | **Low Value, High Rate** | **Low Value, Low Rate** | **High Value, Low Rate** | **High Value, Very Low Rate** |
| | | **$K** | **$K** | **$K** | **$K** |
| **Non-Recurring** | | **$9,265.00** | **$9,265.00** | **$9,265.00** | **$9,265.00** |
| | Concept Definition & Development | $3,973.33 | $3,973.33 | $3,973.33 | $3,973.33 |
| | Risk Reduction | $940.00 | $940.00 | $940.00 | $940.00 |
| | Engineering, Manufacturing & Design | $2,175.00 | $2,175.00 | $2,175.00 | $2,175.00 |
| | Tooling and Long Lead Items | $1,706.67 | $1,706.67 | $1,706.67 | $1,706.67 |
| | Certification Testing | $470.00 | $470.00 | $470.00 | $470.00 |
| | | | | | |
| **Recurring per Unit** | | **$115.20** | **$115.20** | **$11,520.00** | **$11,520.00** |
| | Materials & Purchases | $25.00 | $25.00 | $2,500.00 | $2,500.00 |
| | Fabrication (Incl. Tooling Replacement) | $50.00 | $50.00 | $5,000.00 | $5,000.00 |
| | Assembly | $25.00 | $25.00 | $2,500.00 | $2,500.00 |
| | Testing | $15.00 | $15.00 | $1,500.00 | $1,500.00 |
| | Delivery | $0.20 | $0.20 | $20.00 | $20.00 |
| | | | | | |
| **Operation & Support** | | **$100.00** | **$100.00** | **$100.00** | **$100.00** |
| | Operations | $21.00 | $21.00 | $21.00 | $21.00 |
| | Maintenance | $60.00 | $60.00 | $60.00 | $60.00 |
| | Replacement | $15.00 | $15.00 | $15.00 | $15.00 |
| | Disposal | $4.00 | $4.00 | $4.00 | $4.00 |
| | | | | | |
| **Unit Production Costs** | | **$133.73** | **$300.50** | **$11,705.30** | **$12,446.50** |
| | Number of Amortization Units | 500 | 50 | 50 | 10 |
| | Total Number of Units | 5000 | 500 | 500 | 100 |
| | | | | | |
| **Unit Life Cycle Costs** | | **$133.75** | **$300.70** | **$11,705.50** | **$12,447.50** |

**Figure 10-6 Cost Model Summaries Provide Identification of the Cost Drivers for Insertion**

The life cycle cost model shown in Figure 10-6 has been under development within Boeing for some time. It has been, and continues to be a valuable evaluation tool and a means for guiding engineers through the compilation of cost data required to compute life cycle costs for their concepts. It also provides good data for starting more detailed cost assessments done by cost accounting personnel for the IPT.

**10.1.4 Unit Production Costs –** The cost models developed for AIM-C allow the user to determine total product costs by rolling up the recurring costs with amortized non-recurring costs on a per part basis. Figure 10-6 shows the summary computation for such an analysis. Varying the number of units over which one amortizes the non-recurring costs can change the cost per unit significantly in some cases. In other cases, where the ratio of non-recurring to recurring costs are low, the number of amortization units has very little effect.

**10.1.5 Life Cycle Costs –** The cost models developed for AIM-C also provide a computation of the life cycle costs that are the unit costs plus the operations and support costs averaged per unit. This computation is also shown in Figure 10-6 for the same variations described above.

**10.1.6 Cost Risk Assessment –** Cost risks are determined by how much data and knowledge are available to support the cost estimates provided. At early TRLs in which the cost numbers are developed using previous knowledge and analytical projections, the risk is high. Once the IPT has assembled its plan for how it will develop the knowledge base required to certify the product cost risks come down significantly. As the maturation process progresses and the plan is modified or rework cycles take place, the plan becomes more robust and better defined and the cost risks are again significantly reduced. Once the key features test has been conducted and the plan for certification has been defined cost risks are negligible for the non-recurring portion of the cost model.

In the same way, as the processing limits and tooling requirements become defined the cost risk decreases for recurring costs elements. As the key features test article becomes defined and completed, further cost risk reductions take place. Production planning reduces the risk further and production itself reduces the risk to negligibility.

Operations and support costs have some risk reduction as certification and production are achieved, but the operations and support costs are all projections until the product is actually fielded. Then as knowledge comes in, these costs begin to see real risk reduction. Figure 10-7 shows the general trend for risk reduction as a material system passes the TRL gate reviews toward becoming part of a fielded product. Of course, the general reductions shown herein are revised based on knowledge gained on the specific material system as each review is held.

| Cost Allocation | Technology Development Costs | | | Shared Costs | | | | | Non-Recurring Costs | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Development Cycle | Technology Development | | | Concept Defintion | | | Risk Reduction | | RDT&E | | |
| TRL | 0.25 | 0.5 | 0.75 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Application Cycle Definition | Technology Discovery | Technology Verification | Technology Reproducible | Assembly Concept | Assembly Plan Definition | Key Assembly Detail Definitions | Key Assembly Details Tested | Sub-Components Assembled & Tested | Components Assembled & Tested | Airframe Assembled & Tested | Vehicles Assembled & Flight Tested |
| | | | TRR | SRR | PPR | PDR | CDR | IDR | A/F PDR | A/F CDR | APR |
| Non-recurring Costs | Very High | Very High | Very High | High | Med-High | Med | Med-Low | Low | Very Low | Very Low | Very Low |
| Recurring Costs | Very High | Very High | Very High | Very High | Very High | Very High | High | Med-High | Medium | Med-Low | Low |
| Operations and Support Costs | Very High | Very High | Very High | Very High | Very High | Very High | Very High | Very High | High | High-Med | Med |

**Figure 10-7 Insertion Cost Risk Reduction and Technology Maturity**

**10.1.7 Benefits of AIM-C to Cost Control –** AIM-C has been able to document cost reductions greater than 45% over the cost of the conventional Building Block approach using its coordinated analysis supported by test approach. Conditions under which AIM-C might not be able to save cost for insertion have not yet been identified.

The AIM-C methodology and cost models offer rapid estimation of costs right from the outset of the insertion path. We have included historical data from composite insertion cases that offer resident, existing data from which to make those estimates until the knowledge gathered during the course of the AIM-C process has developed more robust estimates using actual data on cost.

One of the benefits of offering the IPT a detailed test, analysis, existing knowledge guide is that the IPT can look at alternative paths, alternative tests, and alternative analyses to determine what the cost / risk payoffs or penalties might be. And with the AIM-C System having this database and process resident, these evaluations can be performed with the speed of a spreadsheet computation. Since risk assessments are part of the process, the IPT does not need to take a high risk approach unless it is being driven by schedule, cost, or performance requirements to do so. Even in those cases, they can identify what that risk penalty for 'skipping' steps will be.

The AIM-C Cost models offer direct computation of the cost for insertion from TRL of 1 through TRL of 6, ready for certification. But in addition to these direct computations, AIM-C includes a validated model for examining the costs of performance capability or manufacturing limitations on cost or performance in the product itself. The System uses the CAICAT model from the Composite Affordability Initiative to perform these computations. The IPT can also assess the effects of their decisions or the performance of the material system on the potential operations and support costs. These estimates are obviously the least mature of those offered, but the knowledge base increases, these estimates will gain in reliability and robustness. Because the AIM-C process has only indirect effect on the costs of the product or the operations and support costs, these portion so the cost model might be expected to mature a little slower than the non-recurring models which will receive feedback during the use of the AIM-C System and process right from its implementation.

Finally, the cost modeling capability in AIM-C allows the user to examine costs based on unit costs for acquisition or on life cycle. This capability is a key to being able to relate the cost payoffs or penalties for one material system versus another for the IPT at the system level to assess the cost risk, schedule and performance payoffs for various material systems – one of the keys to successful insertion.

**10.2 Schedule** – Schedule is the primary metric used in assessing the value of the AIM-C program. But it is also the metric that helps the IPT to determine what path they will follow for developing the design knowledge base – whether by previous knowledge, test data, or by analysis. The conformance matrix is the guide used to determine the schedule and elapsed time required to implement any conformance plan selected by the IPT. By selecting the method by which each element of the conformance plan will be met, the IPT can get instant feedback on the length of time required to generate the knowledge base required and investigate, via 'what if,' alternative conformance plans. The IPT can also decide to eliminate portions of the recommended conformance plan to reduce schedule, but the risk associated with the plan increases when this is done. The intent was to link cost, schedule, and risk through the Conformance Plan, so that the IPT could get instant feedback on the impact of decisions made on whether to perform test or analyses to gather data, or whether to rely on analysis with previously developed data.

It must be mentioned here that the AIM-C System was never completed to the extent that cost, risk, and schedule were linked to the Conformance Plan. While the calculations can be done off-line, this remains one key element of the process that really needs to be implemented in the system at some later time.

**10.2.1 Using the Conformance Plan to Develop Schedule** – In the same way that the conformance plan is used to determine cost, as described previously, by looking at a baseline plan assembled by the recommended guidelines for conformance, a baseline schedule can be provided to the IPT. The times for tests to be documented, estimated by the lab, funds allocated, setups performed, systems checks made, tests performed, data reduced, and the test data documented, including lessons learned, can be developed from historical data. However, in this case, we relied on the baseline IM7/977-3 database development performed under the F/A-18 E/F program to define these time and elapsed times. Then by using the conformance guidelines developed under the AIM-C program, we set out the times associated with each test series and used the same amount of parallel testing that was performed under the F/A-18 program.

These assumptions allowed us to take the F/A-18 schedule experience and prepare a 'best case', version of that test program. A summary of that schedule is shown in Figure 10-8. In this development, "best case," means that no time was allocated for machine down time or calibration times, no time was set aside for unnecessary waiting for specimen fabrication or machine availability other than when the schedule said that the fabrication or testing was being delayed by other AIM-C related fabrication or testing. "Best case," therefore, refers to the best possible schedule that could be developed using the fabrication, instrumentation, and test times available on the machines used to do the F/A-18 testing.

The goal of this portion of the AIM-C effort was to tie the conformance plan to Microsoft Project and drive the schedule creation from the conformance plan. Today this must be done by hand. While not a serious technical problem to incorporate this element into the system, it was not completed because the other technical elements of the system took precedent over this one.

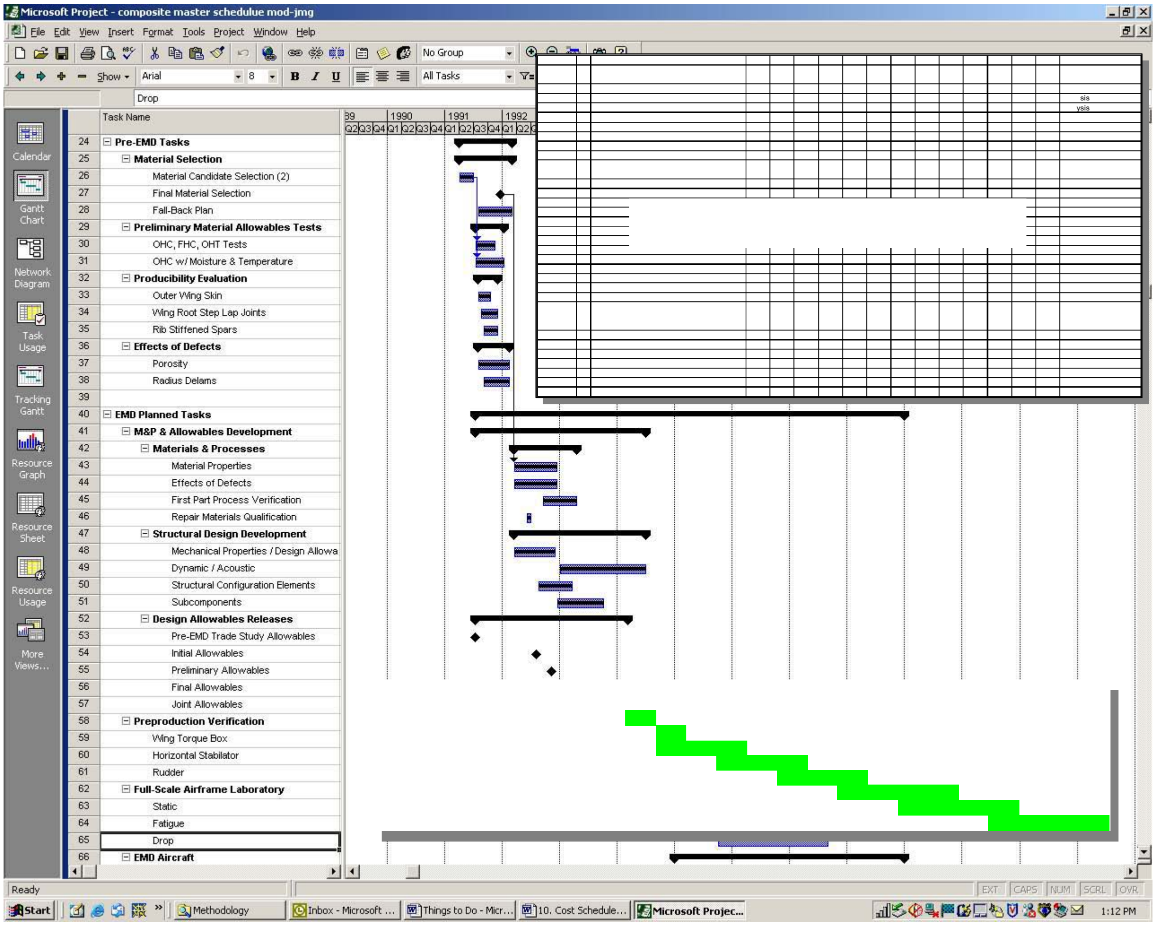



**Figure 10-8 Development of the 'Best Case' Baseline Schedule for AIM-C**

## 10.2.2 Schedule by TRL / Discipline / Knowledge, Analysis, Test

Because the schedule elements are tied to the conformance plan, these elements can be parceled any way the user demands. They can be developed by TRL level since the TRL levels are defined by IPT maturation reviews which are definable on the schedule. All work elements that must be completed prior to a given TRL maturation review can be summed to determine the amount of effort required to meet a given review milestone. The work effort can also be summed by discipline so that the staffing plan for that discipline can be readily determined. This can be a real advantage for program management. And the elements can be divided by how the team intends to develop the knowledge base, by analysis, test, or existing knowledge. This information is probably of greater interest to certification agents than to other management or team members, but it is available.

## 10.2.3 Schedule Risk Assessment –

Schedule risk parallels cost risk in that risks are mitigated as TRLs increase. One of the benefits of the AIM-C methodology is that problems are uncovered at each maturation review by the team and must be dealt with at that meeting before work on subsequent maturation levels can be started. Now the AIM-C team knows that there will be temptations to short cut this discipline and to forge ahead on risk reduction efforts while problems and potential show stoppers identified in earlier maturation steps have not yet been rung out. However, an honest assessment of the maturity of the technology will readily show the level of risk the team has accepted by moving forward in some areas while leaving unanswered questions open in the wake of the effort. The AIM-C methodology puts a premium on the discipline exercised by the IPT team leader in its implementation.

In the same way that cost risk is affected by technology maturity level, so is schedule risk. A similar chart can rather easily be formulated to depict this truth, Figure 10-9. But the reality of this chart is very real from a program management point of view. If the technology is not at a given level when delivered to the program, it cannot be matured in time to meet program milestones. So there are some hard and fast rules for when and at what TRL levels (from a program perspective) technologies can be accepted and when they must be rejected as too high a risk. These levels of risk are depicted in Figure 10-9.

| | | | Product Development Phases | | | |
|---|---|---|---|---|---|---|
| Technology Readiness Level | Readiness Level Definition | Concept Exploration & Definition | Demonstration / Validation | Engineering / Manufacturing Development | Production / Deployment | Operations / Support |
| 10 | Operation and Support | No Risk | | | | Very Low |
| 9 | Production Flight Proven | | | | Very Low | Low |
| 8 | Flight Test Qualified | | | Very Low | Low | Med-Low |
| 7 | Ground Test Certified | | Very Low | Low | Med-Low | Med |
| 6 | Component Ground Test Valdiation | Very Low | Low | Med-Low | Med | Med-High |
| 5 | Subcomponwent Ground Test | Low | Med-Low | Med | Med-High | High |
| 4 | Key Features Comp Test | Med-Low | Med | Med-High | High | Very High |
| 3 | Processing Validation Testing | Med | Med-High | High | Very High | |
| 2 | Materials Validation Testing | Med-High | High | Very High | | Unacceptably |
| 1 | Material Concept Documented | High | Very High | | | High |

**Figure 10-9 Schedule Risk Linked to Technology Maturity**

## 10.3 Technical / Performance Risk

The AIM-C methodology uses a divergence/risk assessment to determine the technical/performance risk at any technology maturation level in the process. The term "divergence/risk analysis" was coined for one of the qualification elements in a recent effort funded by Office of Naval Research "New Materials, New Processes and Alternative Second Source Materials Data Base Generation and Qualification Protocol Development," (Reference[1]). A shortened designation for the program will be "ONR Protocol." Divergence risk is intended to be a measure of the degree of similarity between the issue under consideration and other issues in the experience base of the integrated product team. Divergence and risk analyses are conducted to provide the most affordable, streamlined qualification program while addressing risks associated with using related data, point design qualifications, and so forth. The divergence analysis assists the qualification participants in determining how similar or how different the new material or process is from known and understood materials or processes. Risk analysis is also performed to determine the consequence of reduced testing, testing under different sequences, and so forth.

The consequences of the identified risks are also evaluated using the a concept developed at Boeing's Rocketdyne Division for assessment of the technical maturity of rocket engines. This concept is based on the number of rework cycles required to overcome problems as they are encountered at each level of maturity in the system development. It reflects the fact that the more mature the system development at the time the problem is identified, the higher the number of rework cycles required to overcome the problem and the higher the cost associated with this rework. These assessments drive the AIM-C methodology to make every attempt to make problems visible to the team as early in the development cycle as possible so they can be dealt with before they become costly show stoppers.

10.3.1 Technical / Performance Risk Assessment

The first step in establishing the level of risk is to define the magnitude of divergence between the baseline and the alternate material or process. This is done by listing all the properties, characteristics, descriptors, and attributes associated with the baseline composite materials and processes, then assessing the differences for each of the items on the list.

The list can be top level or detail in nature. Divergence areas could include (1) a change in the raw material source: (2) a change in the processing site or equipment; (3) a change in fiber sizing; (4) a change in fabric style; or (5) a change in resin. The difference could also include a change in the part fabrication process, such as going from hand collation to fiber placement, or from hand collation to resin transfer molding. There could be a material change associated with the fabrication process change or there could be no changes in the material. There may also be equipment changes within the fabrication process. The magnitude of divergence between the material and process combinations defines the starting level of risk.

For example, one of the items on the list could be "resin." In one case, the baseline material is a 350°F curing epoxy such as Hexcel's epoxy resin, 3501-6. To be rated as "no divergence," the alternate material need only be a 350°F curing epoxy resin such as Hexcel's 8552. In another situation, however, the definition of "no divergence" is an alternate resin mixed at an alternate site, but chemically equivalent to the 3501-6.

An assessment is made for each item on the list to determine the level of divergence between the baseline material and alternative material. By definition there will be acceptable levels of divergence for some items (such as the qualification of a new prepreg line) and there will be some items where no divergence is allowed (for example, the resin formulation for qualification of a licensed resin).

Relevant testing requirements are defined and identified with respect to these areas of divergence. At times the testing is used to validate that the divergence does not negatively impact the material or the end use of the material, while at other times testing is used to validate that there is no divergence.

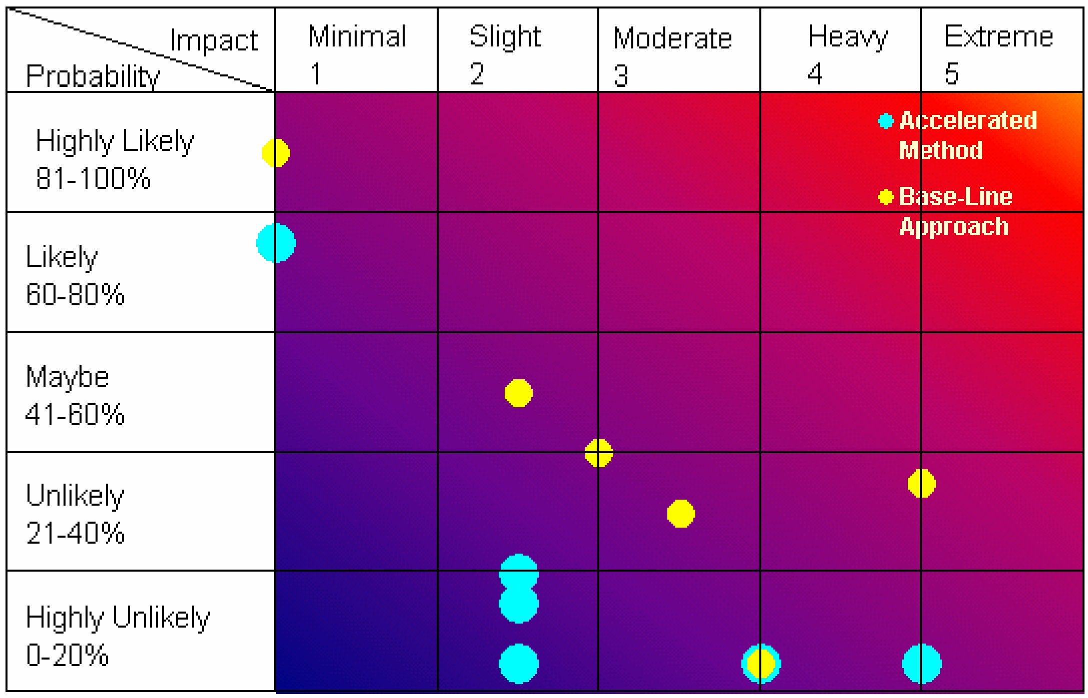
A key element of the divergence assessment is to define the accept/reject criteria to be used in analyzing the test data, audit findings, and processing trials. Establishment of criteria requires a clear understanding of the divergence requirements: equivalent versus equal, similar versus identical, statistically based versus typical values, and so forth..

Risk is directly associated with the uncertainties that stem from the level of divergence. The objective is to manage the risk and reduce it to an acceptable level by effectively structuring and conducting the qualification program. The qualification program focuses on the testing of the alternate material, but risk is also reduced through other activities such as audits, processing trials, and drawing on previous experience.

Risk assessments may also be subjective. What is viewed as high risk to one person could be viewed as a medium risk to another. Past experiences and familiarity with the new material or process will influence a person's perception of the risk level. For these reasons, it is important that the level of material or process divergence be quantified and that a systematic risk assessment process is documented.

Figure 10-10 shows the results of one such analysis. The results for a number of parameters that define the maturity of the material system have been identified and their likelihood of occurrence has been determined. Secondly, the impact of that occurrence has been determined as well and the likelihood versus impact has been plotted on the chart. Note that the points for each parameter of the technology differ in size. There is uncertainty in the determination for these parameters and that uncertainty is reflected in the size of the symbol used to show the risk evaluation. Highest risk on this chart is in the upper right corner where the probability occurrence is very high and the impact of the occurrence is also very high. Rationally designed structures will attempt to do whatever is necessary to get risk evaluations in the lower left hand corner where certification is easiest.

The consequences or impact of the risk parameter can also be developed using the rework versus risk analysis developed by Rocketdyne. In this case, once the risk has been established, one can use a chart like that shown in Figure 10-11. This chart which is based on historical data and experience shows that the relationship between risk and rework cycle, impact, or cost consequences is not linear, but highly non-linear. Problems found early in the risk reduction effort can be reworked at small cost, but rework required at high risk, high maturity of the system can be very expensive. As always cost, schedule and risk are all linked to the maturation of the system. The purpose of the AIM-C methodology is to address system development risk so that the consequences to cost and schedule are minimized until the risk reduction has been completed to the level that the material system can be used with user defined confidence.




Risk Analysis of Hat Stiffened Design Scenerio

Figure 10-10 Risk Analysis

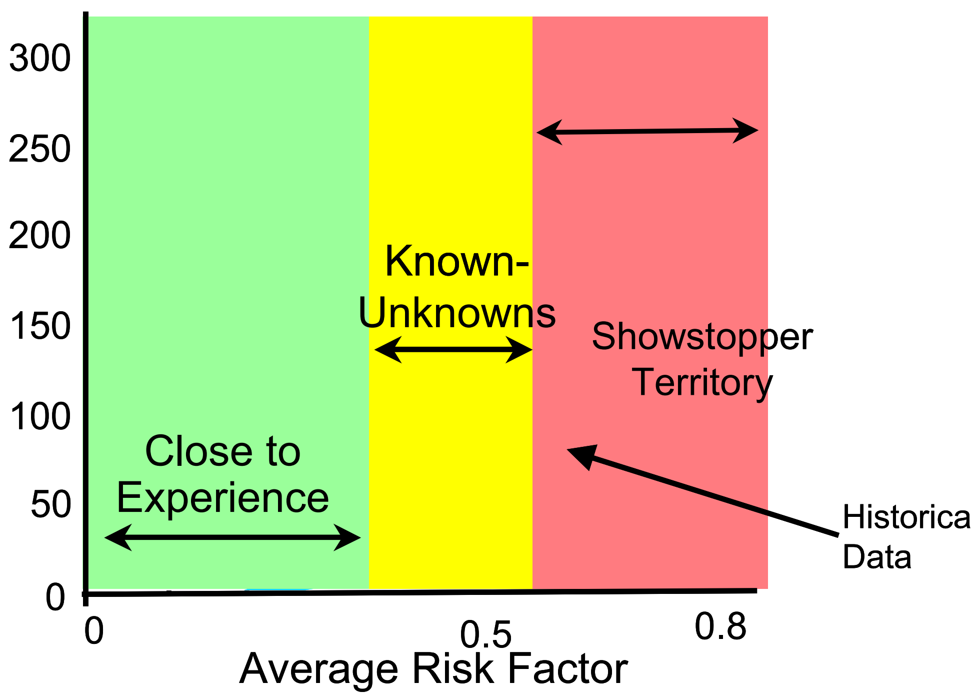



**Figure 10-11 Rework Cycles Link Cost and Schedule to Risk Reduction and Maturation**

## 10.4 Demonstration of the Use of Metrics for Acceleration in AIM-C

In order to demonstrate how the metrics for accelerated insertion are developed and how they are used to evaluate the value of acceleration provided by the AIM methodology, we have chosen to look at a baseline that is a conventional building block approach to certification and the AIM accelerated insertion methodology. For the purposes of this evaluation we chose to use an outer wing as the example case. The experience of the F/A-18 E/F development and some of the schedule experience from the program is used to develop the data herein. But this example (for both the building block approach and the AIM approach) is an idealized case; it assumes no rework, no interruptions, and no changes in requirements during the course of the development and certification program. No program has ever had it that good.

Since component development on an aircraft program is just part of an overall development program there are holds while data for other elements of the system are developed. In this example, we eliminated these holds and treated the development as if it could continue at its own pace independent of any other needs in the program. No component development ever had it this good either. However, our goal was to determine how well AIM serves to improve the insertion time, cost, and risk relative to a building block approach applied in its best-case scenario.

**10.4.1 Baseline Schedule** – The baseline schedule is developed using the AIM software and schedule process, but is based on the baseline building block approach toward component development and certification. Thus the time and costs of identical tests are the same between the two cases. A high level schedule for this effort might look something like that shown in Figure 10-12. We chose to identify the elements of the building block approach as major headings in this chart even though a program would group these with other elements of the plan and avoid duplication among components. But our goal was to treat the two cases as close to the same rules and conditions, as possible.

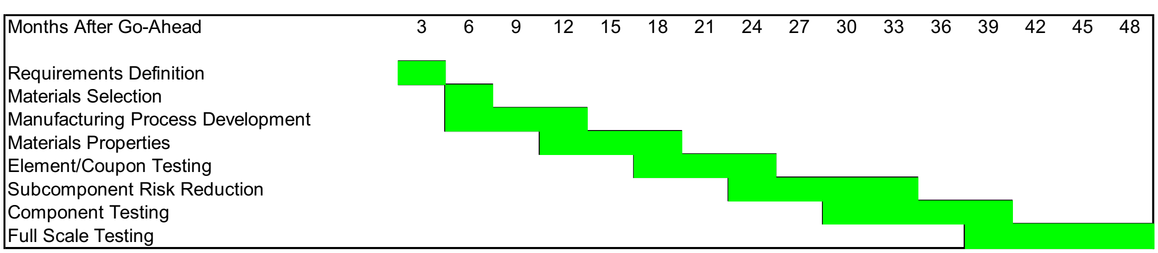



**Figure10-12 Baseline Schedule for Conventional Building Block Certification Approach**

**10.4.2 Baseline Cost** – The baseline cost was computed according to the same ground rules used for the schedule determination. We used the cost modules within the AIM-C system to compute these costs so that the same costing algorithms are used for each scenario. Thus the only difference in cost shown between these two scenarios is that produced by the difference in the Building Block Approach and the AIM-C methodology.

Figure 10-13 shows the cost breakdown for the building Block approach applied to this component.

| | Lab Cost | | | | Mfg Cost | | | | Lab + Mfg | |
|---|---|---|---|---|---|---|---|---|---|---|
| | A | C | M | Total | A | C | M | Total | Total | |
| 2 | 0 | 7130 | 0 | 7130 | 619 | 5601 | 212 | 6432 | 13562 | Fiber & Resin Prop |
| 3 | 8784 | 14205 | 128 | 23117 | 1237 | 11203 | 424 | 12864 | 35981 | Material System Pr |
| 4 | 575 | 11731 | 6045 | 18351 | 600 | 17830 | 8718 | 27148 | 45499 | Process Impact |
| 5 | 0 | 41705 | 11449 | 53154 | 0 | 33563 | 8160 | 41723 | 94877 | Structural Propertie |
| 6 | 200 | 39112 | 8315 | 47627 | 300 | 71846 | 18143 | 90289 | 137916 | Structural Elements |
| 7 | 2523 | 26331 | 14661 | 43515 | 6000 | 55158 | 7085 | 68243 | 111758 | Subcomponets/Co |
| 8 | 111144 | 28887 | 0 | 140031 | 527087 | 10000 | 0 | 537087 | 677118 | Full-scale Ground T |
| Total | 123226 | 169101 | 40598 | 332925 | 535843 | 205201 | 42742 | 783786 | 1116711 | |

**Figure 10-13 Baseline Costs for a Conventional Building Block Approach**

**10.4.3 Baseline Risk** – In the Building Block approach risk is minimized by providing a broad qualification of material and manufacturing systems that sequentially and methodically increases structural size and complexity to the full scale physical hardware. In our experience this has provided a safety of flight reliability that exceeds .999999. The elements that feed this reliability are those that make up the building block approach and the environments and fabrication repetitions that a part of that approach. Figure 10-14 shows the relative contribution made by each portion of the building block approach toward meeting the reliability experienced by our aircraft.

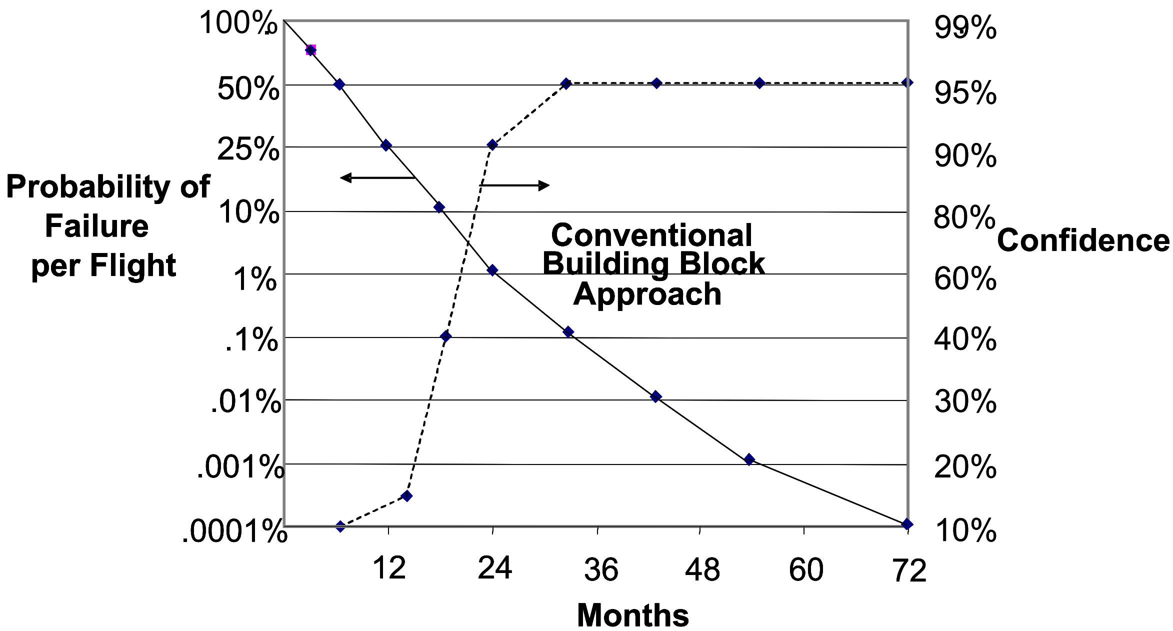



**Figure 10-14 Risk and Confidence Levels Developed Using the Building Block Approach**

**10.4.4 Accelerated Schedule** – The schedule for the AIM accelerated insertion methodology is a compilation of the elements shown in Figure 10-15. The qualification testing is spread through the fabrication maturation activity that leads to the full scale key features test article. But the types of tests are limited to those predicted to most influence the fabrication, and failure modes and loads expected in the key features test. So even though the key features fabrication and testing is by itself an expensive portion of the certification readiness effort, the amount of testing saved by focusing the testing toward this demonstration more than makes up for that additional expense.

But more important, the key features fabrication and test article focuses the certification testing on those loads and failure modes that truly impact the design. This cuts between 25 and 75 percent of the testing out of the certification test plan which no longer has to be all encompassing for allowables as the building block plan had to be. Moreover, the key features test article removed the risk reduction articles from the building block approach (since these really happen too late to impact either the allowables or the design. In the AIM approach the key features test article and its testing impact both the allowables produced and potentially the design should a problem be found in the fabrication or testing of the article. In this case, as in the building block approach evaluation, we’ve assumed that the entire process went off on schedule and without any required rework. This accelerated methodology is scheduled as shown in Figure 10-15.

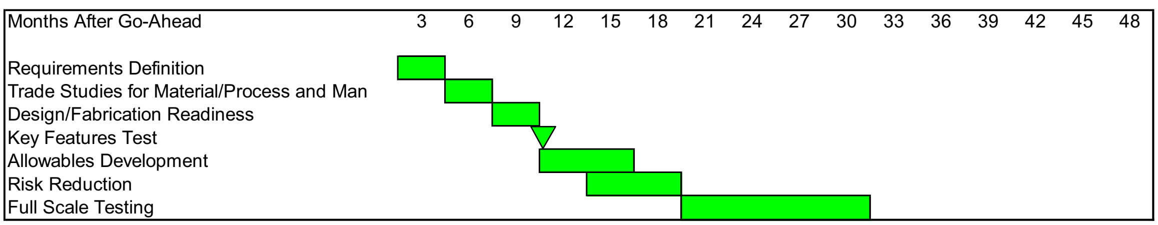



**Figure 10-15 Projected AIM-C Accelerated Insertion Methodology**

The AIM-C best case schedule reduces the time to readiness for full scale testing by more than 50% from 39 months to 18 months. However, we want to point out that the AIM-C methodology was developed to include planned rework cycles that not only can be accommodated, but are planned to occur early enough that a redesign can be incorporated into the configuration before allowables are developed and the design locked in place. This is crucial to the value of the AIM-C methodology – this built in ability to accommodate change before CDR and allowables development there is time built in (or the potential for a hold if you will), to incorporate lessons learned from the key features fabrication and test demonstration article.

**10.4.5 Accelerated Cost** – In the same way, the cost for the IPT and its activities leading to component certification were predicted using the same routines and same costs per test as those used in the evaluation of the baseline approach. All the costs by activity are shown in Figure 10-16. You can see that the cost of the key features fabrication and test article is large, but the payoff in qualification and certification testing is larger and moreover, you leave that test knowing you can build, at full scale, the parts you’ve designed, you can predict their behavior under load (and maybe environment if that's a concern).

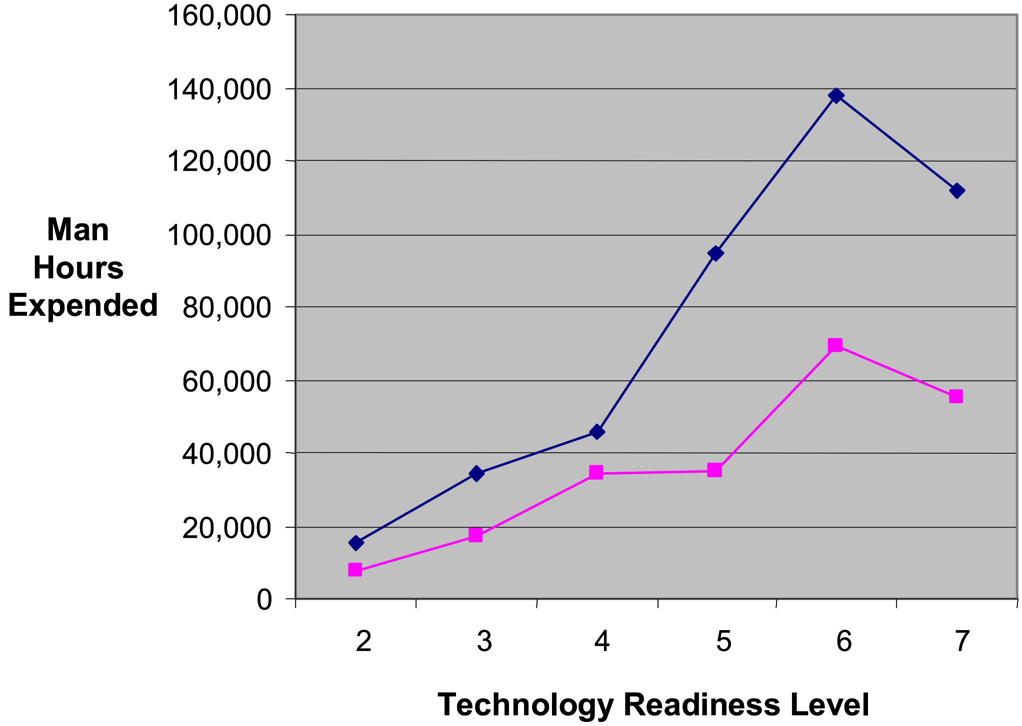



**Figure 10-16. Comparison of Conventional and AIM-C Costs to Readiness for Full Scale Testing**

**10.4.6 Risk Due to Acceleration** – One would think that reducing the number of tests performed and the number of risk reduction articles would increase the overall computed risk of the component at the end of the process, but this methodology puts all the risk into the process and its potential for rework, not in the delivered component. As shown in Figure 10-17, most of the risk is tied up in the early fabrication and testing of the key features article. But once that article has been fabricated and tested, its failure modes and loads predicted and verified, and allowables developed from that test knowledge base, the reliability is not only greater than that produced by the building block approach, but it renders the full scale test almost redundant since we could already have run a full scale outer wing test as the key features test.

Confidence levels shown in this chart assume that analysis of previous tests can be used to develop confidence in the predicted design values before any testing is performed. The assumption was that the greater the number of prior tests, the greater the confidence in those results. However, the results of the work in AIM-C Phase 1 have shown that tests plus analysis develops confidence faster than either alone. And thus we do not show real acceleration in confidence until the number tests becomes equivalent to those performed under the Building Block Approach. We get improved confidence when we can use analyses to project results with confidence and this depends entirely on the level of validation of the models through previous testing.

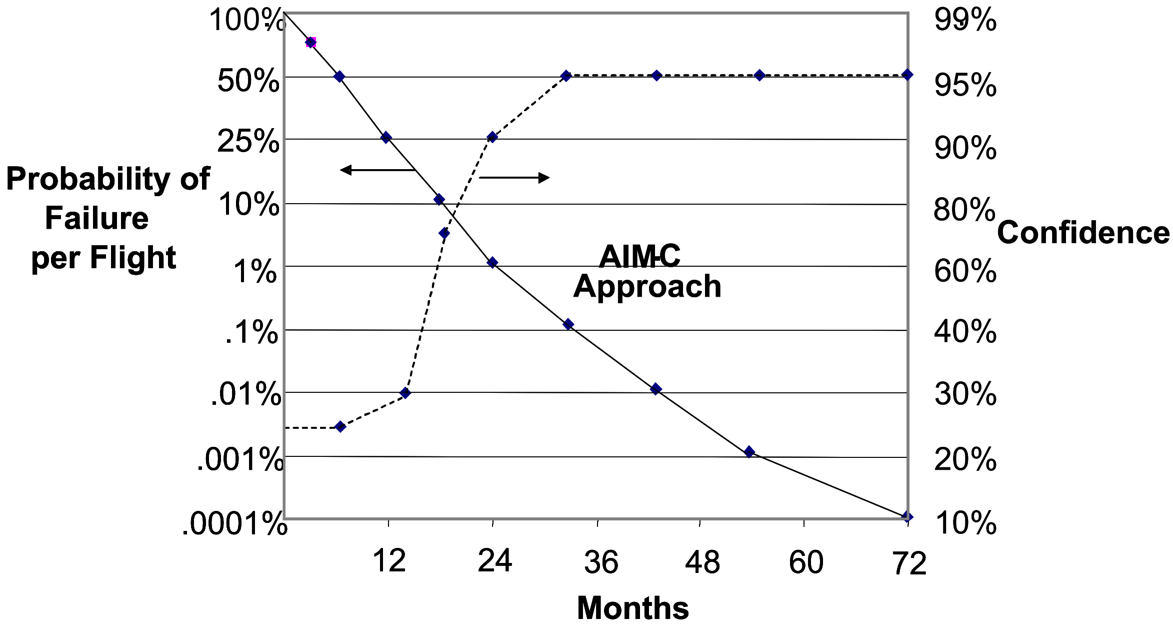



**Figure 10-17. Risk and Confidence Levels Developed Using the AIM-C Approach**

**10.4.7 The Benefits of Acceleration** – Using the formats previously presented to summarize the benefits of the AIM-C methodology, we produce the data shown in Figures 10-15 to 10-17, for schedule, cost, and risk respectively. Based on the baseline conventional building block approach and the project AIM-C optimized building block approach, the time to implement the new material has been reduced by 55%, the cost by 45%, and the risk has been reduced by an order of magnitude for the already high values obtained by the conventional building block approach. The experience gained with teams of people running through the methodology both using conventional tools and approaches, as well as using the AIM-C methodology has resulted in comparable results although the total acceleration varied depending on the scale and complexity of the component selected for study. In general, the smaller and simpler the component, the less the savings (sometimes there is even a penalty for very small and simple parts), and greatest with the larger and more complex parts that so often have caused new technologies to be left on the table when they could have provided significant cost or weight savings.

Figure 10-18 compares the risk reduction afforded by the AIM-C approach in comparison to the conventional building block approach. While it is often hard to realistically compare risk reduction schemes by the amount of risk reduced, this analysis based on performing and focusing on early risk and scale-up risk reduction provides payoffs throughout the development program.

Figure 10-19 summarizes the benefits of the AIM-C methodology on cost and schedule for accelerated insertion of materials and Figure 10-18 summarizes the more rapid risk reduction capable using the AIM methodology. All these evaluation metrics are linked and changes in any affect the other two, but the AIM methodology offers continuous evaluation of these parameters throughout the technology maturation process. The AIM team feels that the methodology described herein is applicable to nearly any technology and not just to materials or structures technologies.

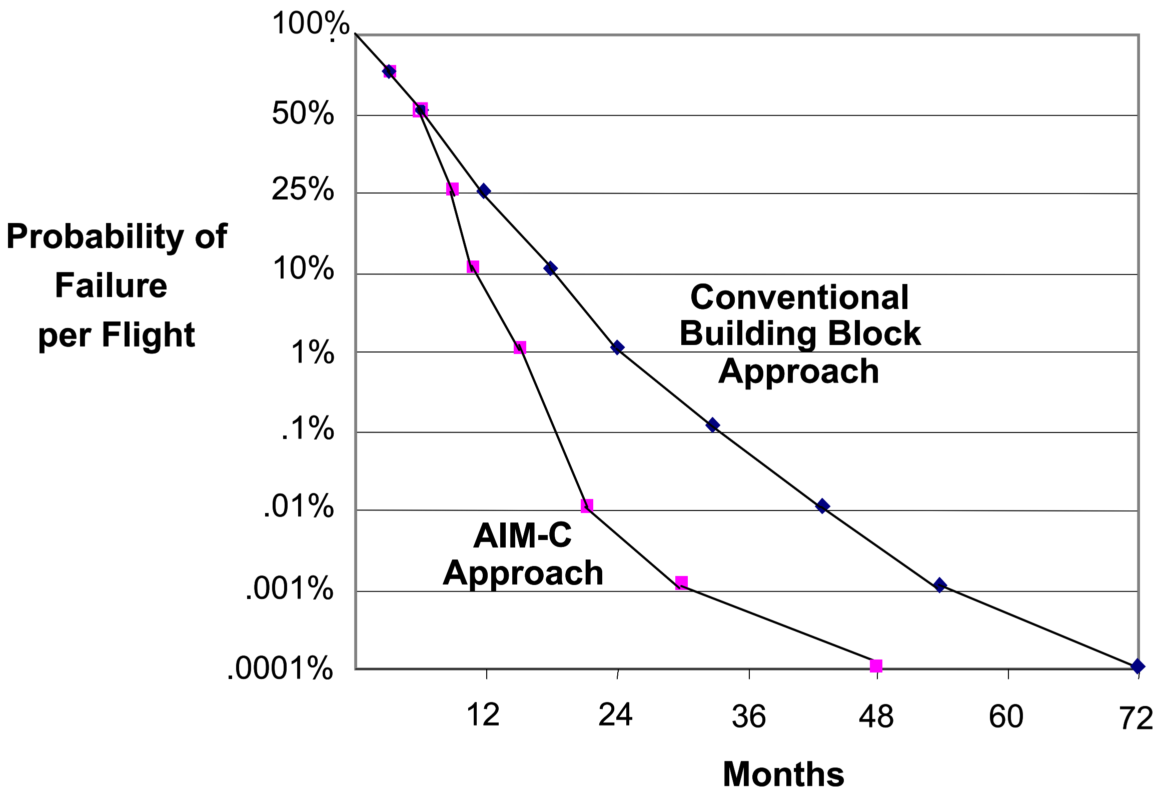



**Figure 10-18. Risk Assessment for Conventional Building Block Approach Compared to the AIM-C Approach**

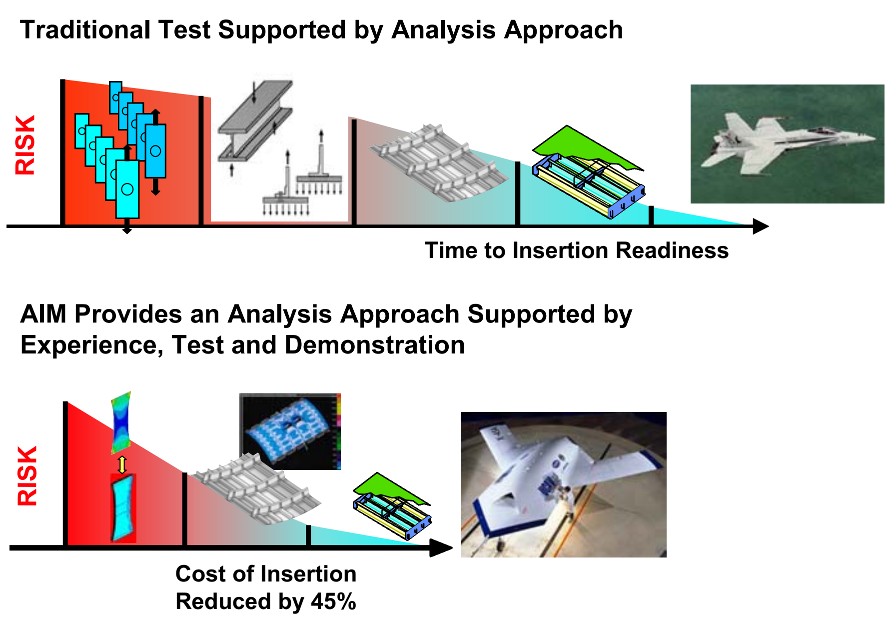



**Figure 10-19 AIM-C Process Achieves Accelerated Insertion**

# 11 AIM Materials and Process Methodology

## Overview

The AIM methodology for accelerating the insertion of new materials involves characterization of new materials relative to requirements as well as exploration of the processing window for that material relative to basic material properties and application specific geometries.

## Composite Materials Screening

### *Time Frame*

Allow at least 6 months for properly evaluating composite material candidates. Consider all the data resources available: suppliers, Department of Defense (DOD) and industry experience with candidate materials, Gray Beard Reviews, and homework /legwork. Validate the source and pedigree of the information to decide its value to decision making.

### *Requirements*

Make a list of requirements based on:

- Aircraft Specification:
    - Maximum operating temperature – corresponding glass transition (Tg) requirement
    - Operating environment – saturated moisture content and effect on the strength properties
    - Chemical resistance – understand resin chemistry, any corrosion issues due to presence of imides
    - Process control/process verification requirements
- Design Requirements
    - Assess adhesive compatibility if there is cocured /co-bonded structure.
    - Honeycomb structure will require a special cure cycle(s) if cocured to the core.
    - How thick is the thickest laminate? What is the thinnest?
    - What are the preliminary margins of safety and can we account for effects of defect in a design
    - Are there large cocured structures that will require massive tooling and slow heat-up rates?
- Manufacturing Requirements

- Optimize the number of cure cycles required.
- Address storage /out time capabilities and requirements.
- Address tack life / handling capabilities and requirements.

### *Data Comparison*

The analyst must understand processing, cure cycle parameters, laminate quality, fiber areal weight (FAW) and Resin Content in addition to the specimen configuration and test set-up to properly evaluate data, regardless of source. It is recommended that side-by-side tests be performed (especially for hot/wet and compression strength after impact (CSAI) properties) for leading material candidates. Do not water boil hot/wet specimens. If you do not have time to fully moisturize the specimens, expose the specimens to the same conditions at approximately 190F/95%RH for at least 30 days to get a quick look at effects of moisture and temperature on material properties.

Compare suppliers “Material Specification” type test data for several batches, if available. The specimens are not representative of design allowables (usually all zero plies) tension/compression/interlaminar shear, but the data provide a better side-by-side comparison for strength and stiffness between material candidates.

### *Manufacturing Evaluation*

A manufacturing evaluation is a must for the final material candidates' screening. Fabricate a couple of parts representing important features such as: thick tapered skins and possibly honeycomb sandwich. Assess:

- Material handling for fresh material and after 30+ days out time. Verify strength drop-off via RT/Dry interlaminar shear coupon for out-time to 35 or 40 days.
- Work with suppliers to adjust bagging schematics and cure cycle for a specific material: high/low flow, vacuum/pressure/temperature cycle.
- If possible, imbed sensors to better understand resin/adhesive flow during cure.
- Carefully perform nondestructive inspection (NDI) to document differences in porosity levels, and other possible defects for different materials.
- Take photomicrographs; perform glass transition temperature determinations, differential scanning calorimetry for degree of cure determinations, and fiber areal weight/resin content testing for specimens taken at various locations to verify degree of cure and laminate quality. Document results.

- Look for unknown particles, unusual ply patterns, etc in photomicrographs. It is better to ask questions at this stage than see inconsistent batch-to-batch properties and lower allowables.
- Check morphology of resin and chemistry.

This does not exclude the application of AIM methodology to test and evaluation at the screening level. However, for purposes of definition the rest of this section deals with the methodology after the screening level. At this point, the methodology is divided into 8 steps which generally run in sequence but which often require looping back through levels as new information and/or requirements become known. The steps are:

1. Definition of requirements
2. Assessment of capabilities
3. Definition of conformance requirements
4. Constituent level basic material data collection
5. Composite level basic material data collection
6. Basic process development
7. Process cycle space exploration and optimization
8. Structure specific material and process application

Progression through these steps involves experience, test and simulation with the relative involvement of each dependent upon the level and applicability of past experience, the relevance of available test methods to requirements, and the confidence in available simulation methods respectively. Engineering judgment is critical to determining the appropriate level of involvement of these three information-generating methods.

The final product of progressing through the AIM methodology for materials and processes is a robust processing cycle for a given material system for an intended application with understood sensitivities and limitations. The knowledgebase developed can also be used for extrapolation to other applications through methodology directed test and simulation.

For the AIM-C program this methodology was developed around an autoclave cured addition reaction epoxy/graphite composite system as applied to hat stiffened aircraft primary structure. For purposes of discussion, progression through this application will be periodically sited here. The basic methodology is universally applicable to any material and process insertion.

## 11.1 Defining Requirements, Assessment Capabilities and Conformance Activities

### Requirements

Fundamental to the successful insertion of any new material is the clear definition of requirements for that material. Ideally these requirements have been clearly identified and universally agreed upon in all relevant categories prior to proceeding with an insertion. In reality, for complex insertion cases such as organic matrix composites into high performance aircraft, requirements evolve as designs mature and operating environment definitions change. In addition a lack of understanding of materials limitations can cause problems as a material and process are pushed into a previously unexplored processing/operating zone. Therefore the AIM Methodology requires not only the definition of performance requirements but also the definition of material and process performance relative to those requirements with an understanding of the uncertainty in both.

A system of Technology Readiness Levels has been developed as part of the overall AIM methodology. (Appendix A). These readiness levels can be used to help define what the requirements are at different stages of a material insertion. Levels referred to as "X"RLs are then developed for the specific material type (in this case autoclave cured composites) and application (Flat panels and Hat Stiffened Panels).

Knowledge of potential requirements growth areas (examples: Increase in temperature operating environment, increase in design dimensions to accommodate stiffness) should be accommodated in data collection and setup of parametric simulations where economically reasonable. Another potential growth area is the range of application for that material. If the material is to be used in a co-cured stiffened structure but the nature of the stiffening scheme has not been determined the AIM-Methodology allows for evaluation using any preexisting templates. This effort up front can save significant time and money later as changes occur by avoiding the flows associated with repeating characterization at different conditions and/or regeneration of simulations.

## Assessment Capabilities

Requirements are met by comparison to results generated by one of three general assessment capability categories defined in the AIM methodology. These categories are experience, test data and simulation. These capabilities should not be confused with material and process system capabilities. Assessment capabilities are the level, pedigree and certainty associated with the categories described above.

The AIM –C system has a number of simulation templates that can be used for parametric studies in the area of producibility and process development. For example Template 9 addresses heat up rate and exotherm issues for flat parts with one or two sided tooling. This simulation can be used to project a material systems performance over a range of part thicknesses, tooling materials and thicknesses, autoclave capabilities and cure cycles evaluating thermal response, viscosity, degree of cure, and relative residual stress. However, this simulation currently does not provide information on material flow and consolidation, critical areas for successful part scale up. For these items we gain some insight by using the producibility module ASCOM simulation for edge thinning along with consulting the heuristics available with the Producibility module for general trends and performance of resins of a similar nature. Finally, depending on the remaining information required, a test plan based on producibility module guidelines will be required to cover un-addressed areas, and improve confidence in results from simulation and heuristics as necessary.

Directly related the capability of the simulation tools is the confidence in the input datasets and subsequent simulation models. During different stages of the insertion process the same simulation may be repeated with improved input data as such data becomes available. For example initial cure cycle development simulation work may be adequately performed using the processing module and template 9 with a simple kinetics and viscosity models based on limited tests and handbook values for other resin and fiber properties. When available, certain properties from datasets for other material systems that have already been entered into the AIM system may be used based on engineering judgment.

## Conformance Activities

Once the insertion requirements and assessment capabilities have been established the insertion process moves to the conformance stage. Figure 11-1 shows the methodology flow that occurs independent of the insertion methodology. This basically describes the high-level conformance activities and cost relative to requirements. These activities and costs will differ depending on the proposed insertion method (Building Block, AIM, Other). Once the high level requirements and conformance activities have been selected the process moves on to the intermediate conformance level as shown in Figure 11-2.

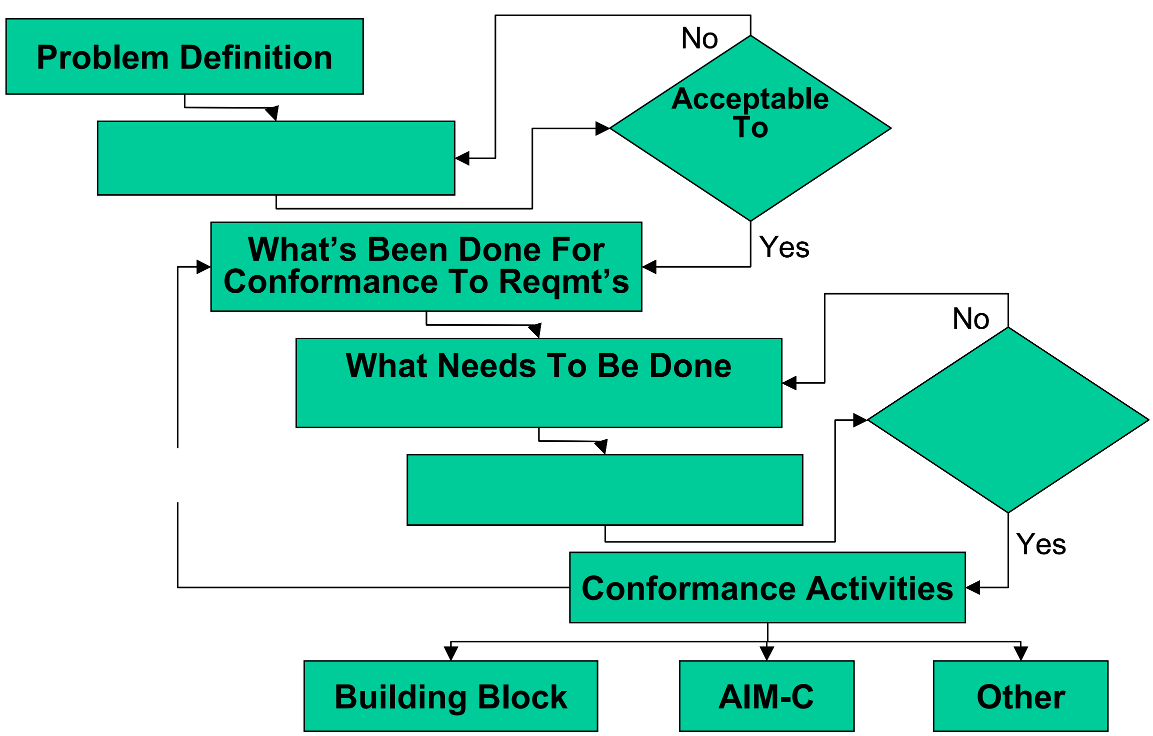



**Figure 11-1 – High Level Conformance Activity, Independent of Insertion Methodology**

The intermediate conformance activities are shown as a loop in Figure 11-1 indicating that conformance activities may be cycled and repeated based upon the outcome. For example heuristics may not provide adequate information on the response of a part during processing necessitating the fabrication of a test part. With the AIM methodology the results of this test part are captured in an update of the appropriate area resulting in an increase in maturity. If results are good, subsequent activity may occur (for example consulting the heuristics may help bracket the conditions for running a design scan using an analytical template, the results of which are used to establish the fabrication conditions for a test part to validate the most challenging areas of a processing window). Once the conformance summary chart requirements are met the insertion process can exit from this loop.

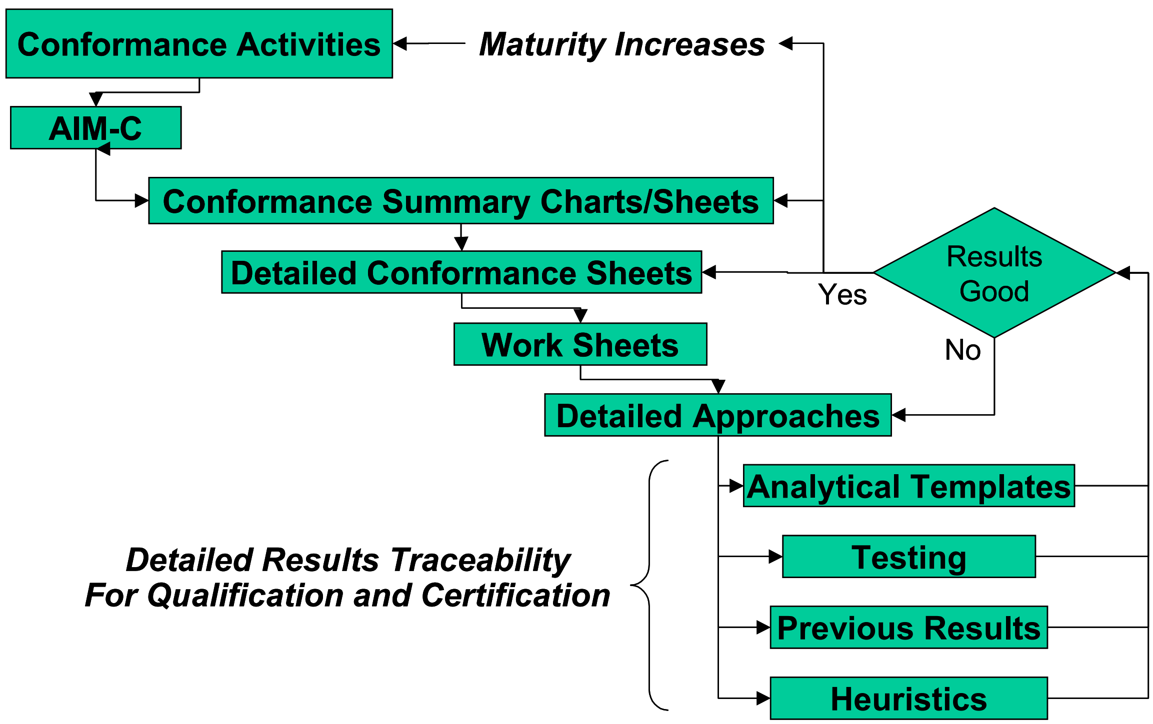
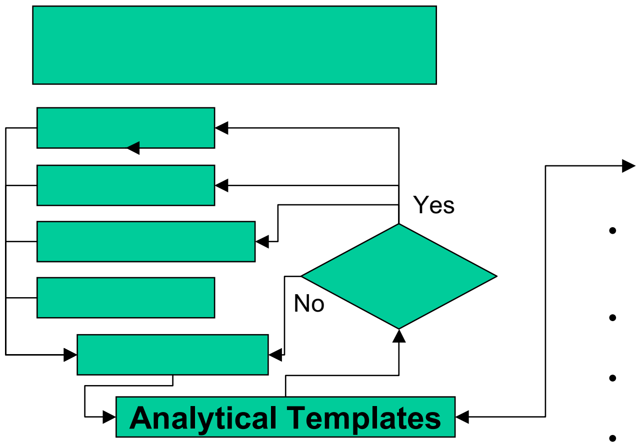



**Figure 11-2 – Intermediate Level Conformance Activity Flow with in AIM Methodology**

Figure 11-3 describes the benefits of the AIM Methodology and how results from conformance activities are used to satisfy multifunctional requirements. The following sections describe specific activity at this level for the AIM Materials and Processes insertion methodology.




***Detailed AIM-C Examples***

- Able to Meet Requirements for Multiple Areas at Same Time Using Integrated Models and Analysis
- Enables Traceability to Specific Requirements From Details and Data
- Applies The Approach of Maximizing Analysis and Minimizing Test
- Does Not Eliminate Testing But Tends to Direct It
- Enables Integrating Conformance Through Multiple Areas/Disciplines Using Common Information/Data/Test and/or Evaluation Specimens

**Figure 11-3 – Benefits of AIM Methodology at Detailed Conformance Level**

## Material Data Collection

Material data collection falls into three categories for composite materials: constituent level (resin and fiber), laminate level, and part specific level. These categories are linked through experience and where available, simulation. It is this linkage and the confidence in this linkage that provides one of the means for insertion acceleration. Linkages can be both forward, building from constituent level properties to laminate and structure or reverse, extracting constituent level data from laminate tests. The utility of the forward linkage is self-explanatory as it offers a means of performance prediction. The reverse linkage allows difficult to measure constituent level properties to be extracted from higher-level test. Once extracted these properties have more utility than the higher-level test alone as they are no longer liked to a composite system.

Organic composite material properties are linked not only to constituent type and variability but also to processing conditions. The AIM methodology includes linkage of properties to processing conditions through simulation, test and experience. This area is still heavily dependent upon test given the current state of simulation capability. Simulations are used to help define processing limits within which the material property variation has been established by testing.

Data collection occurs in stages based on pre-existing information, schedule and technology readiness level. These stages are roughly divided into three levels
–Basic level – The basic level starts with the use of an existing characterized material which has been deemed similar by engineering judgment plus modification based on limited test data in key areas where significant deviations are known to exist from the “make from” material.

–Intermediate level – improve basic level dataset with additional test data, some validation
–Advanced level - full characterization with independent validation

Priority of the data collection is based on the activities for which the system is being tasked. The priority levels are as follows:
1 – Required information. This includes foremost, health and safety information along with cost and vendor estimated properties.
2 - Basic modeling/Heuristics comparison – These are the properties required to support basic coupon level processing feasibility through empirical evaluation and simulation
3 - Intermediate modeling/Heuristics comparison – This level is required for coupon level performance prediction/Sub element processing assessment, initial non-room temp dry performance
4 - Advanced Modeling – Required for sub element performance prediction/Element level Processing Assessment, various temp-dry performance
5 - Stochastic Modeling - Uncertainty prediction - Involves collecting uncertainty information on key inputs as identified by sensitivity studies

## Constituent Level Basic Material Data Collection

As previously described the AIM insertion methodology relies on experience, test and simulation. As a foundation for materials and processes simulations for organic matrix composites constituent level data must be available. As an example Figure 11-4 and Figure 11-5 list the properties of interest for organic matrix composites along with how the property is obtained (test or analysis) and identification of test method and/or analysis type. Many constituent properties such as item 2.1.10 cannot be directly measured, therefore they are measured in laminate form and the required property back calculated using known relationships. These relationships may be embedded into AIM analytical tools or may be applied offline.

| 1. | RESIN - THERMOSET | How Obtained, Test or Anlaysis | Test/Analysis Identification | See Note | Priority (Note 10) |
|---|---|---|---|---|---|
| **1.1** | **TEST TYPE/PROPERTIES - UNCURED RESIN** | | | | |
| | | | | | |
| 1.1.1 | Viscosity | Test | ASTM D 4473 | 1, 2 | 2 |
| 1.1.2 | Reaction Rate | Test | DSC via ASTM D 3418 and ISO 11357 | 2 | 3 |
| 1.1.3 | Heat of Reaction | Test | DSC via ASTM D 3418 and ISO 11357 | | 2 |
| 1.1.4 | Volatile Content/evolution temperature | Test | TGA | 2 | 2 |
| 1.1.5 | Volatile Type | Test/product knowledge | FTIR/Formula access | 2 | 2 |
| 1.1.6 | Volatile Vapor Pressure | Test | | | 3 |
| 1.1.7 | Resin Cost | Specified Value | Based on vender input | | 1 |
| 1.1.8 | Density | Analysis | Based on cured/uncured test data | 4 | 3 |
| 1.1.9 | Resin Cure Shrinkage | Analysis | Based on volumetric test data | | **3** |
| 1.1.10 | CTE | Analysis | based on TMA or linear dilatometer data | 1 | **3** |
| 1.1.11 | Thermal Conductivity | Analysis | Assumed to be that of cured resin | 5 | 2 |
| 1.1.12 | Specific Heat | Analysis | Assumed to be that of cured resin | 5 | 3 |
| 1.1.13 | Kinetics Model | Analysis | Based on Reaction Rate | | 3 |
| 1.1.14 | Viscosity Model | Analysis | Based on Kinetics Model, Test Data | | 3 |
| | Glass Transition Temperature | Analysis | Based on DSC or DMA Test Data | | 3 |
| 1.1.15 | Volatile Type | Redundant | | | |
| 1.1.16 | Volatile Vapor Pressure | Redundant | | | |
| 1.1.17 | Volatile Content | Redundant | | | |
| 1.1.18 | Health and Safety Information | MSDS | | | 1 |
| | | | | | |
| **1.2** | **TEST TYPE/PROPERTIES - CURED RESIN** | | | | |
| | | | | | |
| 1.2.1 | Tensile Stress to Failure | Test | ASTM D638 | 8 | 1 |
| 1.2.2 | Young's Modulus, Tensile | Test | ASTM D638 | 8 | 1 |
| 1.2.3 | Tensile Strain to Failure | Test | ASTM D638 | 8 | 1 |
| 1.2.4 | Glass Transition Temperature | Test | ASTM D3418 | 6 | 1 |
| 1.2.5 | Volatile Content | Test | ASTM D3530 | | 3 |
| 1.2.6 | Density | Test | ASTM D-792 | 4 | 3 |
| 1.2.7 | Modulus as a Function of Temp | Test | Function of Temp and Degree of Cure | 7 | 3 |
| 1.2.8 | CTE | Test | ASTM E831 or linear diletometry | 8 | 2 |
| 1.2.9 | Thermal Conductivity | Test | ASTM C177 | | 2 |
| 1.2.10 | Solvent Resistance | Test | ASTM D543 | | 3 |
| 1.2.11 | Specific Heat | Test | ASTM E-1269 or Modulated DSC | | 3 |
| 1.2.12 | Bulk Modulus | Analysis | | 8 | 3 |
| 1.2.13 | Shear Modulus | Test | ASTM E143 | 8 | 3 |
| 1.2.14 | Poisson's Ratio | Test | ASTM E143 (Room Temp) | 8 | 3 |
| 1.2.15 | Coefficient of Moisture expansion | Test | No Standard | 8 | 4 |
| 1.2.16 | Compression Strength | Test | ASTM D695 | 8 | 3 |
| 1.2.17 | Compression Modulus | Test | ASTM D695 | 8 | 3 |
| 1.2.18 | Mass Transfer Properties | Test | Veight gain vs time, Ficks Law and modeling | | 4 |
| 1.2.19 | Viscoelastic Properties | Analysis | | | 4 |
| 1.2.20 | Toughness Properties | Test | | | 4 |
| 1.2.21 | Tg, Wet | Test | ASTM D3418 | 9 | 1 |
| 1.2.22 | CME | Test | | | 4 |
| 1.2.23 | Solvent (Moisture) Diffusitivity | Test | | | 4 |
| 1.2.24 | Volatile Type | Test | FTIR or similar | | 4 |
| 1.2.25 | Volatile Vapor Pressure | Test | | | 4 |

**Notes**

1 Initial measurements are by test. Test data is extrapolated to other temperaturs and degree of cure
2 Similar test methods acceptable
3 Use appropriate test method for volatile type
4 Water displacement method, density gradient column, or other methods are appropriate
5 See cured resin test types
6 DMA method acceptable
7 Ref. Bogetti and Gillespi, or Johnston
8 tested at varying temperatures, modeled as a function of temperature
9 tested at varying concentrations, modeled as a function of concentration
10 Priority Key
1 - Get in the door/Heuristics comparison
2 - Basic modeling/Heuristics comparison - Coupon level processing feasibility
3 - Intermediate modeling/Heuristics comparison - Coupon level performance prediction
/Sub element processing assessment, initial non room temp dry performance
4 - Advanced Modeling - Sub element performance prediction/Element level Processing Assessment,non room temp-dry performance
5 - Stochastic Modeling - Uncertaitny prediction - Involves collecting uncertainty information on (TBD) inputs

**Figure 11-4 –Resin Properties**

| 2. | FIBER | How Obtained, Test or Anlaysis | Test/Analysis Identification | See Note | Priority (Note 5) |
|---|---|---|---|---|---|
| 2.1 | TEST TYPE/PROPERTIES - FIBER | | | | |
| 2.1.1 | Tensile Strength | Analysis | SACMA SRM 16-94 | 1 | 1 |
| 2.1.2 | Tensile Modulus E11 (longitudinal) | Analysis | SACMA SRM 16-94 | 1 | 1 |
| 2.1.3 | Tensile Strain to Failure | Analysis | SACMA SRM 16-94 | 1 | 1 |
| 2.1.4 | Yield (MUL) | Analysis | SACMA SRM 13-94 | | 3 |
| 2.1.5 | Density | Test | SACMA SRM 15-94 | | 3 |
| 2.1.6 | Heat Capacity (Cp) | Test | ASTM E-1269 or Modulated DSC | 2 | 3 |
| 2.1.7 | Thermal Conductivity Longitudinal | Analysis | ASTM E-1225 | 1, 2 | 3 |
| 2.1.8 | Thermal Conductivity Transverse | Analysis | ASTM E-1225 | 1, 2 | 3 |
| 2.1.9 | CTE - Axial | Analysis | Modeling with Lamina and resin CTE information | 1, 2 | 3 |
| 2.1.10 | CTE - Radial | Analysis | Modeling with Lamina and resin CTE information | 1, 2 | 3 |
| 2.1.11 | Filament Diameter | Test | Scanning Electron Microscopy | | 3 |
| 2.1.12 | Filament Count | Test | Vendor | | 3 |
| 2.1.13 | Transverse Bulk Modulus | Analysis | | 3 | 3 |
| 2.1.14 | Youngs Modulus, E22 Transverse | Test | Analysis combined with mechanical test data | 1 | 3 |
| 2.1.15 | Shear Modulus, G12 | Analysis | Analysis combined with mechanical test data | 1 | 3 |
| 2.1.16 | Shear Modulus, G23 | Analysis | Analysis combined with mechanical test data | 1 | 3 |
| 2.1.17 | Poissons Ratio, 12 | Analysis | Analysis combined with mechanical test data | 1 | 3 |
| 2.1.18 | Poissons Ratio, 23 | Analysis | Analysis combined with mechanical test data | 3 | 3 |
| 2.1.19 | Compressive Strength | Analysis | Analysis combined with mechanical test data | 1 | 1 |
| 2.1.20 | Cost | Specified Value | Vendor Provided | 4 | 1 |
| 2.1.21 | T(g) | Test | DMA | | 1 |
| 2.1.22 | wet T(g) | Test | DMA | | 1 |
| 2.1.23 | Health and Safety | MSDS | | | 1 |
| **2.2** | **TEST TYPE/PROPERTIES - FIBER SURFACE** | | | | |
| 2.2.1 | Sizing Type | Specified Value | | | 3 |
| 2.2.2 | Fiber Surface Roughness | Test | SEM or similar | | 3 |
| 2.2.3 | Surface Chemistry | Specified Value | Surface Chemstry (XPS, etc) | | 3 |
| 2.2.4 | Fiber CME beta1 (Longitudinal) | Test | | | 4 |
| 2.2.5 | Fiber CME beta2 (transverse) | Test | | | 4 |

**Notes**

1 Backed out from lamina test data
2 Tested and modeled as a function of temperature
3 Predicted from basic principles
4 Based on vender supplied relationship
5 Priority Key
 1 - Get in the door
 2 - Basic modeling/Heuristics comparison - Coupon level processing feasibility
 3 - Intermediate modeling/Heuristics comparison - Coupon level performance prediction /Sub element processing assessment, initial non room temp dry performance
 4 - Advanced Modeling - Sub element performance prediction/Element level Processing Assessment,non room temp-dry performance
 5 - Stochastic Modeling - Uncertaitny prediction - Involves collecting uncertainty information on (TBD) inputs

**Figure 11-5 – Fiber Properties**

Composite Level Basic Material Data Collection is conducted concurrently with testing performed to support the needs of fiber level data collection as most of the fiber properties must be analytically backed out of lamina level tests. These tests are described in Figure 11-5. The values for lamina shear modulus are analytically reduced to the fiber component of that shear modulus using the resin mechanical properties described in Figure 11-4. These constituent level properties, when recombined in the lamina module, will give the same value as the lamina level test. The added benefit is that a lamina level shear modulus can now be estimated at a different temperature or with a different resin system. Lamina level test results can be directly used in higher level AIM modules. Characterization of critical mechanical properties may also be conducted at the composite level after prescribed environmental exposures to operating fluids, temperatures, humidity, and loading cycles on an application specific and certification approach basis.

Characterization of the uncured composite material is conducted according to Figure 11-6. These properties are currently used directly in assessing prepreg and processing characteristics. These variables are available in the AIM architecture in the prepreg module and can be used in the future for processing simulations as capability expands in the AIM-C system.

| 3. | PREPREG | How Obtained, Test or Anlaysis | Test/Analysis Identification | See Note | Priority (Note 5) |
|---|---|---|---|---|---|
| | | | | | |
| 3.1 | TEST TYPE/PROPERTIES - CHEMICAL | | | | |
| 3.1.1 | Viscosity | Test | ASTM D 4473 | 1, 2 | 3 |
| 3.1.2 | Degree of Cure | Test | DSC via ASTM D 3418 and ISO 11357 | | 3 |
| | | | | | |
| 3.2 | TEST TYPE/PROPERTIES - PHYSICAL | | | | |
| 3.2.1 | Resin Areal Weight | Test | digestion /burn-out ASTM D3171 or ASTM D3529 | | 2 |
| 3.2.2 | Fiber Areal Weight | Test | digestion /burn-out ASTM D3171 or ASTM D3529 | | 2 |
| 3.2.3 | Mass Fraction Fiber | Test | digestion /burn-out ASTM D3171 or ASTM D3529 | | 2 |
| 3.2.4 | Prepreg Heat Capacity | Analyisis | Rule of mixtures of cured resin / fiber | | 3 |
| 3.2.5 | Density | Analyisis | Rule of mixtures of cured resin / fiber | | 3 |
| 3.2.6 | Volume Fraction Fiber | Analyisis | From mass fraction and densities | | 3 |
| 3.2.7 | Prepreg Ply Thickness | Both | Measured for unconsolidated, calculated for consolidated | 3 | 2 |
| 3.2.8 | Prepreg Areal Weight | Analyisis | From fiber areal weight | | |
| 3.2.9 | Fiber Bed Permeability, x | Test | Speciallized test | | 4 |
| 3.2.10 | Fiber Bed Permeability, y | Test | Speciallized test | | 4 |
| 3.2.11 | Fiber Bed Permeability, z | Test | Speciallized test | | 4 |
| 3.2.12 | Drape | Test | Generally qualitative | | 3 |
| 3.2.13 | Tack | Test | Generally qualitative | | 3 |
| 3.2.14 | Viscoelastic Properties | Analyisis | | | 4 |
| 3.2.15 | Prepreg Defect Probability | Analyisis | | | 4 |
| 3.2.16 | Fiber Bed Elasticity | Test | | | 4 |
| 3.2.17 | Backing Material | Specified Value | | | 3 |
| 3.2.18 | Separator Material | Specified Value | | | 3 |
| 3.2.19 | Available Widths | Specified Value | | | 3 |
| 3.2.20 | Cost | Specified Value | | | 1 |

Notes
1 Initial measurements are by test. Test data is extrapolated to other temperaturs and degree of cure
2 Similar test methods acceptable
3 The prepreg module has the capability to enter either measured (test) or it will calculate the value (analysis)
4 Priority Key
1 - Get in the door
2 - Basic modeling/Heuristics comparison - Coupon level processing feasibility
3 - Intermediate modeling/Heuristics comparison - Coupon level performance prediction/Sub element processing assessment, initial non room temp dry performance
4 - Advanced Modeling - Sub element performance prediction/Element level Processing Assessment,non room temp-dry performance
5 - Stochastic Modeling - Uncertaitny prediction - Involves collecting uncertainty information on (TBD) inputs

**Figure 11-6 Composite Level Prepreg Characterization**

## Basic Process Cycle Development and Exploration

Basic process cycle development begins with the recommended manufacturers cure cycle that is typically based upon resin testing with some limited composite testing. At this point the basic requirements for achieving a fully cured reasonably consolidated flat small flat panel are understood. The challenge is in determining the impact of cure cycle variation on the spectrum of mechanical performance requirements, scaling up part size and shape, and including other materials.

Current simulation tools can offer some insight into relative effects on residual stress from cure cycle variation but they cannot deal with the more complex issues of resin phase formation vs. time-temperature history and defect formation during cure and the resulting effect on mechanical properties. Simulations can yield information on temperature, degree of cure, edge flow, viscosity versus cure cycle, autoclave conditions and tooling conditions. Therefore for the case of organic matrix composites one must explore processing effects on mechanical properties primarily through test. Once performance has been tied to processing as a function of degree of cure, and consolidation has been tied to viscosity and time simulations can be used to ensure that the required times and temperatures are still achievable given the proposed tooling, part configuration and autoclave cure environment.

Some insight into consolidation can be achieved by using simulation but the primary means of development in this area still resides with test and experience. Feature based panels are fabricated to represent the range of expected geometries and thicknesses using material representative of production conditions including maximum and/or minimum out-time conditions and then evaluated for porosity and fiber waviness to determine the number of required debulk cycles for adequate extraction of volatile materials.

As far as the simulation capabilities the following sequence can be used to complement the information generated from test.

Assumptions:

1. Key resin time and temperature requirements defined by supplier. (Yes, See cycle below)
2. Recommended manufacturers cure schedule available (Yes, See cycle below)
3. Volatile type and content identified (No Significant Volatiles)
4. Reaction byproduct type and content Identified (No significant byproducts)
5. DOC range identified based on resin testing (Yes, 0.80 to 0.90)
6. Existing well characterized fiber used (Yes, IM7)
7. Very preliminary DSC (3 to 6) and RDS (3 to 6) data exists and has been put into initial kinetics and viscosity models (Yes, assume existing models)
8. Resin modulus and CTE Data available as a function of cure and has been entered into models (Yes, assume existing models)
9. Prepreg cure only, no cocure
10. T(g) as function of DOC available

Objective:
Establish cure cycle window using simulation tools to cover anticipated application and processing equipment.

Approach:

## Step 1

Evaluate recommended cure cycle for practicality.
Manufacturers Recommended cure cycle

Autoclave - 85 PSI
Bag – vacuum at 22 inches Hg
Both prior to temperature application
Ramp Rate 1 to 5 F per minute
Hold temperature 350 +/- 10F
Hold Time 360 +15/-0 minutes
Cool down 5F maximum

Do the specified parameters fall within reasonable equipment capabilities? YES

## Step 2

Simulate manufacturers recommended cure cycle maximums and minimums with 0.100 inch part on thin tooling and extract output (Representative of coupon allowable type part):

1. Run nominal case
2. Run maximum heat rates and minimum hold times and temperatures
3. Run minimum heat rates and maximum hold times and temperatures

Evaluate-
Degree of Cure
Minimum viscosity and viscosity profile
Gelation Time and Temperature
Vitrification Time and Temperature (Inst. T(g)> T)
Evaluate by Exercising resin module stand-alone with cure cycle driver

## Step 3

Expand cure envelope at flat panel level through simulation

1. Run Isothermal Holds to Explore potential Hold Temperatures
2. Run design scan on heat and cool rates to limits of equipment. (if material path independent)
3. Run design scan varying cure hold temperature by double recommended range
4. Run Design scan on cycle with intermediate temperature hold as determined from viscosity profile.

Evaluate-
Degree of Cure
Minimum viscosity and viscosity profile
Gelation Time and Temperature
Vitrification Time and Temperature (Inst. T(g)> T)

## Step 4

Define thin flat panel cure window based on DOC, Viscosity and reduction in residual stress requirements

## Step 5

Explore effects of part and tool thickness on cure cycle window.

Evaluate part thickness and tool thickness to 2” with various tool materials, similar to template 9, with emphasis on meeting DOC and Viscosity requirements while maintaining temperature requirements. Evaluate residual stress output.

Over what range of thickness and tool materials can part temperature requirements be met given equipment limitations?

### Step 6

Explore effects of 3D and tool constraint on residual stress, temperature response, degree of cure

Evaluate representative anticipated applications (I-beam?, Hat?) with different tooling materials using existing parametric meshes within the AIM system. If a high degree of confidence exists at this stage in the final configuration and a generic part model is not available, generate an application specific model .

Assess impact on residual stress in critical areas (Radius filler, flange edge)

Assess resin modulus development vs. tool expansion

### Step 7

Define cure cycle recommendations for allowables panels

This sequence along with the previously described test panel fabrication will bring the user to the level of understanding for processing defect free panels with a cycle suitable for scaling to a production process with a reasonable confidence depending upon the ultimate demands of the design.

## Structure Specific Material and Process Application

This section deals with the application of the selected material and basic resin processing requirements to a specific part configuration, in this case a hat stiffened fuselage panel. The objective of this effort is to down-select viable tooling and cure approaches for hat-stiffened structure while still maintaining the required basic resin cure requirements. Figure 11-7 describes the flow for traversing the AIM-C Methodology for material insertion into the hat stiffened panel demonstration, part of the initial AIM-C program.

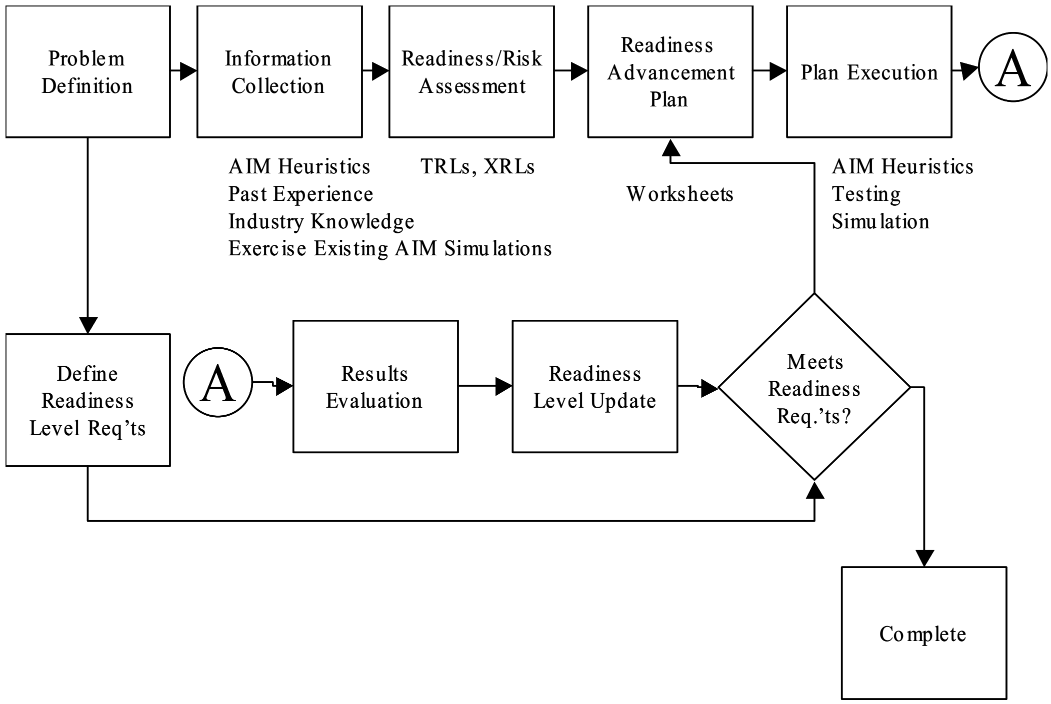



**Figure 11-7 – Flow for Application of AIM-C Methodology**

Figure 11-8 shows a typical mesh as generated by the AIM-C processing module parametric hat mesh generator. The decision to develop a parametric mesh generator as part of the methodology was based on the desire to be able to quickly accommodate design changes and also offer a tool with future utility for other hat stiffened applications. This is a key to the AIM methodology in order to offer future users a library of models that can be available in the early stages of material insertion to offer some insight into material performance in more complex structure.

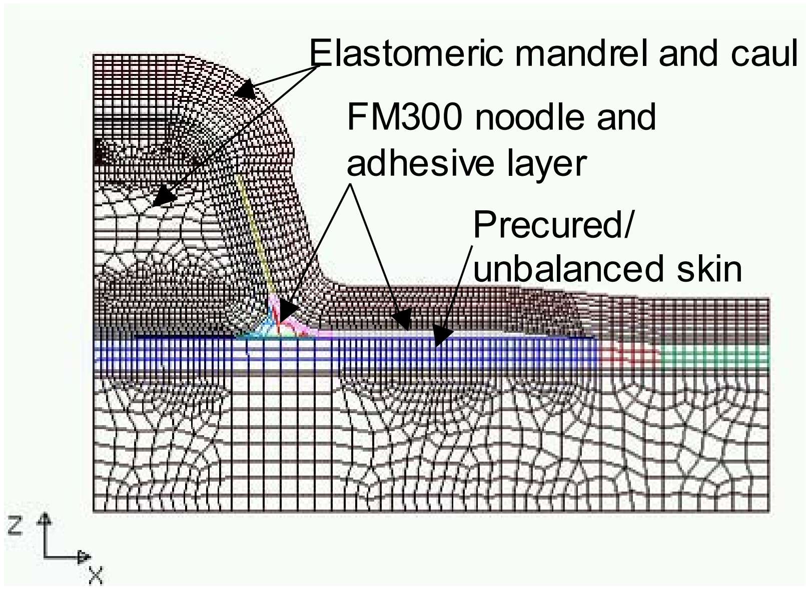



**Figure 11-8 – Typical AIM-C Hat Stiffened Panel Processing Module Simulation Mesh**

The methodology represented in Template 12 which is described in Figure 11-9 can be applied to any class of structures. The key ingredients are the pre and post processors which allow the insertion and extraction of key variables of interest. Investing in this architecture allows rapid reassessment of configurations and processing conditions when unexpected events occur.

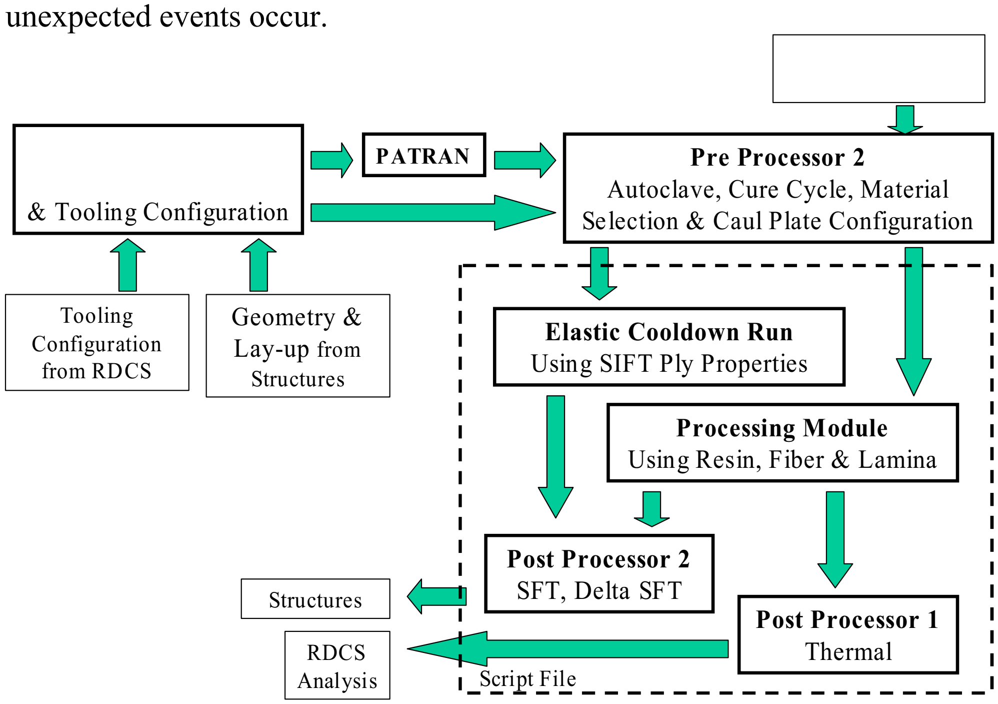



**Figure 11-9 – Template 12 Flow Chart**

Going into this segment of process development it was understood from previously performed tooling and part thickness sensitivity studies that meeting temperature requirements would not be a challenge. Part fabrication iteration was ultimately necessary to resolve some over consolidation issues which were not anticipated by modeling or simulation. However, with the benefit of hindsight the shortcoming in the simulation were identified (Low CTE value provided by vendor, conservative fill factor and mandrel shape interaction with caul sheet) and corrected. Three additional approaches were explored through simulation and test with success. This is an example of (1) simulation driven test followed by (2) simulation update based on test results and (3) ultimate success through test validation. Had pre-existing hat panel fabrication data been available simulation update and validation may have been possible prior to fabrication of the first test article. This makes a strong case for the AIM methodology where prior insertion cases are documented through data collection not only for process validation but also for comparison to existing simulation results and validation of future simulation results when that simulation capability becomes available for integration into the AIM system.

# 12. Producibility

The producibility methodology and process follows the overall process for insertion as shown in Figure 12-6. The producibility/fabrication methodology also includes an approach to using this generated information to determine if and how parts can be made to the application requirements. This could be considered a comparison of capabilities to requirements.

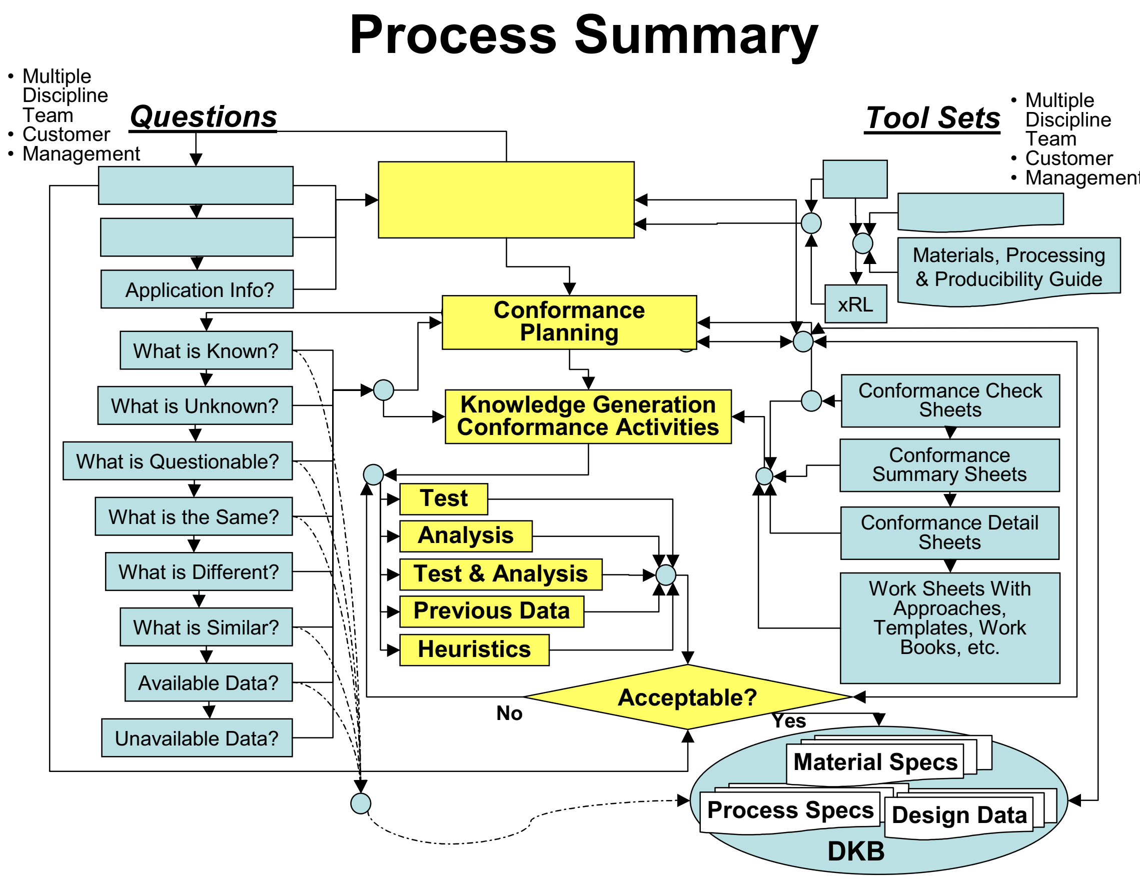



**Figure 12-6 Process Summary for Methodology**

The following sections give (1) an introduction and overview of the producibility methodology, (2) problem statement-requirements pertaining to producibility, (3) conformance planning, (4) knowledge generation approach, (5) knowledge generation activities and (6) part assessment methodology for producibility.

## 12.1 INTRODUCTION

Producibility/fabrication activities for new material insertion are conducted by multiple engineering disciplines for producibility on an integrated product team (IPT). These disciplines include Manufacturing, Material and Processing, Tooling, and Quality. The IPT establishes the producibility knowledge base for new materials or processes. This knowledge base information is used along with overall producibility knowledge for application part manufacturing assessments relative to fabrication, quality and tooling (Figure 12-7).

- **Producibility Item Knowledge Generation** Is Conducted When Qualifying and Certifying a New and/or Changed Material and/or Process to Establish the Knowledge Base
- **Part Producibility Assessment** Is Conducted When Answering Questions About Manufacturing Specific Components/Articles Using the Knowledge Base

**Figure 12-7 Producibility Assessment Types**

The producibility knowledge base covers the manufacturing and quality items shown in Figure 12-8. These are for fabrication only and do not include assembly or assembly related items.

| Producibility Operations/Processes | Quality Aspects |
|---|---|
| • Cutting<br>• Layup<br>• Debulking<br>• Bagging<br>• Cure<br>• Tooling<br>• NDE | • In-process<br>• Final Part |

**Figure 12-8 Producibility Areas**

To achieve accelerated material insertion, there are three stages to establishing producibility information that culminates with a generic, full scale application, feature based demonstration part early for IPT evaluation. These stages (Figure 12-9) are (1) Quick Look assessments, (2) Detailed assessments, and (3) Validation assessments. The first stage rapidly assesses potential show stopper issues that may be encountered with a new material when fabricating components. Stage 2 assesses the producibility details of a new material to establish a producibility knowledge base for specifications, part quality and part producibility assessments. Stage 3 validates that producibility parameters and limits are acceptable for component certification. These three stages correspond to the stages of qualification and certification in the overall program

*The Approach for Producibility Item Assessment Provides……………*

| Activity | **Stage 1**<br>Quick Look | **Stage 2**<br>Detailed Assessments | **Stage 3**<br>Validations |
|---|---|---|---|
| **Purpose** | Define Item Variable Parameters | Define Item Parameter Limits | Validate Item Parameters |
| **Feature Based Parts** | • Flat Panel<br>• Ramped Panel<br>• Generic Full Scale Part | • Multi-Thickness Panels<br>• Ramped Panel<br>• Generic Part Element | • Full Scale Generic Application Component |

*……………..Knowledge for Qualification and Certification*
*Along with Knowledge for Part Producibility Assessments*

**Figure 12-9 Producibility Item Assessments in Three Stages with Feature Based Parts**

Producibility is a subset of the overall AIM-C approach and directed at capability for qualification and certification. A comparison of the overall AIM-C approach and producibility approach is shown in Figure 12-10.

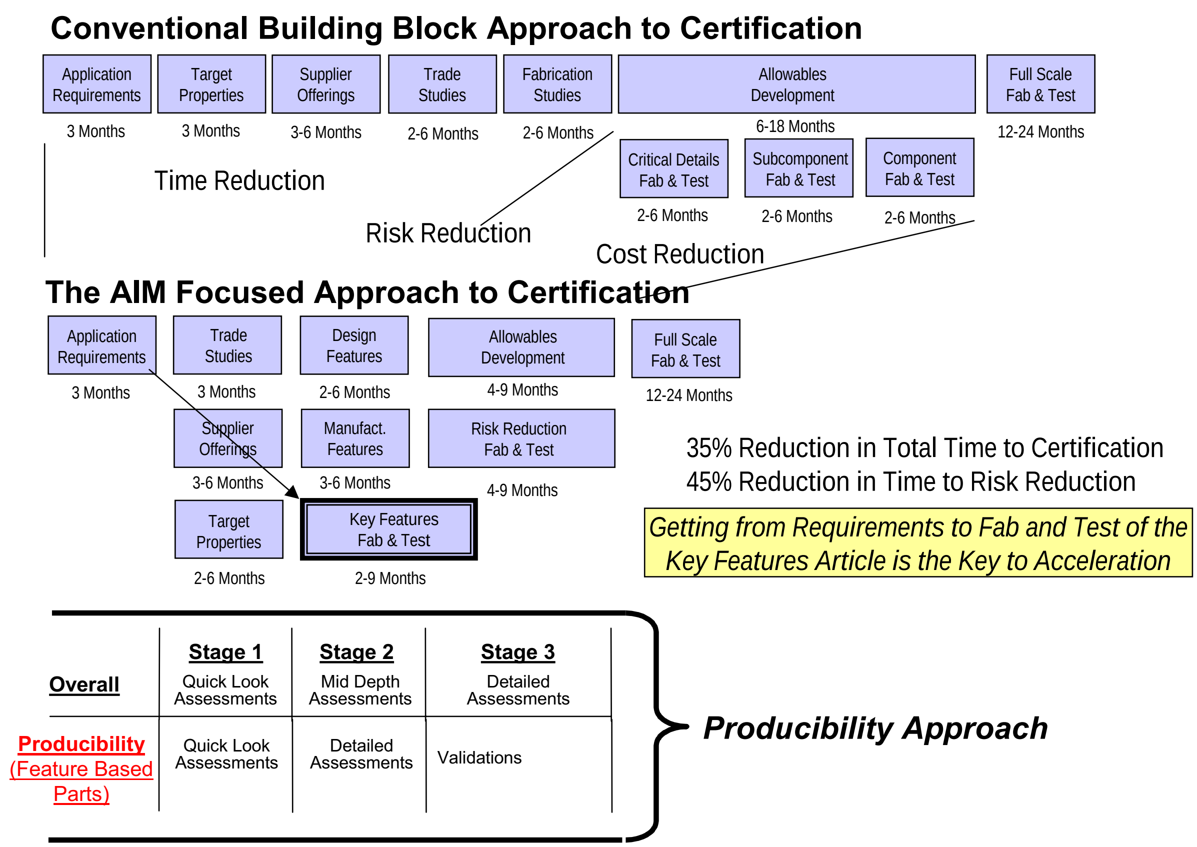



**Figure 12-10 AIM Focused Approach for Qualification and Certification**

Producibility knowledge generation for accelerated insertion follows the overall process of Problem Statement-Application Requirements, Conformance Planning, Knowledge Generation-Conformance Activities, and Conformance Assessments (Figure 12-11). The generated producibility knowledge for a new material or process is added to the general producibility knowledge base for specific part producibility assessments. These specific part producibility assessments are aimed at answering the questions of (1) Can the part be made? (2) What will be the quality of the part? (3) What are the tooling options for the part?

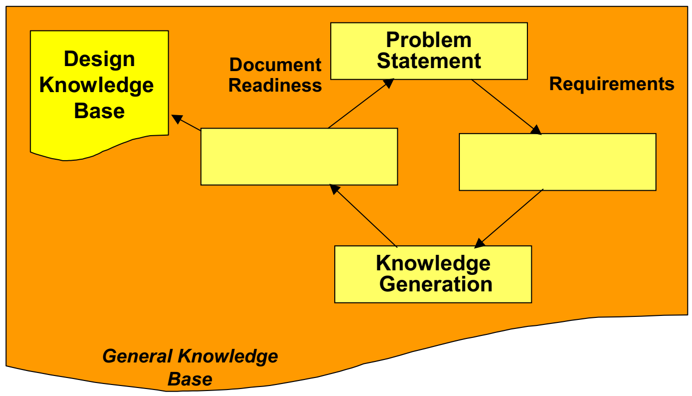



**Figure 12-11 Overall AIM-C Process for Material/Process Insertion**

For producibility, the process is to identify requirements within the problem statement, establish conformance planning documents, obtain knowledge base information and use it for part producibility assessments. This process is shown in Figure 12-12 going from the problem statement through use of the information.

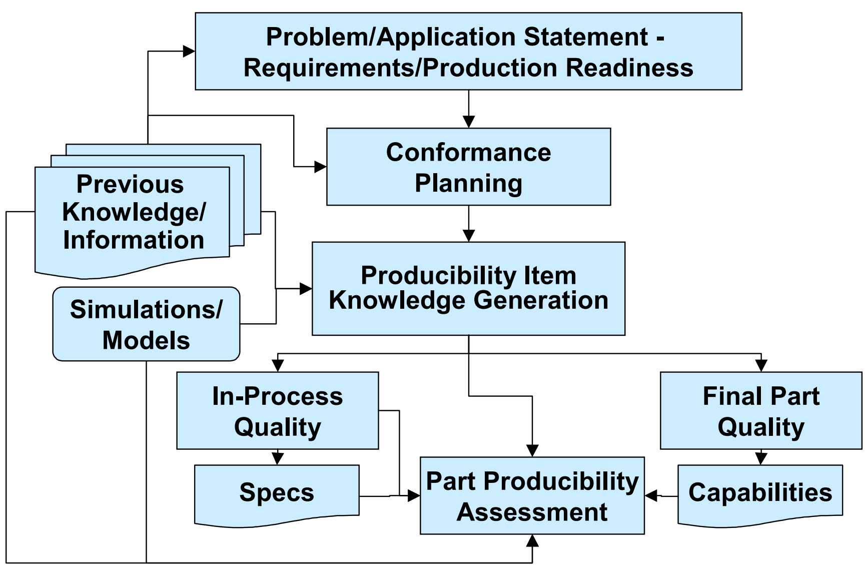



**Figure 12-12 Overall Producibility Process**

### 12.1.1 Benefits of This Producibility Methodology

The following chart (Figure 12-8) summarizes the features and benefits of the producibility approach and process. There are two primary payoffs from the producibility approach and process. First is early show-stopper identification. Second is evaluation of the broad producibility picture for the application thereby minimizing the potential rework because of encountering it during actual part fabrication late in the certification process.

| Feature | Benefit |
|---|---|
| Qualification + Certification | Full Identification of Why Producibility Activities are being Conducted Relative to the Problem/Application Statement |
| Production Readiness | Unique Addition to Requirements |
| Producibility Knowledge Generation and Part Producibility Assessment As Two Different Producibility Activity Types | Enables Establishing and Using Producibility Knowledge for General and Part Specific Needs |
| Producibility Item Knowledge Generation With In-Process and Final Part Quality | Enables Guideline/Specification Generation and Part Quality Capabilities With Substantiated Data |
| Feature Based Application Part Assessment | Generically Applicable to All Applications |
| Defined, Generic Process | Flexible to Allow Various User View Points |
| Problem Statement + Requirements + Conformance + Usage | Gives Complete Producibility Picture of Why, What, When, and How |

**Figure 12-13 Features and Benefits from Producibility Approach/Process**

## 12.2 PROBLEM STATEMENT – REQUIREMENTS

Component requirements flow down to the TRL chart for specific exit criteria according to categories of disciplines or areas. Figure 12-14 highlights Producibility/fabrication exit criteria going from a TRL of 1 through 10 and is primarily based on successful part fabrication. For new material insertion, the primary producibility TRL goal is 4. This essentially means that stability has been demonstrated with multiple parts and that final process specification exist. The intent for this stability is to enable generation of design allowables, subcomponents and components for certification. Previous experience has shown that stability has not been achieved for applications with scale up and this necessitated significant rework because of being a potential show stopper. For this reason, the TRL exit criteria for levels 2 and 3 address application featured generic elements, subcomponents and full-scale components to minimize risk at the time of actual application component fabrication.

| TRL | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Application Risk | Very High | High | High - Med | Med - High | Medium | Med - Low | Low | Low - Very Low | Very Low | Negligible |
| Application Maturity | Concept Exploration | Concept Defintion | Proof of Concept | Preliminary Design | Design Maturation | Component Testing | Ground Test | Flight Test | Production | Recycle or Dispose |
| Certification | Certification Elements Documented | Certification Plan Documented | Certification Plan Approved | Preliminary Design Allowables | Subcomponent Testing | Full Scale Component Testing | Full Scale Airframe Tests | Flight Test | Production Approval | Disposal Plan Approval |
| Design | Concept Exploration/ Potenital Benefits Predicted | Concept Defintion/ Applications Revised by Lamina Data (Coupons) | Applications Revised by Laminate Data (Coupons)/ Design Closure | Applications Revised by Assy Detail Test Data (Elements)/ Preliminary Design | Applications Revised by Subcompnent Test Data/ Design Maturation | Applications Revised by Component Test Data/ Ground Test Plan | Applications Revised by Airframe Ground Tests/ Flight Test Plan | Production Plan | Production Support | Disposal Support |
| Assembly | Assembly Concept | Assembly Plan Defintion | Key Assembly Detail Defintions | Key Assembly Details Tested | Subcomponents Assembled | Components Assembled | Airframe Assembled | Flight Vehicles Assembled | Production | Disassembly for Disposal |
| Structures | Preliminary Properties-Characteristics | Initial Properties Verified by Test | Design Properties Developed | Preliminary Design Allowables | B-Basis Design Allowables | A-Basis Design Allowables | | | Flight Tracking/ Production Spport/ Fleet Support | Retirement for Cause |
| Materials | Lab Prototype Materials | Pilot Production Materials | Pre-Production Materials | Production Materials/ Material Specs | | | EMD Material Supplied | LRIP Material Supplied | Production Material Supplied | Support for Recycle or Disposal Decisions |
| Fabrication | Unfeatured-Panel Fabrication | Feature Based Generic Small/Subscale Parts Fabricated | Property-Fab Relationships Tested/ Target Application Pilot Production of Generic Full Size Parts | Process Specs/ Effects of Fab Variations Tested/ Elements Fab'd/ Production Representative Parts Fab'd | Subcompnents Fab'd | Full Scale Components Fabricated | EMD Fabrication | Low Rate Initial Production (LRIP) | Production | Recycle or Disposal |
| Cost Benefits | Cost Benefit Elements ID'd & Projected | ROM Cost Benefit Analysis | Cost Benefit Analysis Reflect Size Lessons Learned | Cost Benefit Analysis Reflect Element and Production Representative Part Lessons Learned | Cost Benefit Anlysis Reflect Subcomponent Fab & Assembly Lessons Learned | Cost Benefit Anlysis Reflect Component Fab & Assembly Lessons Learned | Cost Benefit Anlysis Reflect EMD Lessons Learned | Cost Benefit Anlysis Reflect LRIP Lessons Learned | Cost Benefit Anlysis Reflect Production Lessons Learned | Cost Benefit Anlysis Reflect Disposal Lessons Learned |
| Supportability | Repair Items/Areas Identified | Repair Materials & Processes Identified | Repair Materials & Processes Documented | Fab Repairs Identified | Fab Repair Trials/ Subcomponent Repairs | Component Repairs | Production Repairs Identified | Flight Qualified Reapirs Documented | Repair-Replace Decisions | Support for Recycle or Disposal Decisions |
| Intellectual Rights | Concept Documentation | Patent Disclosure Filed | Proprietary Rights Agreements | Data Sharing Rights | Vendor Agreements | Material and Fabrication Contracts | Production Rate Contracts | Vendor Requal Agreements | Post-Production Agreemtns | Liability Termination Agreements |

**Figure 12-14 Requirement Flow Down to the TRL Chart for Producibility/Fabrication**

The feature based part fabrication approach is for knowledge generation and is compatible with the exit criteria at TRL level 1 through 4. Two issues arose when establishing the producibility methodology/process using the readiness level concept with specific exit criteria.

1. Producibility subdivides into the manufacturing operations/processes of cutting, layup, debulking, bagging, cure, tooling, and NDE where each could be at a different maturity level and not be captured correctly at the upper TRL level.

2. Production readiness for each of the operations/processes in producibility is not captured.

Producibility for fabrication is comprised of several areas or items. These are cutting, layup, debulking, bagging, cure, tooling and non-destructive evaluations (NDE). These would form individual technology readiness level sheets for producibility one level below the top level summary sheet for readiness. Specific exit criteria would be established for each area or item maturity going from concept definition through qualification and into certification.

This readiness level concept then leads to the question of how can production readiness be incorporated into requirements for qualification. Production readiness has a series of generic evaluation categories that have to be addressed, regardless of the technology (materials, processing, producibility, etc.). These are shown in Figure 12-15.

| | |
|---|---|
| **Material** | **Final Product Quality** |
| **Processes** | **Application Maturity** |
| **Equipment** | **Cost Benefit Analysis** |
| **Tooling** | **Supportability** |
| **Variability** | **Regulatory** |
| **In-Process Quality** | **Intellectual Property** |

**Figure 12-15 Production Readiness Categories**

By combining the production readiness categories with XRL maturity step numbering, a generic matrix worksheet can be established where individual blocks can be filled in for exit criteria. Figure 12-16 shows a generic example TRL for production readiness and technology readiness requirements that are applicable for composite materials, processing and producibility. The categories include technical requirements and ones associated with production readiness. Being generic, it covers all assessment areas. It should be noted that not all areas or maturity level exit criteria may be specifically applicable to qualification and certification of materials, processing, producibility or answering of the problem statement.

| (x)RL Rating | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| | | | | | 5.0 - 5.4 | 5.5 - 5.9 |
| MATERIAL | Material ingredients/ combinations never used previously. No industrial base capability available. Constituent properties and compatibility issues unknown. | Material ingredients/combinations made in a laboratory environment. No industrial base capability available. Constituent properties and compatibility issues identified. | Key material ingredient characteristics identified for processing, quality, and application. Potential approaches identified to remedy incompatibilities. | Critical functions/ characteristics of material/ ingredients demonstrated. New material within state-of-the-art. Indirect material requirements identified. Facility requirements identified. | Proof-of-concept completed for production, properties, and scale-up of material under relevant conditions achieved (including resolving of material incompatibilities). | Material requirements/out based on models and/or prototypes and/or pilot pla relavent environment. Ma capacity (e.g., single sour offshore only, pilot plant, e |
| PROCESSES | Requires technology never used previously. No industrial base capability available. Constituent properties and compatibility issues unknown. | Requires yields/tolerances/ throughput/scale not previously achieved. New process needed requiring state-of-the-art advance. Critical facility or vendor not available. Process compatibility issues identified. | Key characteristics identified for process, quality, and application. Potential approaches identified to remedy incompatibilities. | Critical functions/ characteristics of processing demonstrated. New process operates within state-of-the-art. Facility requirements identified. Indirect materials or process steps identified. | Proof-of-concept completed for production, properties, and scale-up of process achieved under relevant conditions (including resolving of material incompatibilities). One or more requirements only marginally achievable. | Process requirements/out based on models and/or prototypes and/or pilot pla Marginal capacity (e.g., si source, offshore only, etc) |
| EQUIPMENT | Appropriate equipment does not exist and/or requirements are not known. | Necessary equipment requirements identified including key technology areas. | Key characteristics identified for process, quality, and application. Characteristics applicable to technology areas and individual equipment pieces. | Critical functions/ characteristics of individual equipment pieces demonstrated. Indirect materials and facility requirements identified. Equipment accuracy requirements defined. | Initial proof-of-concept testing completed including critical scale-up issues. | Integration of equipment parts/systems demonstrat |
| TOOLING | Appropriate tooling does not exist or requirements are not known. | Necessary tooling requirements identified and includes key technology areas. | Key characteristics identified for process, quality, and application. Characteristics applicable to technology areas and individual equipment pieces. | Critical functions/ characteristics of individual tooling pieces demonstrated. Indirect materials and facility requirements identified. Tooling accuracy requirements defined. | Initial proof-of-concept testing completed including scale-up issues. | Integration of tooling parts/details/systems demonstrated. |
| VARIABILITY | Drivers of variability unknown or not understood. | Some items of variability identified. | Key drivers of variability identified. Methods of measuring identified. | Variabilities roughly characterized. | Variabilities measured with tests on representative samples/items and used as base line capabilities. Proof-of-concept for scale-up variablity issues identified. | Variability requirements O based on models and/or prototypes and/or pilot pla |
| QUALITY - IN-PROCESS | Requires technology never used in manufacturing previously. No industrial base capability available | Requires Q/A capability levels not previously achieved. | Key quality characteristics identified. | Critical quality functions/characteristics demonstrated. Indirect material and/or process steps identified. Facility requirements identified. Defects identified | Proof-of-concept for quality practices/procedures/techniques successfully demonstrated including scale-up issues. | Quality requirements/outp based on models and/or prototypes. Defects evalu |
| QUALITY - FINAL PRODUCT | Requires technology never used in manufacturing previously. No industrial base capability available | Requires Q/A capability levels not previously achieved. | Key quality characteristics identified. | Critical quality functions/characteristics demonstrated. Indirect material and/or process steps identified. Facility requirements identified. Defects identified. | Proof-of-concept for quality practices/procedures/techniques successfully demonstrated including scale-up issues. | Quality requirements/outp based on models and/or prototypes. Defects evalu |
| APPLICATION MATURITY | New technology required; state-of the art advance. One or more requirements may be unachievable. | Relevant unit problems identified, technologies understood and tested at unit level. | Primary functions/characteristics understood and demonstrated. | Critical functions/characteristics demonstrated; physical phenomena understood. | Component/breadboard successfully tested in relevant environments,OR, existing item requiring major modification tested. One or more requirements only marginally achievable. | Generic small-subscale pr parts or engineering mode successfully tested in rele environments, OR, existin requiring significant modif tested. |
| COST/BENEFIT ANALYSIS | Cost/benfits not known. | High level costs/benefits identified. | Costs/benefits defined. | Key costs/benfits have had a preliminary assessment for quantification. | Key costs/benfits have been shown in a relavent environment with scale-up. | Key costs/benfits have be shown with models and/or prototypes. |
| SUPPORTABILITY | Requires repair technology never used before. No capability available. | New repair processes requiring state-of-the-art advanced. | Key characteristics identified for repair processes. | Critical repair functions and characteristics demonstrated. | Proof-of-concept completed for repair procedures under relevant conditions including scale-up issues, OR, major modification of proven repair procedure completed. | Repair requirements OK b on models and prototypes significant modification of repair procedures comple |
| REGULATORY | Potential problems unknown. | Potential regulatory issues identified. | Federal, state, and local applicable regulations identified (i.e. OSHA, NIOSH, EPA, air, water, building, shipping, etc.). | Regulatory issues understood. | Potential approaches identified to eliminate regulatory concerns. | Initial proof-of-concept tes potential approaches succ completed. |
| **Intellectual Property** | | Proprietary material and process concepts identified. | Patent disclosures based on data drafted. Trademark and potential trade secret issues identified. | Reduction to practice in progress. Strategy to issue patents or preserve technology as trade secret accepted. | Patent Applications drafted. Trade secret practices in place. | Reduction to practice verif |

**Figure 12-16 Example TRL Worksheet Chart for Production Readiness Requirement Identification**

A TRL chart covering detailed requirements/production readiness summary chart covering qualification and certification is established for each of the producibility items shown in Figure 12-17. In other words, each producibility item has its own TRL chart for requirements and production readiness.

**Producibility Operations/Processes**

- Cutting
- Layup
- Debulking
- Bagging
- Cure
- Tooling
- NDE

**Figure 12-17 Producibility Items**

The approach used to generate the detailed requirement summary charts is to ask questions from each block of the generic TRL matrix chart worksheet as to whether it applies to the producibility item. If so, in what way does it apply? This approach ties detailed requirements up through top level TRL requirements for component applications relative to conformance activities

Examples of detailed requirement TRL charts for cutting, layup, debulking and cure are shown in Figure 12-18. The individual TRL sheets for producibility areas and items are in Appendix A.

**Figure 12-18. Detailed Requirements TRL Charts for Cutting, Layup, Debulking and Cure.**

## Conformance Planning

The feature based producibility parts are fabricated at different stages or maturity levels and are a metric of producibility maturity. This maturity aspect of the feature based approach is shown in Figure 12-19 where the darkened box indicates the primary activity maturity with the feature based approach. Flat and ramped panels are the basic parts for producibility assessments and comparisons at all maturity levels to ensure that any specific changes to parameters do not impact overall parameter impact on quality. These sheets for producibility parts fabrication establish a check sheet for what has been made and what has to be made. It is established within a multiple discipline environment with participation and concurrence with customers and customer groups.

**Producibility Methodology/Process Steps (Feature Based)**

**Stage 1** Quick Look Assessments

**Stage 2** Detailed Assessments

**Stage 3** Validation

**TRL**

| Area | | Application | 0.25 | 0.50 | 0.75 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Producibility Evaluations, In-Process Quality, Final Quality | 1 | Flat Panels (.125) | | | | X | x | x | x | | | |
| | 2 | Ramped Panels | | | | X | x | x | x | | | |
| | 3 | Multiple Thickness Flat Panels (.08, .125, .250, .5) | | | | | X | x | | | | |
| | 4 | Generic Elements | | | | | X | | | | | |
| | 5 | Feature Based Full Scale Generic Component | | | | x | | X | | | | |
| Other | | Effect of Defects | | | | x | X | x | x | | | |

*Note: Flat and Ramped Panels Are Re-made When Matl's or Processes Are Changed*

***Feature Based Producibility is Used to Establish the Producibility Knowledge Base Through Producibility Item Assessments***

**Figure 12-19 Producibility Maturity Based on Featured Parts**

A detailed description of planned producibility evaluations and knowledge generation for the different areas and items are shown in Figure 12-20. This also forms a check sheet of what is to be done and when it is to be done. The darkened boxes are when the primary activities for that activity will be conducted. There are several activities that generate information through the whole maturity cycle and this information is accumulated for the overall producibility knowledge base.

| Operation | Activity | 0.25 | 0.50 | 0.75 | TRL 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Hand Cutting | Requirements | | | | x | | | | | | |
| | Spool Information | | | | x | | | | | | |
| | Indirect Materials ID/Compatability | | | | x | x | | | | | |
| | Tack, Original | | | | x | | | | | | |
| | Tack, Out Time | | | | x | | x | | | | |
| | Tack, Freezer Time | | | | | | x | | | | |
| | Variability, Dimensions | | | | x | | | | | | |
| | Variability, Angle | | | | x | | | | | | |
| | Specification, Draft Items/Areas | | | | x | x | | | | | |
| | Specification, Preliminary | | | | | | x | | | | |
| | Specification, Final | | | | | | | x | | | |
| Hand Layup | Requirements | | | | x | | | | | | |
| | Indirect Materials ID/Compatability | | | | x | x | | | | | |
| | Tack, Original (lay down and removal) | | | | x | | | | | | |
| | Tack, Out Time (lay down and removal) | | | | x | | x | | | | |
| | Tack, Freezer Time | | | | | | x | | | | |
| | Variability, Dimensions | | | | x | | | | | | |
| | Variability, Angle | | | | x | | | | | | |
| | Specification, Draft Items/Areas | | | | x | x | | | | | |
| | Specification, Preliminary | | | | | | x | | | | |
| | Specification, Final | | | | | | | x | | | |
| Debulking | Requirements | | | | x | | | | | | |
| | Indirect Materials ID/Compatability | | | | x | x | | | | | |
| | Methods, Plies/Times/Temps/Pressures | | | | x | x | | | | | |
| | Limits, Plies/Times/Temps/Pressures | | | | | x | | | | | |
| | Specification, Draft Items/Areas | | | | x | x | | | | | |
| | Specification, Preliminary | | | | | | x | | | | |
| | Specification, Final | | | | | | | x | | | |
| Bagging | Requirements | | | | x | | | | | | |
| | Indirect Materials | | | | x | x | | | | | |
| | Edge Gaps, Initial | | | | x | | | | | | |
| | Edge Gaps, Limits | | | | | x | | | | | |
| | Specification, Draft Items/Areas | | | | x | x | | | | | |
| | Specification, Preliminary | | | | | | x | | | | |
| | Specification, Final | | | | | | | x | | | |
| Cure | Requirements | | | | x | | | | | | |
| | Initial Times/Temps/Pressures | | | | x | | | | | | |
| | Material Combinations | | | | x | | | | | | |
| | Limits, Times/Temps/Pressures | | | | | x | | | | | |
| | Limits, Heat up/Cool Down/Tooling/Equipment | | | | x | x | | | | | |
| | Specification, Draft Items/Areas | | | | x | x | | | | | |
| | Specification, Preliminary | | | | | | x | | | | |
| | Specification, Final | | | | | | | x | | | |
| Tooling | | | | | x | x | x | x | | | |
| NDE | | | | | x | x | x | x | | | |

**Figure 12-20 Producibility Area/Item Maturity Level Activities**

In-process quality addresses item variability that is measured/controlled during individual item or operation execution. For composites producibility, in-process quality variability covers the areas shown in Figure 12-21. The investigations and knowledge generation of in-process variability impact is conducted on each individual item during quick look assessments at Stage 1 (TRL=1) and detailed assessments at Stage 2 (TRL=2) as shown in
Figure 12-22

- **Indirect/Support Materials**
- **Ply Angle**
- **Ply Lap/Gap**
- **Out Time**
- **Freezer Time**
- **Cure Time, Temp, Pressure**
- **Heat-up Rates**
- **Cure Abort Conditions**
- **Debulk Time, Temp, Pressure, Methods**
- **Bagging Gaps, Breathers, Bleeders**
- **NDE Standards**

**Figure 12-21 In-Process Quality Items**

| | | | TRL | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Area** | **Item** | **Activity** | **0.25** | **0.50** | **0.75** | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| In-Process Qulaity | Cutting | Times | | | | x | | | | | | |
| | | Temperatures | | | | x | | | | | | |
| | | Dimensions | | | | x | | | | | | |
| | | Angles | | | | x | | | | | | |
| | | Indirect Manterial Compatability | | | | x | x | | | | | |
| | | Limitations | | | | | x | | | | | |
| | | Specification, Draft Items/Areas | | | | x | x | | | | | |
| | | Specification, Preliminary | | | | | | x | | | | |
| | | Specification, Final | | | | | | | x | | | |
| | Hand Layup | Times | | | | x | | | | | | |
| | | Temperatures | | | | x | | | | | | |
| | | Pressures | | | | x | | | | | | |
| | | Indirect Material Compatability | | | | x | x | | | | | |
| | | Dimensions | | | | x | | | | | | |
| | | Angles | | | | x | | | | | | |
| | | Limitations | | | | | x | | | | | |
| | | Specification, Draft Items/Areas | | | | x | x | | | | | |
| | | Specification, Preliminary | | | | | | x | | | | |
| | | Specification, Final | | | | | | | x | | | |
| | Debulking | Plies | | | | x | | | | | | |
| | | Times | | | | x | | | | | | |
| | | Temperatures | | | | x | | | | | | |
| | | Pressures | | | | x | | | | | | |
| | | Indirect Material Compatability | | | | x | x | | | | | |
| | | Limitations | | | | | x | | | | | |
| | | Specification, Draft Items/Areas | | | | x | x | | | | | |
| | | Specification, Preliminary | | | | | | x | | | | |
| | | Specification, Final | | | | | | | x | | | |
| | Bagging | Indirect Material Compatability | | | | x | x | | | | | |
| | | Edge Gaps | | | | x | | | | | | |
| | | Limitations | | | | | x | | | | | |
| | | Specification, Draft Items/Areas | | | | x | x | | | | | |
| | | Specification, Preliminary | | | | | | x | | | | |
| | | Specification, Final | | | | | | | x | | | |
| | Cure | Times | | | | x | | | | | | |
| | | Temperatures | | | | x | | | | | | |
| | | Pressures | | | | x | | | | | | |
| | | Aborts | | | | | x | | | | | |
| | | Limitations | | | | | x | | | | | |
| | | Specification, Draft Items/Areas | | | | x | x | | | | | |
| | | Specification, Preliminary | | | | | | x | | | | |
| | | Specification, Final | | | | | | | x | | | |
| | Other | Out Time | | | | x | | x | | | | |
| | | Freezer Time | | | | | | x | | | | |

**Figure 12-22 In-Process Quality Area/Item Maturity Level Activities**

Final part quality addresses accept/reject criteria commonly used for composite parts (Figure 12-23). The investigation and assessments of final part quality impact is conducted on each individual item during quick look assessments at Stage 1 (TRL=1) and detailed assessments at Stage 2 (TRL=2) as shown in Figure 12-24. These evaluations yield capabilities for material and producibility that is then compared to application requirements to see whether these requirements can be met with the capabilities. This information is also used during part producibility assessments.

- **Geometric Dimensions**
- **Thickness**
- **Voids**
- **Porosity**
- **Inclusions**
- **Surface Waviness**
- **Surface Finish**
- **Fiber Volume/Resin Content**
- **In-Plane Fiber Distortion**
- **Out of Plane Fiber Distortion**

**Figure 12-23 Final Part Quality Items**

| | | | TRL | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Area** | **Item** | **Activity** | **0.25** | **0.50** | **0.75** | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| Final Quality | Voids/ Porosity | Debulking | | | | x | | | | | | |
| | | Bagging | | | | x | | | | | | |
| | | Cure | | | | x | | | | | | |
| | | Flat Panels | | | | x | | | | | | |
| | | NDE Defect Detectability | | | | x | x | | | | | |
| | | NDE Defect Detectability Limits | | | | x | x | | | | | |
| | | Ramps | | | | x | | | | | | |
| | | Multiple Thickness Flat Panels | | | | | x | | | | | |
| | | NDE Thickness Standards | | | | | x | | | | | |
| | | Hats | | | | | x | | | | | |
| | | NDE Multiple Material Standards | | | | | x | | | | | |
| | | Size Scale up | | | | x | | x | | | | |
| | | Specification, Draft Items/Areas | | | | x | x | | | | | |
| | | Specification, Preliminary | | | | | | x | | | | |
| | | Specification, Final | | | | | | | x | | | |
| | Delaminations/ Inclusions | Indirect Material Detectability | | | | x | | | | | | |
| | | Indirect Material Detectability Limits | | | | | x | | | | | |
| | | Multiple Material Separation Detectability | | | | | x | | | | | |
| | | Specification, Draft Items/Areas | | | | x | x | | | | | |
| | | Specification, Preliminary | | | | | | x | | | | |
| | | Specification, Final | | | | | | | x | | | |
| | Thickness | Material Capability | | | | x | | | | | | |
| | | Producibility Capability | | | | x | x | | | | | |
| | | Specification, Draft Items/Areas | | | | x | x | | | | | |
| | | Specification, Preliminary | | | | | | x | | | | |
| | | Specification, Final | | | | | | | x | | | |
| | In-Plane Fiber Distortion | | | | | | | x | | | | |
| | | | | | | | | x | | | | |
| | | | | | | | | | | | | |
| | Out of Plane Fiber Distortion | | | | | | | x | | | | |
| | | | | | | | | x | | | | |
| | | | | | | | | | | | | |
| | Other | Effects of Defects | | | | | x | x | x | | | |

**Figure 12-24 Final Part Quality Area/Item Maturity Level Activities**

## 12.4 Knowledge Generation

The approach for producibility knowledge generation is comprised of two steps. First is to generate the producibility knowledge and information at an item level for each item to satisfy qualification and certification requirements. Second is to summarize information from each item as to its impact on either in-process quality or final part quality. This concept is shown in Figure 12-25.

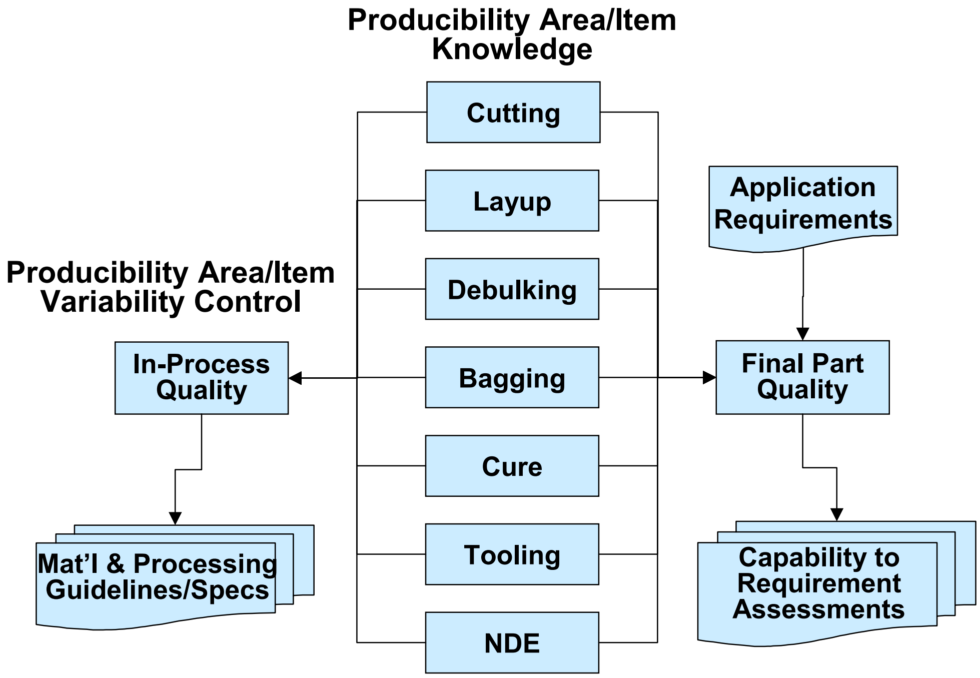



**Figure 12-25 Producibility Item Assessment Process**

The in-process quality information goes into material and processing guidelines/specification for controls and tolerances. Final part quality information is used for comparisons of capabilities to application requirements as a means of assessing whether the application parts can be made with the materials and producibility operations.

Producibility knowledge generation activities are conducted to establish the knowledge base for qualification and certification using a feature based part approach. This feature based producibility approach is a key aspect of producibility methodology. This approach is based on manufacturing a series of increased complexity parts starting with flat, constant thickness panels going up to full scale generic components based on the application (Figure 12-26). Parameters for producibility areas and items are established using flat and ramped panels. These parameters are then either validated or modified when making multiple thickness flat panels, application elements, and generic full scale components. One of the unique aspects of this approach is that mechanical and physical properties can be obtained during producibility development and utilized for the design knowledge base properties and effects of defects very early in qualification and certification activities. Steps 1, 2, and 3 are applicable to any application that would be considered and evaluation results are used to establish producibility parameters. Steps 4 and 5 are generic components that are based on the application being certified. These parts would contain key features of the application for early producibility evaluations and assessments.

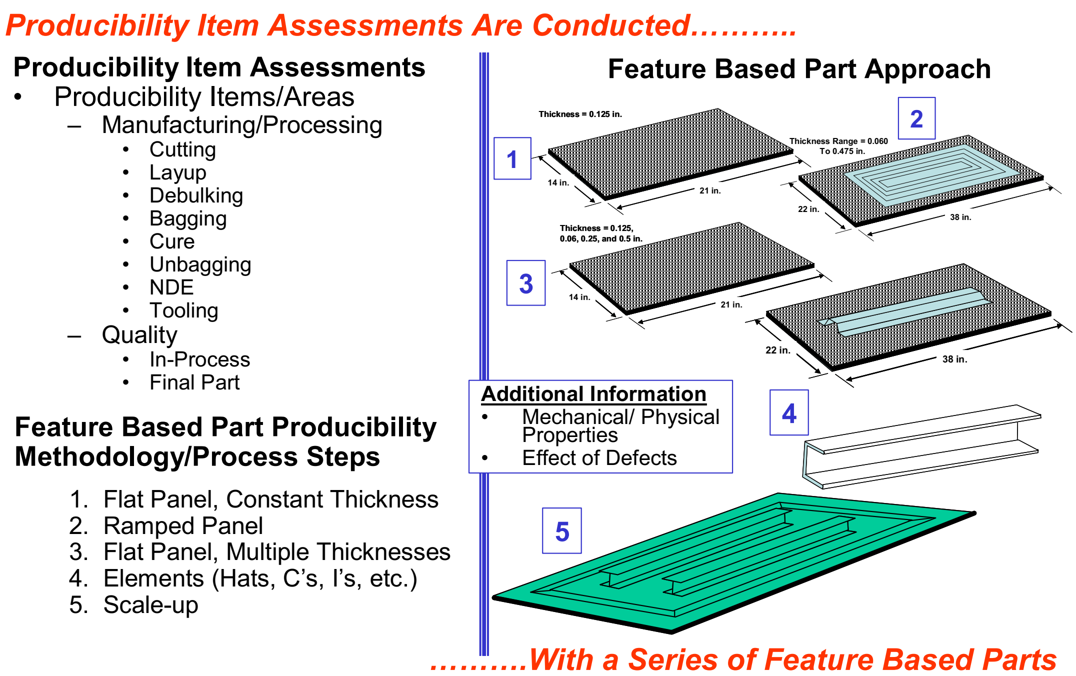



**Figure 12-26 Feature Based Producibility Assessment Parts**

Producibility knowledge is generated through these different parts at the different maturity levels. Figure 12-27 shows the parts and types of information generated for the knowledge base on producibility at TRL of 1.

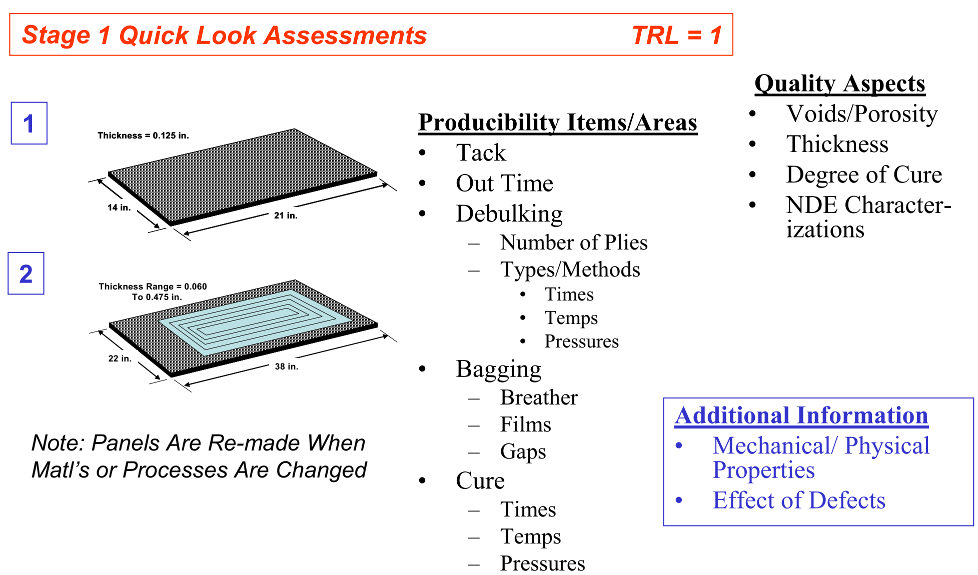



**Figure 12-27 TRL = 1 (Stage 1) Parts and Information**

Figure 12-28 shows the parts and types of information generated for the knowledge base on producibility at TRL of 2.

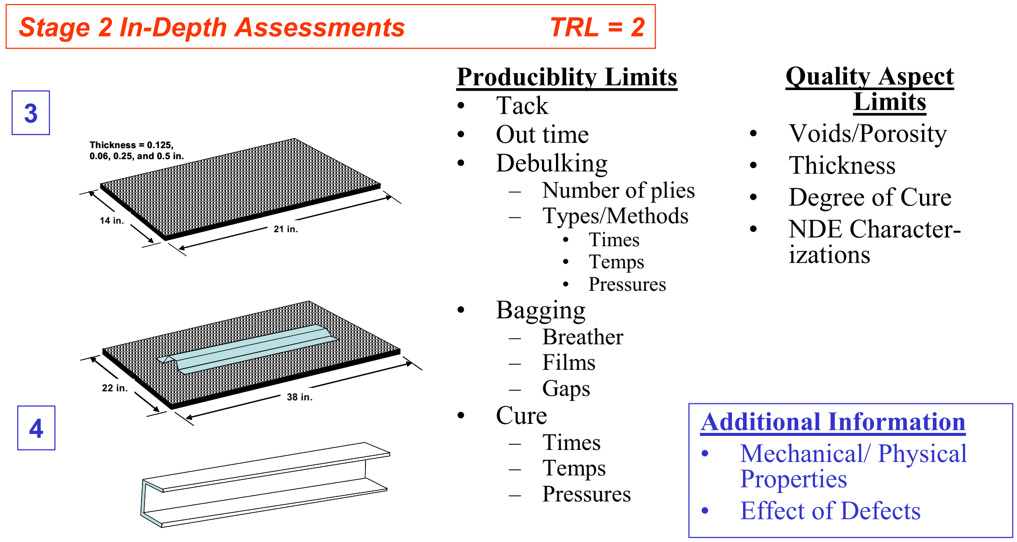



**Figure 12-28 TRL = 2 (Stage 2) Parts and Information**

Figure 12-29 shows the parts and types of information generated for the knowledge base on producibility at TRL of 1.

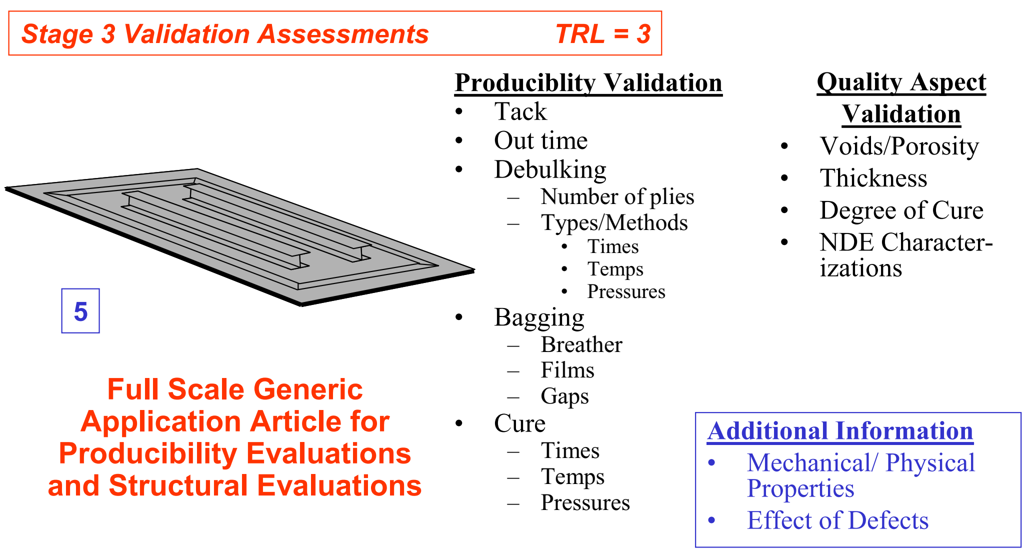



**Figure 12-29 TRL = 3 (Stage 3) Parts and Information**

To better understand and describe this feature based approach, an overall process flow chart was established and is shown in Figure 12-30. The different types of symbols are shown in Figure 12-31

A few items to note in this Figure are as follows:

- A certain amount of material information is required to establish initial producibility parameters
- Similar material producibility can be utilized for initial parameters
- Lessons learned can also be applied to establish initial parameters
- Simulations and modeling can be used for initial parameters and for producibility limits investigations
- All panel and producibility results (good and bad) are usable and documented for the knowledge base
- Effects of defects are continuously evaluated during all activities.
- A full scale component is made very early for quick look assessments and for validation of producibility parameters
- The full scale validation component is tested for design property generation/validation too.
- Most producibility items are assessed by making parts or with shop trials, but some simulation and models are utilized for their special capabilities

*Process Flow For Feature Based Producibility Assessments …………..*

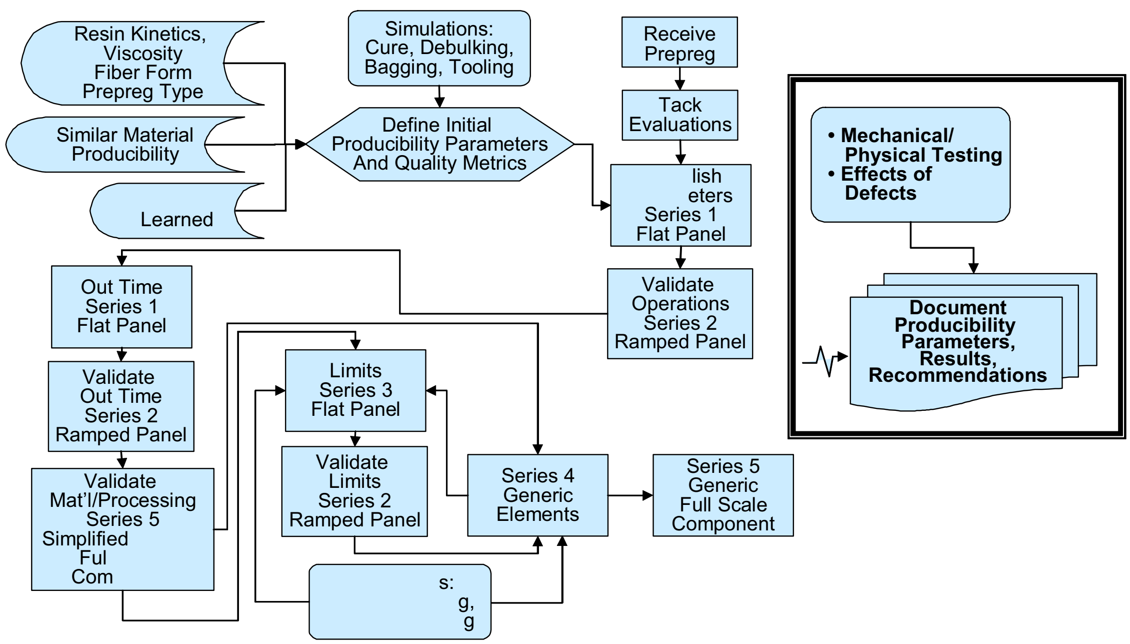



**Figure 12-30 Process Flow for Producibility Assessments**

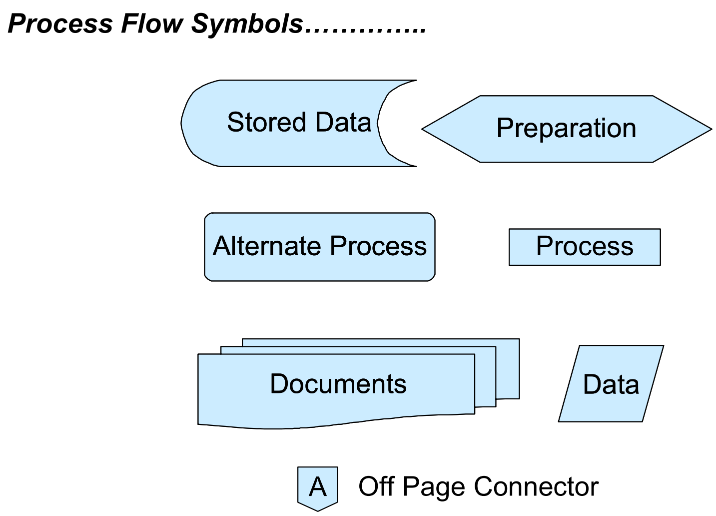



**Figure 12-31 Flow Chart Symbols**

This overall producibility knowledge generation process flow was broken down into more details at TRL of 1 and TRL of 2. Figure 12-32 shows the TRL 1 activity process flow. Figure 12-33 and Figure 12-34 show the TRL 2 activity process flows.

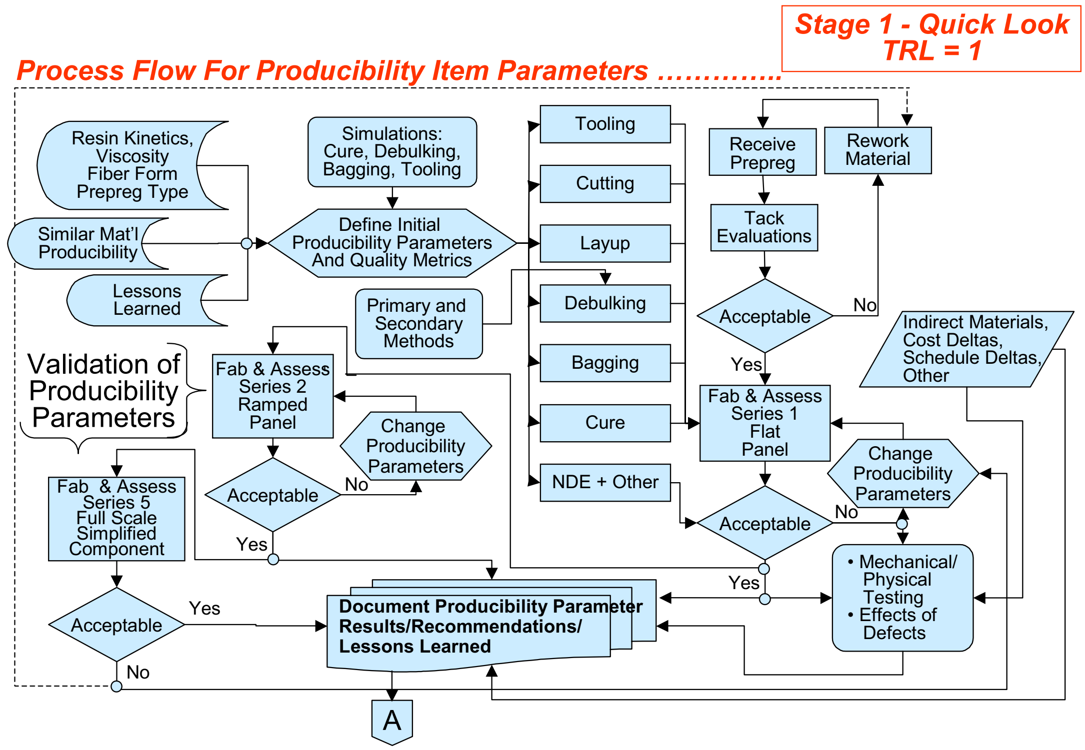



**Figure 12-32 Producibility Process Flow for TRL = 1 Activities**

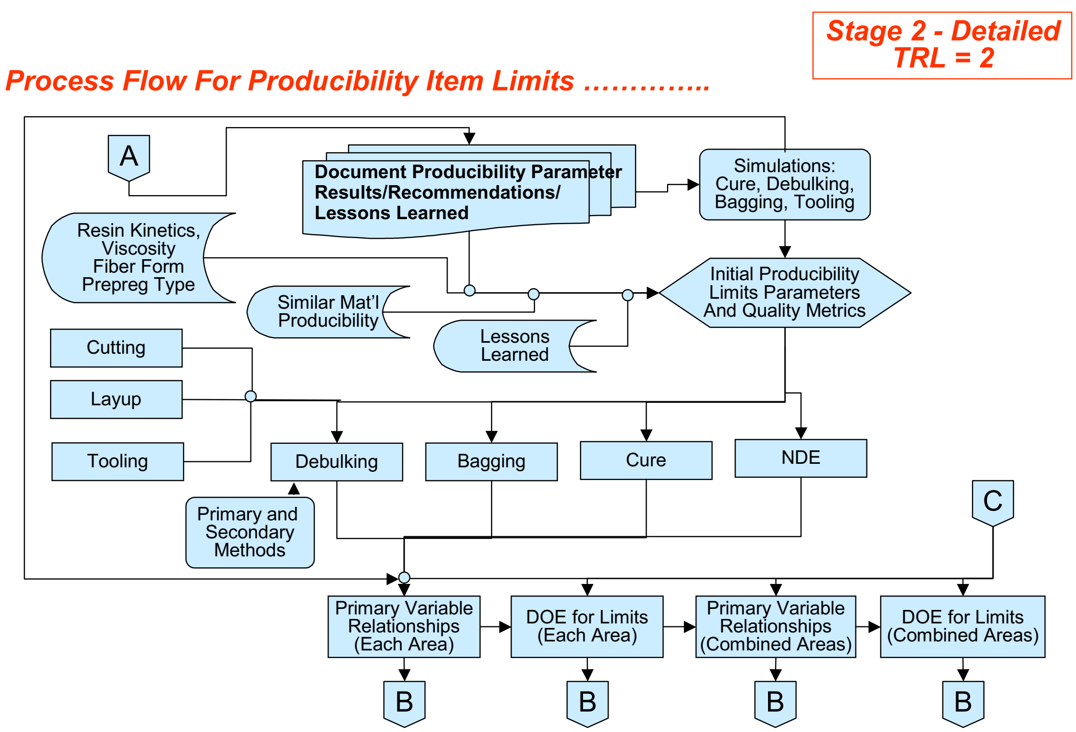



**Figure 12-33 Producibility Process Flow for TRL = 2 Activities**

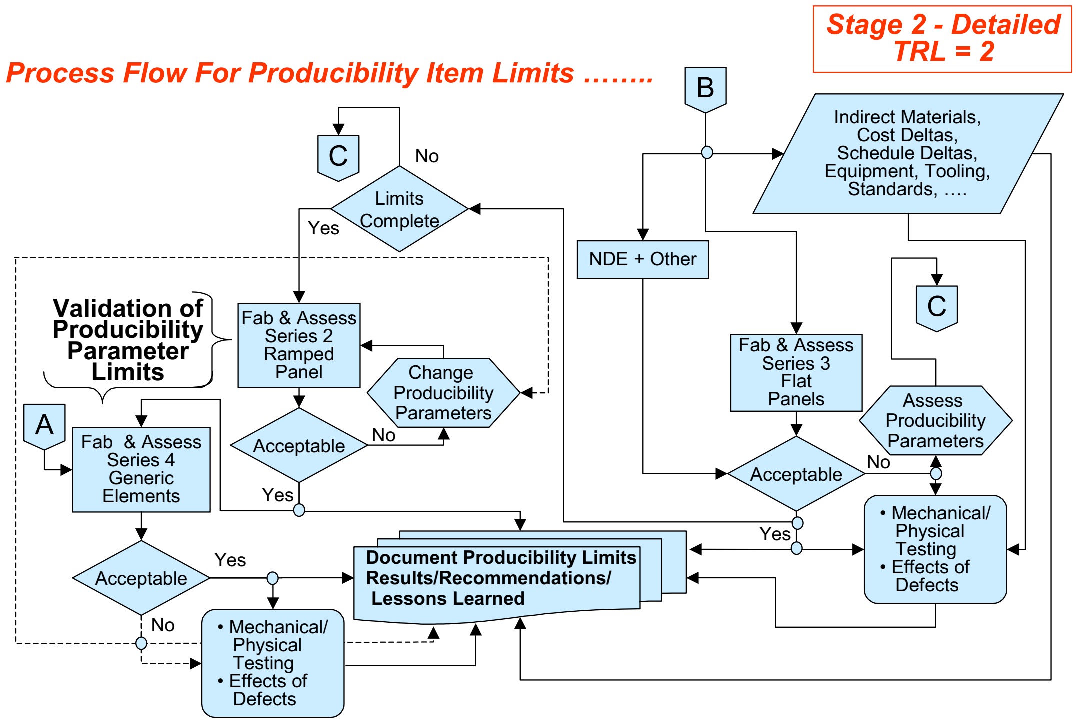



**Figure 12-34 Producibility Process Flow for TRL = 2 Activities, Continued**

## 12.5 Part Producibility Assessment

Producibility part assessments are conducted when answering questions about manufacturing application components Figure 12-30. It can be considered as a way of using producibility knowledge base information from producibility item activities, final part quality and other knowledge to answer manufacturing questions in an IPT environment. The size of this is huge relative to application diversity and the needed amount of information is huge.

- **Part Producibility Assessments** Are Conducted When Answering Questions About Manufacturing Specific Components/Articles Using the Knowledge Base

**Figure 12-35 Part Producibility Activities**

As a step in developing the part producibility assessment methodology, an evaluation was conducted to address producibility information needed at the time of part trade studies on a hat stiffened panel. A review of IPT activities was conducted from a producibility standpoint and results are listed as the seven activities in Figure 12-36. The first three items are from part requirements. Items 4 and 5 are a trade off of manufacturing (final part quality from producibility item assessments) and tooling capabilities (from previous knowledge other than what is generated in the AIM-C process) is compared to requirements. Items 6 and 7 are the producibility operations, in-process quality and final part fabrication.

**IPT Activities**

1. **ID Defects To Be Minimized**
2. **ID Surface(s) That Need to be Maintained**
3. **ID Acceptable Tolerances**
4. **Define Assembly/ Manufacturing Method**
5. **Define Tooling Approach**
6. **Define Producibility/ Quality Steps**
7. **Make Parts**

**Figure 12-36 Integrated Product Team (IPT) Producibility Activities During Trade Studies**

By using the feature based part producibility assessment approach, the hat stiffened demonstration (HSD) panel could be broken down into specific features or characteristics as shown in Figure 12-37.

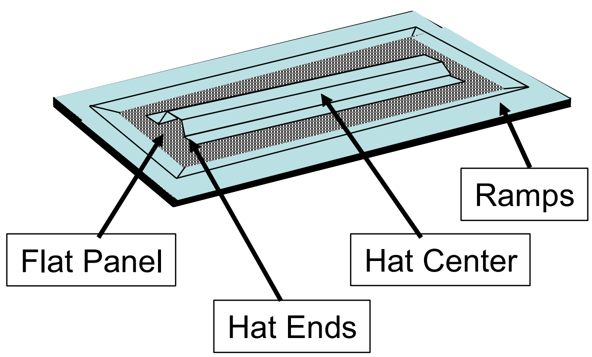



**Figure 12-37 Feature Based Part Producibility Concept**

When IPT needs were investigated further, what the team really wanted was an identification of part defects and variability relative to tooling options, manufacturing operations and material. The metric that they wanted was dimensions for the different types of variability. Using this information requirement, a six step process was established to utilize the feature based approach for usable producibility information for the IPT during trade studies. These process steps are shown in Figure 12-33. It appears that this is a generic process and can be utilized for any part.

1. Define Configuration
2. Identify Features/ Characteristics
3. Identify Defects Associated With Features/ Characteristics
4. Identify Tooling Options
5. Associate Defects to Tooling, Producibility and Material Areas
6. Quantify Defects Relative to Tooling, Producibility and Material Areas

**Figure 12-38 Generic Feature Based Part Producibility Assessment Process**

Combining the IPT activities, parts features and feature based assessments gives the overall picture of part assessments in an IPT environment for trade study information. This is shown in Figure 12-34.

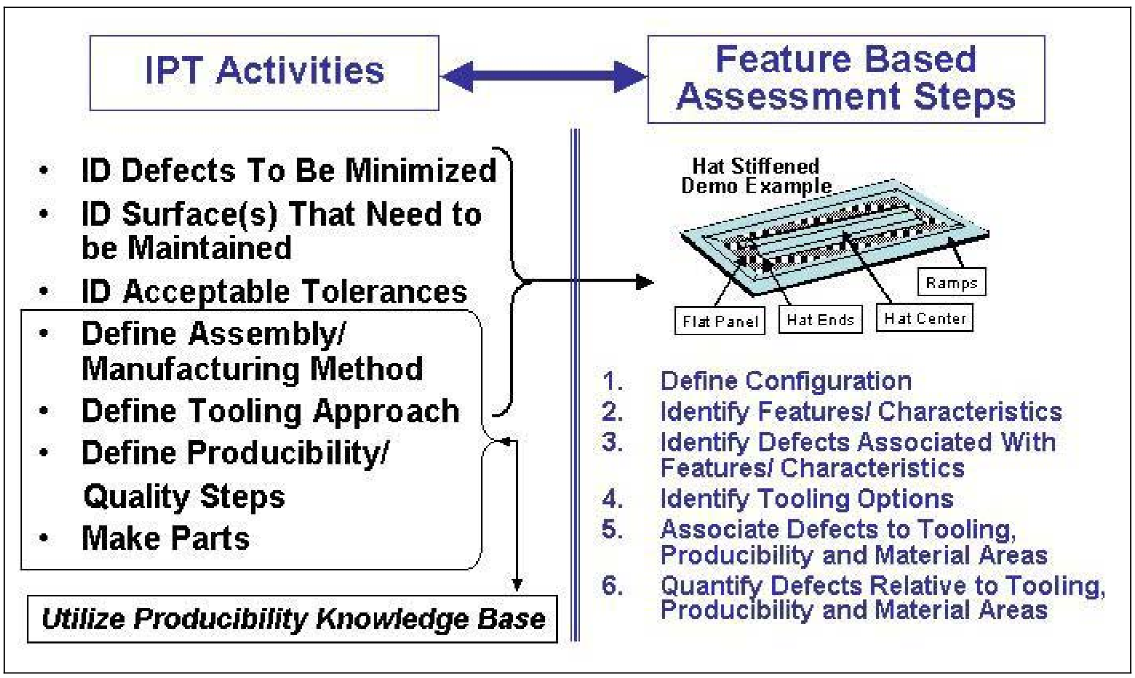



**Figure 12-39 IPT Trade Study With Part Producibility Assessment Process**

The information or knowledge for assessment steps 2, 3, and 4 comes from previous knowledge or history. Information or knowledge for assessment steps 5 and 6 comes from producibility item assessment results and from previous knowledge or history. One information and history void area is dimensional quantification of defects relative to tooling, producibility and materials. Consequently, results from this part assessment process are very subjective and varies from person to person and company to company according to previous experience and opinion.

### *12.5.1 Part Producibility Assessment example introduction*

The part assessment test case was a hat stiffened panel. This part is shown in Figure 12-40 with the different features identified.

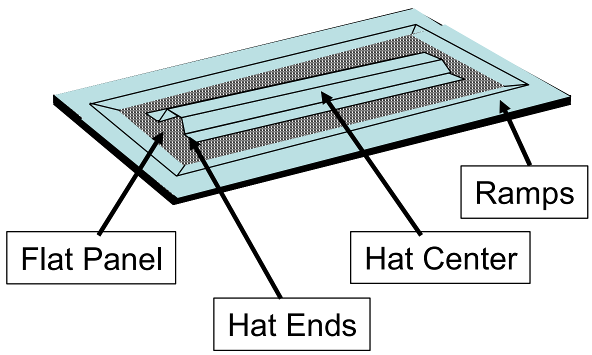



**Figure 12-40 Hat Stiffened Part for Part Assessment Activities**

The primary part features were flat panels, ramped sections and a hat section with center and end areas. Results from part producibility assessments using the process are described according to the part breakdown into features. The results for these part features are presented in a series of figures that correspond to the assessment steps show in Figure 12-41. Each part feature is evaluated by the process steps. This identifies issues in the overall part by understanding issues at the individual feature level of the part.

1. **Define Configuration**
2. **Identify Features/ Characteristics**
3. **Identify Defects Associated With Features/ Characteristics**
4. **Identify Tooling Options**
5. **Associate Defects to Tooling, Producibility and Material Areas**
6. **Quantify Defects Relative to Tooling, Producibility and Material Areas**

**Figure 12-41 Six Step Process for Feature Based Part Assessments**

This assessment process uses information from producibility knowledge generation along with overall producibility knowledge. The process itself is generic and applicable to a wide range of parts, but there are several things that need to be noted. Different people with different composites experience and history will come up with different answers. There is no single answer that is correct, but the answers arrived at by following the process will be valid for the individuals or groups using the process and utilizing their overall producibility knowledge.

The following sections cover example assessment results for the part features shown in Figure 12-40

### *12.5.2Flat Panel Part Feature Assessment Example*

The first step for assessment is identification and definition of the configuration. This is shown in Figure 12-37.

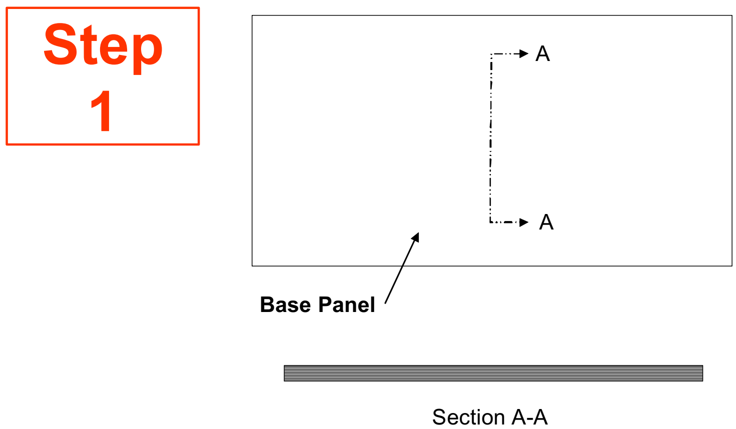



**Figure 12-42 Flat Panel Configuration**

The second step is identification of features or characteristics associated with the configuration. These are shown in Figure 12-38.

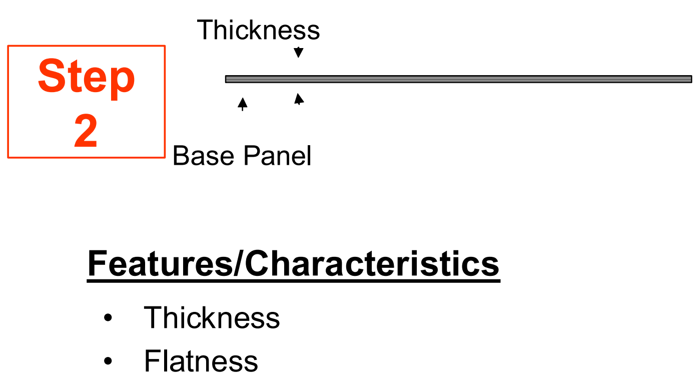
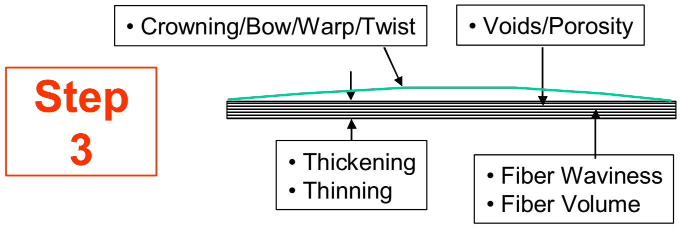



**Figure 12-43 Flat Panel Features, Step 2**

The third step is identification of defects associated with the configuration or characteristics. These are shown in Figure 12-39.




**Defects**

- Voids/Porosity
- Thickness
- Flatness
- In-plane Fiber Waviness
- Out of Plane Fiber Waviness
- Resin Content (Fiber Volume)

**Figure 12-44 Flat Panel Defects, Step 3**

The fourth step is identification of possible tooling options to make the part configuration. These are shown in Figure 12-40.

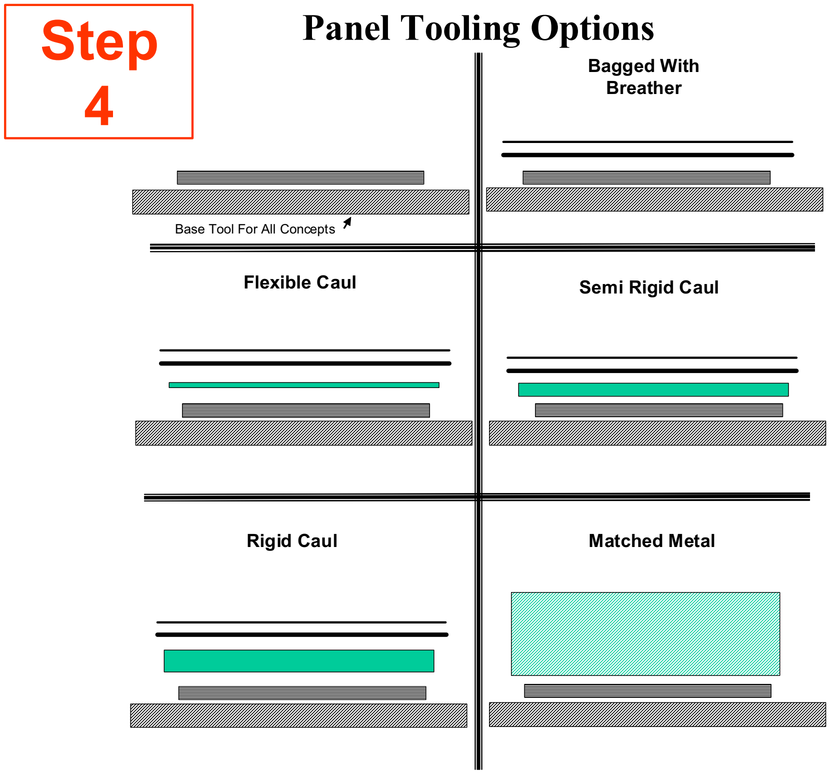



**Figure 12-45 Flat Panel Tooling Options, Step 4**

The fifth step is association of defects to tooling options, producibility areas and items and material. The matrix of these associations is shown in Figure 12-41.

| Step 5 — Panel Defects | Tooling | Cauls | | | | Producibility | | | | | | | Mat'l |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | None (Bag) | Flexible | Semi Rigid | Rigid | Matched Metal | Cutting | Layup | Debulking | Bagging | Cure | Unbagging | Trimming | Prepreg |
| Center Out to Edges | | | | | | | | | | | | | |
| Thinning | x | x | x | | | | | x | x | | | | x |
| Thickening | x | x | x | | | | | x | | | | | x |
| Voids/Porosity | | | | | | | | x | x | x | | | x |
| Fiber Waviness (Out of plane) | x | x | x | x | x | | x | x | x | x | | | x |
| Fiber Waviness (In-plane) | x | x | x | x | x | | x | x | x | x | | | x |
| Surface Finish/Roughness | x | x | x | | | | | x | x | | | | |
| Crowning/Warp/Bow/Twist (Flatness) | | | | | | | | | | | | | |
| Edges | | | | | | | | | | | | | |
| SAME AS ABOVE | | | | | | | | | | | | | |
| Net - (Thinning - Fiber Variation) | x | x | x | x | x | x | x | x | x | x | | | |

**Figure 12-46 Flat Panel Defect Mapping to Tooling, Producibility, Material Matrix, Step 5**

The sixth step is quantification of the defect associations identified in step five. Figure 12-42 show these quantifications.

| Step 6 — Panel Defects | Tooling | | | | | Producibility | | | | | | | Mat'l |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Cauls | | | | | | | | | | | |
| | None (Bag) | Flexible | Semi Rigid | Rigid | Matched Metal | Cutting | Layup | Debulking | Bagging | Cure | Unbagging | Trimming | Prepreg |
| Center Out to Edges | | | | | | | | | | | | | |
| Thinning | <0.015 | <0.015 | <0.01 | <0.003 | <0.003 | | | x | x | | | | x |
| Thickening | <0.015 | <0.015 | <0.01 | <0.003 | <0.003 | | | x | | | | | x |
| Voids/Porosity | <1% | <1% | <1% | <1% | <1% | | | x | x | x | | | x |
| Fiber Waviness (Out of plane) | <.015 | <.015 | <.005 | <.005 | <.005 | | x | <.015 | <.015 | x | | | x |
| Fiber Waviness (In-plane) | <.015 | <.015 | <.005 | <.005 | <.005 | | x | x | x | x | | | x |
| Surface Finish/Roughness | ±.003 to .015 | ±.003 to .015 | <±.010 | <±.003 | <±.003 | | | ±.003 to .015 | ±.003 to .015 | | | | |
| Crowning/warp/Bow/Twist (Flatness) | Varies According to Layup and Geometry | | | | | | | | | | | | |
| Edges | | | | | | | | | | | | | |
| SAME AS ABOVE | | | | | | | | | | | | | |
| Net - Thinning | (-20%) | (-20%) | (-10%) | (-2%) | (-2%) | ±.020 | ±.050 | -10% | -10% | x | | | |

**Figure 12-47 Flat Panel Defect Quantification, Step 6**

### *12.5.3 Ramped Panel Part Feature Assessment Example*

The first step for assessment is identification and definition of the configuration. This is shown in Figure 12-43.

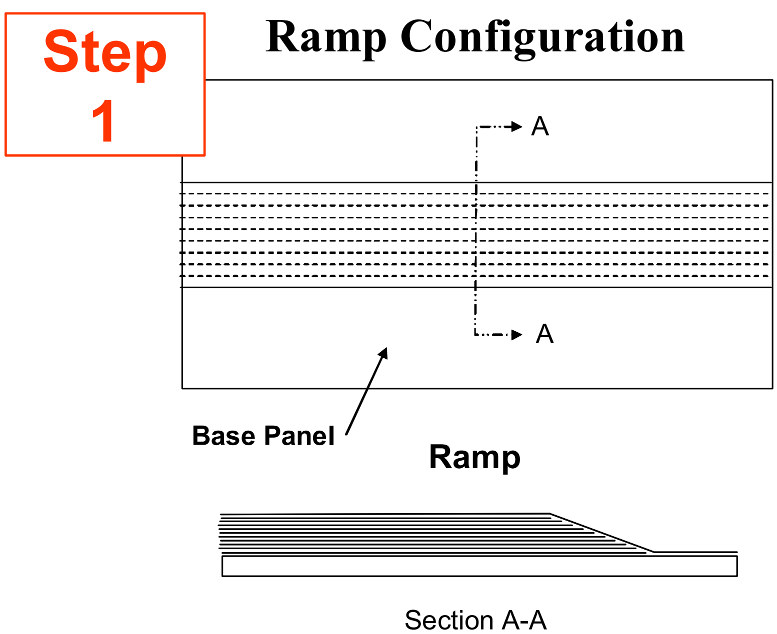



**Figure 12-48 Ramp Configuration, Step 1**

The second step is identification of features or characteristics associated with the configuration. These are shown in Figure 12-44.

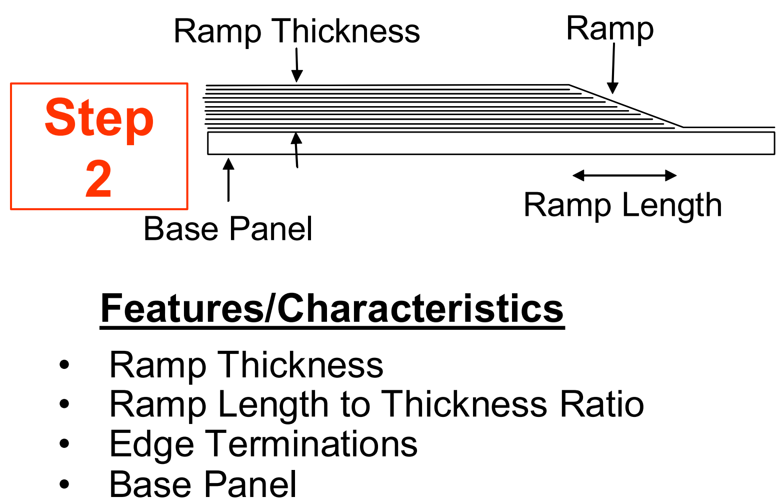



**Figure 12-49 Ramp Features/Characteristics, Step 2**

The third step is identification of defects associated with the configuration or characteristics. These are shown in Figure 12-45.

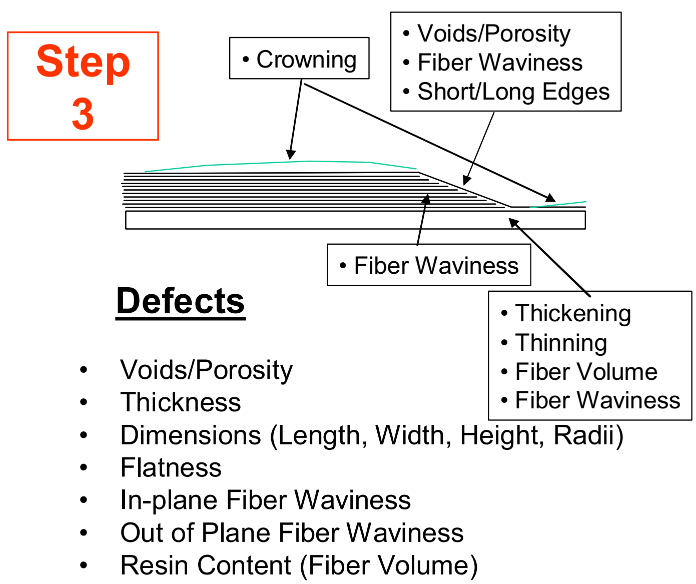



**Figure 12-50 Ramp Defects, Step 3**

The fourth step is identification of possible tooling options to make the part configuration. These are shown in Figure 12-46.

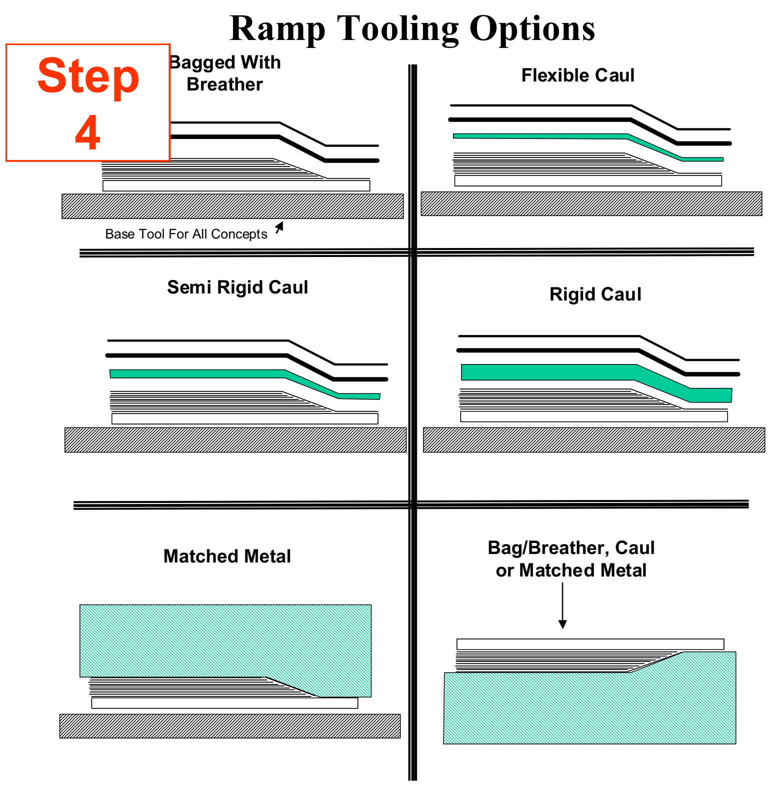



**Figure 12-51 Ramp Tooling Options, Step 4**

The fifth step is association of defects to tooling options, producibility areas and items and material. The matrix of these associations is shown in Figure 12-47.

| Step 5 — Ramp Defects | Tooling: None (Bag) | Cauls: Flexible | Cauls: Semi Rigid | Cauls: Rigid | Matched Metal | Producibility: Cutting | Layup | Debulking | Bagging | Cure | Unbagging | Trimming | Mat'l: Prepreg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ramp Area** | | | | | | | | | | | | | |
| Long Edges | | | x | x | x | x | x | | | | | | |
| Short Edges | | | x | x | x | x | x | | | | | | |
| Fiber Waviness | x | x | | | | | x | x | x | x | | | |
| Voids/Porosity | | | | | | | | x | x | x | | | |
| Surface Finish/Roughness | x | x | | | | | | | x | | | | |
| **Ramp End to Flat Area After Ramp** | | | | | | | | | | | | | |
| Thinning | x | x | x | | | | | x | x | x | | | |
| Thickening | x | x | x | x | x | | | x | x | x | | | |
| Fiber Waviness | x | x | x | | | | x | x | x | x | | | |
| **Flat Area Before/After Ramp** | | | | | | | | | | | | | |
| Crowning | x | x | x | | | | | x | x | | | | |
| Surface Finish/Roughness | x | x | | | | | | x | x | | | | |
| Thinning/Thickening | x | x | x | x | x | | | | | | | | x |

**Figure 12-52 Ramp Defect Mapping to Tooling, Producibility, Material Matrix, Step 5**

The sixth step is quantification of the defect associations identified in step five. Figure 12-48 show these quantifications.

**Step 6**

| Ramp Defects | Tooling | Cauls | | | | Producibility | | | | | | | Mat'l |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | None (Bag) | Flexible | Semi Rigid | Rigid | Matched Metal | Cutting | Layup | Debulking | Bagging | Cure | Unbagging | Trimming | Prepreg |
| Ramp Area | | | | | | | | | | | | | |
| Long Edges | | | x | x | x | ±.02 | ±.05 | | | | | | |
| Short Edges | | | x | x | x | ±.02 | ±.05 | | | | | | |
| Fiber Waviness | <±.015 | <±.015 | <±.015 | <±.015 | <±.015 | | ±.015 | ±.015 | ±.015 | x | | | |
| Voids/Porosity | <1% | <1% | <1% | <1% | <1% | | | 1%-2% | 1%-2% | x | | | |
| Surface Finish/Roughness | ±.003 to ±.015 | ±.003 to ±.015 | <±.005 | <±.002 | <±.002 | | | ±.003 to ±.015 | ±.003 to ±.015 | | | | |
| Ramp End to Flat Area After Ramp | | | | | | | | | | | | | |
| Thinning | <.005 | <.01 | <.005 | | | | | x | x | x | | | |
| Thickening | <.005 | <.01 | <.01 | <.01 | <.01 | | | x | x | x | | | |
| Fiber Waviness | <.015 | <.015 | <.005 | <.005 | <.005 | | <.005 | <.005 | <.005 | x | | | |
| Flat Area Before/After Ramp | | | | | | | | | | | | | |
| Crowning | <.015 | <.015 | <.01 | <.002 | <.002 | | | <.015 | x | | | | |
| Surface Finish/Roughness | ±.003 to ±.015 | ±.003 to ±.015 | <±.005 | <±.002 | <±.002 | | | ±.003 to ±.015 | ±.003 to ±.015 | | | | |
| Thinning/Thickening | <.015 | <.015 | <.01 | <.01 | <.01 | | | | | | | | x |

**Figure 12-53 Ramp Defect Quantification, Step 6**

## *12.5.4 Hat Stiffener Part Feature Assessment Example*

The first step for assessment is identification and definition of the configuration. This is shown in Figure 12-49.

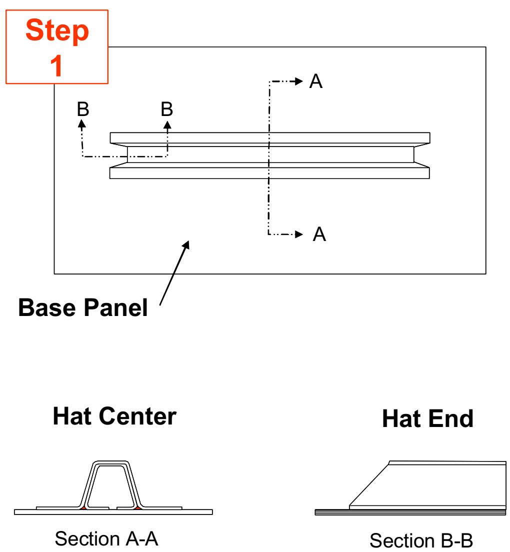
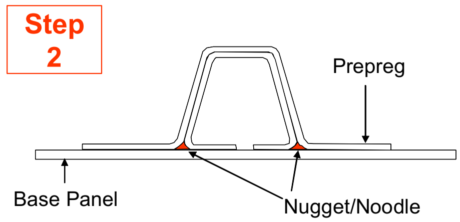



**Figure 12-54 Hat Configuration, Step 1**

The second step is identification of features or characteristics associated with the configuration. These are shown in Figure 12-50.




**Features/Characteristics**

- Inside Corners/Radii
- Outside Corners/Radii
- Nugget/Noodle
- Multiple Materials
- Flat Surfaces
- Edge Terminations
- Base Panel

**Figure 12-55 Hat Features, Step2**

The third step is identification of defects associated with the configuration or characteristics. These are shown in Figure 12-51 and 12-52.

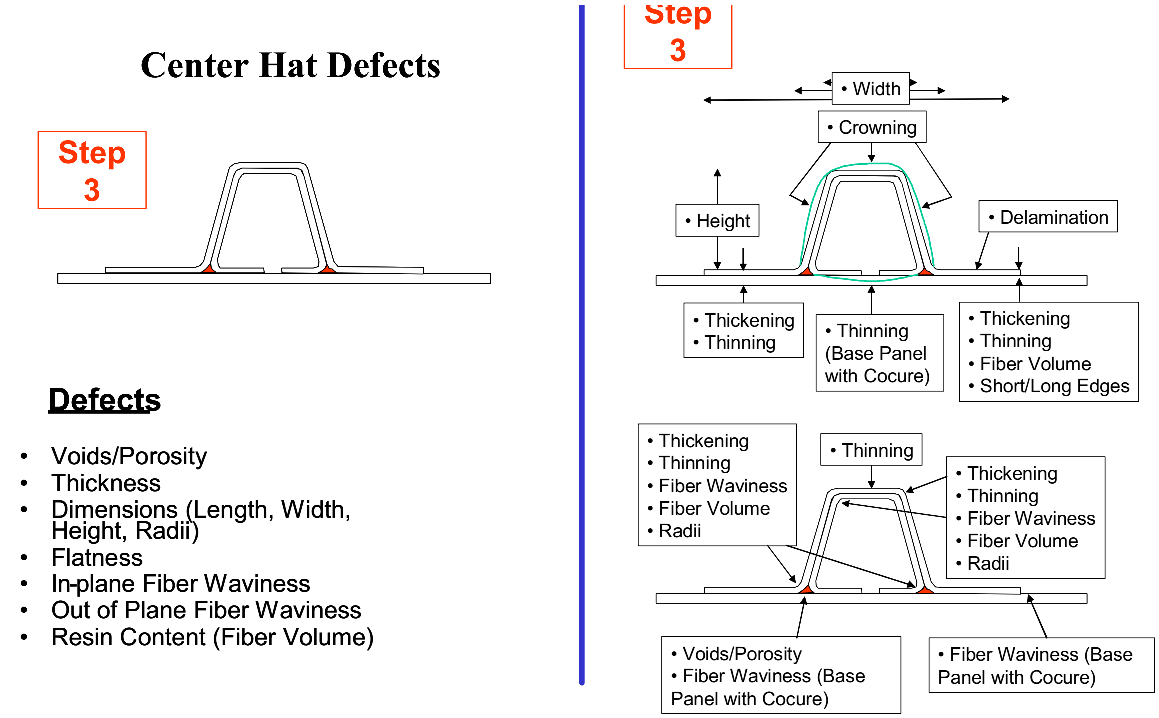



**Figure 12-56 Hat Defects, Step 3**

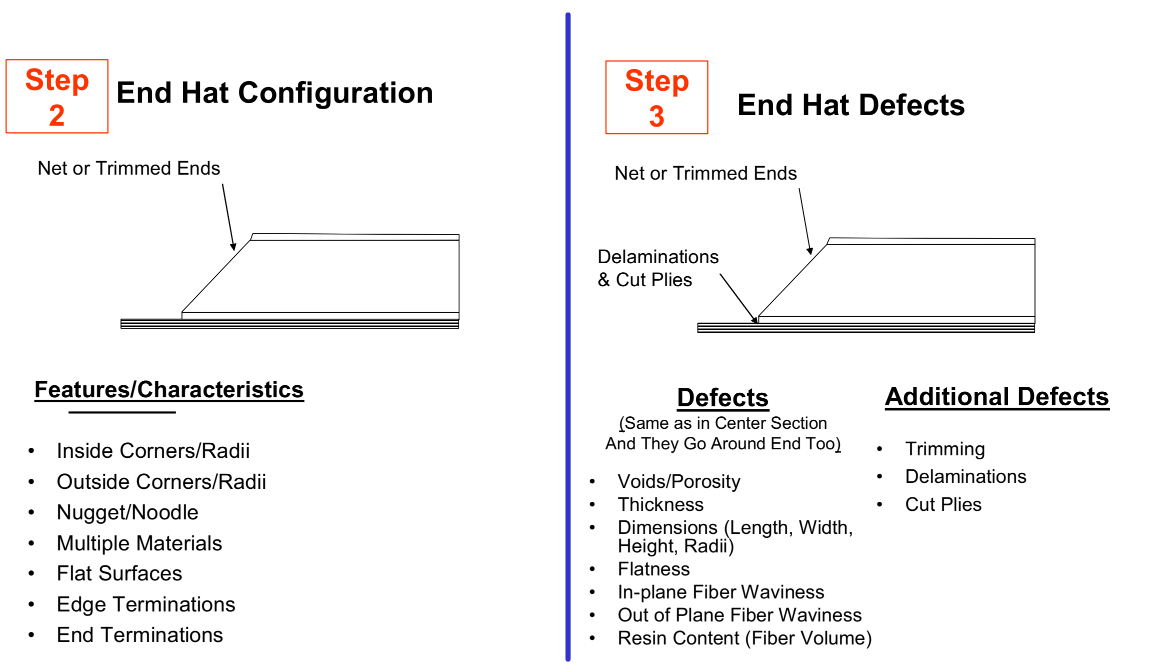



**Figure 12-57 End Hat Features and Defects, Steps 2 and 3**

The fourth step is identification of possible tooling options to make the part configuration. These are shown in Figure 12-53.

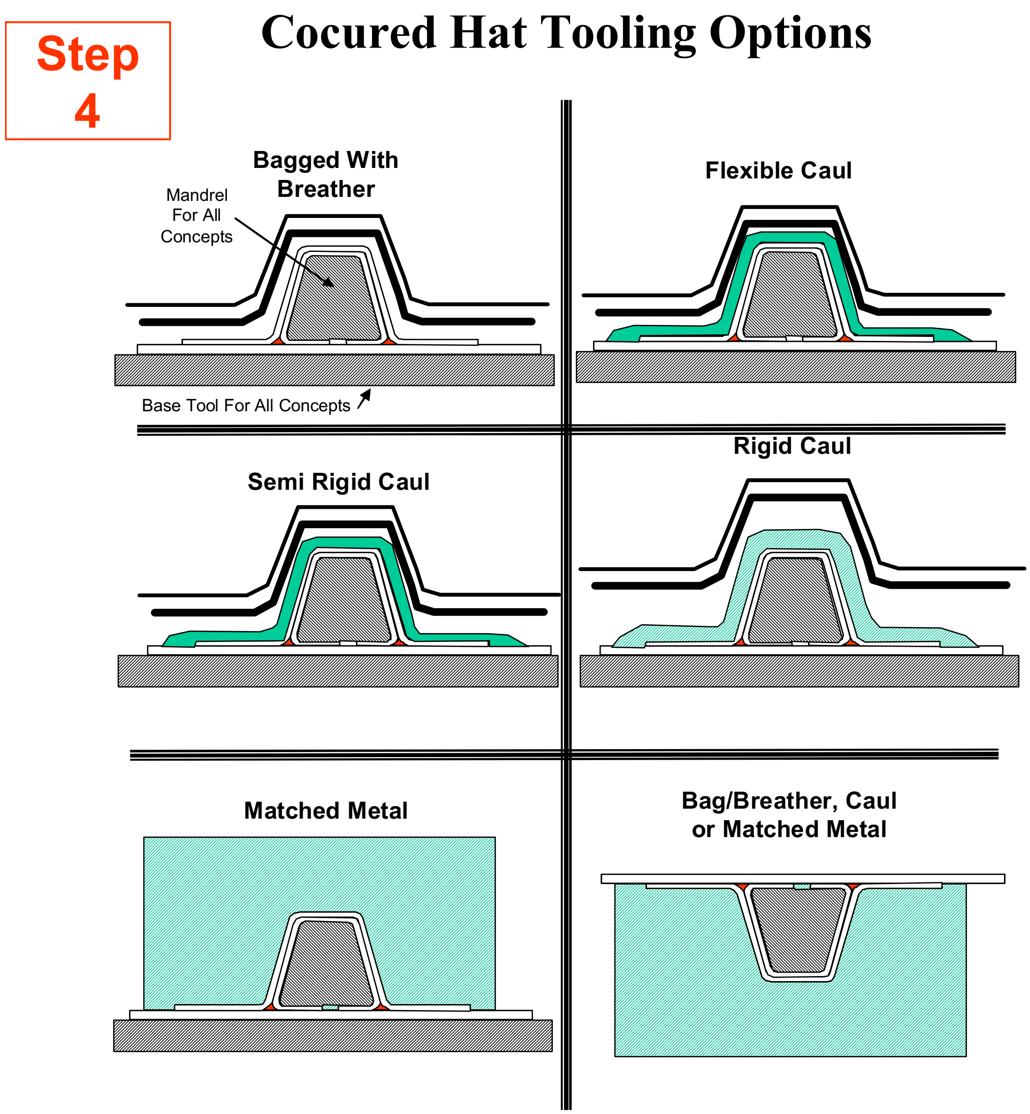



**Figure 12-58 Hat Tooling Options, Step 4**

The fifth step is association of defects to tooling options, producibility areas and items and material. The matrix of these associations is shown in Figure 12-54.

| Step 5 — Hat Defects | Tooling | Tooling | Tooling | Tooling | Tooling | Tooling | Tooling | Producibility | Producibility | Producibility | Producibility | Producibility | Producibility | Producibility | Mat'l |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Cauls | Cauls | Cauls | | | | | | | | | | |
| | Mandrel | None (Bag) | Flexible | Semi Rigid | Rigid | Matched Metal | End Shims | Cutting | Layup | Debulking | Bagging | Cure | Unbagging | Trimming | Prepreg |
| Center | | | | | | | | | | | | | | | |
| Top Crown | x | x | x | x | | | | | | | x | x | | | |
| Side Crown | x | x | x | x | | | | | | | x | x | | | |
| Top Thinning | x | x | x | x | x | x | | | | | x | x | | | |
| Bottom Thinning | x | | | x | x | x | | | | | | x | | | |
| Upper Radii Thickening | x | | | x | x | x | | | x | x | x | x | | | |
| Upper Radii Thinning | | x | x | | | | | | x | x | x | x | | | |
| Upper Radii Fiber Waviness | x | x | x | | | | | | | x | x | | | | |
| Lower Radii Thickening | x | x | x | x | x | x | | | x | x | x | x | | | |
| Lower Radii Thinning | | x | x | x | x | x | | | x | x | x | x | | | |
| Flange Thickening | | | | x | x | x | | x | x | | | | | | x |
| Flange Thinning | | | | | | | | x | x | | | | | | x |
| Flange Edge Fiber Volume | | | x | x | | | | x | x | x | | | | | |
| Flange Edge Fiber Waviness | | x | x | | | | | | | x | x | x | | | |
| Nugget/Noodle Porosity/Voids | | | | | | | | | x | x | | x | | | |
| Nugget/Noodle Fiber Waviness | x | x | x | x | x | x | | | x | x | x | x | | | |
| Surface Finish/Roughness | | x | x | | | | | | | | x | | | | |
| Ends | | | | | | | | | | | | | | | |
| SAME AS ABOVE | | | | | | | | | | | | | | | |
| Net - Fiber Variation | | x | x | | | | | x | x | x | x | x | | | |
| Excess - Cut Fibers | | | | | | | | | | | | | | x | |
| Delamination | x | | | | | | x | | | | | | x | | |
| Along Length | | | | | | | | | | | | | | | |
| Spacing | | x | x | x | | | | | | | | | | | |
| Straightness | | x | x | | | | | | | | | | | | |

**Figure 12-59 Hat Defect Mapping to Tooling, Producibility, Material Matrix, Step 5**

The sixth step is quantification of the defect associations identified in step five. Figure 12-55 shows these quantifications. The text that follows the figure provides an example of how one might use the information provided.

Step 6

| Hat Defects | Tooling | | | | | | | Producibility | | | | | | | Mat'l |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Cauls | | | | | | | | | | | | |
| | Mandrel | None (Bag) | Flexible | Semi Rigid | Rigid | Matched Metal | End Shims | Cutting | Layup | Debulking | Bagging | Cure | Unbagging | Trimming | Prepreg |
| **Center** | | | | | | | | | | | | | | | |
| Top Crown | x | < .060 | < .060 | < .015 | <.005 | <.005 | | | | | x | x | | | |
| Side Crown | x | < .060 | < .060 | < .015 | <.005 | <.005 | | | | | x | x | | | |
| Top Thinning | x | <.015 | <.015 | <.015 | <.015 | <.015 | | | | | x | x | | | |
| Bottom Thinning | x | <.01 | <.01 | <.015 | <.015 | <.015 | | | | | | x | | | |
| Upper Radii Thickening | | | | < .010 (15%) | < .010 (15%) | < .010 (15%) | | | x | x | x | x | | | |
| Upper Radii Thinning | <.01 | < .010 | < .010 | | | | | | x | <.006 | <.01 | x | | | |
| Upper Radii Fiber Waviness | | <.015 | <.01 | | | | | | | <.006 | <.006 | | | | |
| Lower Radii Thickening | <.01 | < .010 (15%) | < .010 (15%) | < .010 (15%) | < .010 (15%) | < .010 (15%) | | | x | <.006 | <.006 | x | | | |
| Lower Radii Thinning | <.01 | < .010 (15%) | < .010 (15%) | < .010 (15%) | < .010 (15%) | < .010 (15%) | | | x | x | x | x | | | |
| Flange Thickening | | | | | <.01 | <.01 | | x | x | | | | | | x |
| Flange Thinning | | <.01 | <.01 | <.005 | | | | x | x | | | | | | x |
| Flange Edge Fiber Volume | | | +5%, -60% | +5%, -60% | | | | ± .02 | ± .05 | x | | | | | |
| Flange Edge Fiber Waviness | | <.03 | <.03 | <.015 | | | | | | x | x | x | | | |
| Nugget/Noodle Porosity/Voids | | < 3%, < .5 in2 | < 3%, .5 in2 | < 3%, < .5 in2 | < 3%, < .5 in2 | < 3%, < .5 in2 | | | x | x | | x | | | |
| Nugget/Noodle Fiber Waviness | <.015 | <.015 | <.015 | <.015 | <.015 | <.015 | | | | x | x | x | | | |
| Surface Finish/Roughness | <.01 | ±.003 to ±.015 | ±.003 to ±.015 | <.01 | <.002 | <.002 | | | | ±.003 to ±.015 | ±.003 to ±.015 | | | | |
| **Ends** | | | | | | | | | | | | | | | |
| SAME AS ABOVE | | | | | | | | | | | | | | | |
| Net - Fiber Variation | | +5%, -60% | +5%, -60% | | | | | ± .02 | ± .05 | x | x | x | | | |
| Excess - Trimming Defects | | | | | | | | | | | | | | <.03 | |
| Delamination | x | | | | | | <.125 in2 | | | | | | <.5 in2 | | |
| **Along Length** | | | | | | | | | | | | | | | |
| Spacing | | <.125 | <.125 | <.06 | <.06 | <.03 | | | | | | | | | |
| Straightness | | <.125 | <.125 | <.09 | <.09 | <.09 | | | | | | | | | |

**Figure 12-60 Hat Defect Quantification, Step 6**

The quantified defects for a hat cured using semi-rigid and flexible caul plates are shown in Figure 12-55. There are significantly more defect areas involving this hat due to its greater tooling and processing complexity. Reading down the highlighted columns, the configuration data show an improvement in crowning for the semi-rigid caul plate of 0.015 inch versus 0.060 inch for the flexible caul plate, as the stiffer semi-rigid caul plate reacts better with the thermal expansion of the hat mandrel. A large potential fiber volume decrease, -60%, is seen for both caul plate types. This defect is due to an over-pressure condition during autoclave cure when there is a mismatch between the trim of the hat plies and the caul plate. A large delamination, 0.125 $in^{2,}$ is indicated for an end shim. This value seemed much larger in magnitude than the others and its origin was not clear. Further discussions revealed that the cause of the delamination was the end shim. The qualification of this defect required additional attention and is described in a later paragraph. A 0.5 $in^2$ delamination caused by unbagging, while also very large by comparison, is due to the skill of the technician. Some data for the configuration and producibility defects still require investigation. The continuation of this process would highlight the location and magnitude of these defects for structural analysis.

Based on a further evaluation of the end shim delamination condition is was determined that a significant hat termination processing feature defect exists.

A review of this feature revealed that the end shim did not exist in the early lay-up of this part but was added later to correct a skin waviness issue. The primary problem was due to the hat mandrel, which extended over the end flange and caused thickness variation, out-of-plane ply waviness (tool mark-off) in the panel flange beyond the hat net trim. A secondary problem was also revealed. During the mechanical trimming operation to achieve the flush hat termination, potential damage to the flange surface plies could occur.

The solution was to add thin end shim (caul plate) in the flange area between the part surface and the hat mandrel that also separated the oversize hat plies from the skin. This may not have been a concern initially because these plies would be trimmed back to the end of the end shim.

The result was a successful improvement to ply waviness problem and protection of the flange laminate during trimming operation.

The unintended consequence was the introduction of another defect between the end of the shim and the trimmed hat laminate. A discontinuity is created at the intersection of the hat termination and the flange laminate as shown in Figure 12-56.

The end shims can create a significant defect that must be included in the analysis of the hat panel. The discontinuity is large (caul plate thickness by hat foot length) it is located at a critical load introduction site for each hat leg and the hat noodles and the discontinuity can occur at both ends of every hat. This evaluation led to a proposed revision to the Feature Based Part Assessment methodology document as shown in Figure 12-57.

Part quality is highly operator/technician skill dependant and could be addressed through awareness training

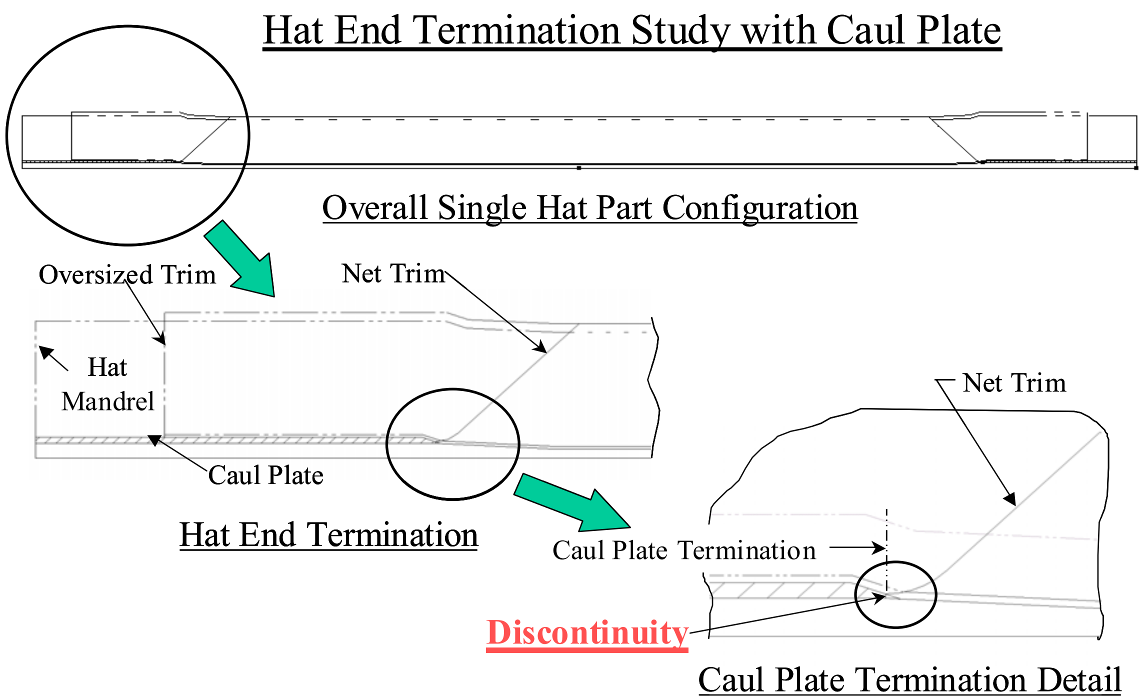



**Figure 12-56. Hat End Termination Study with Caul Plate**

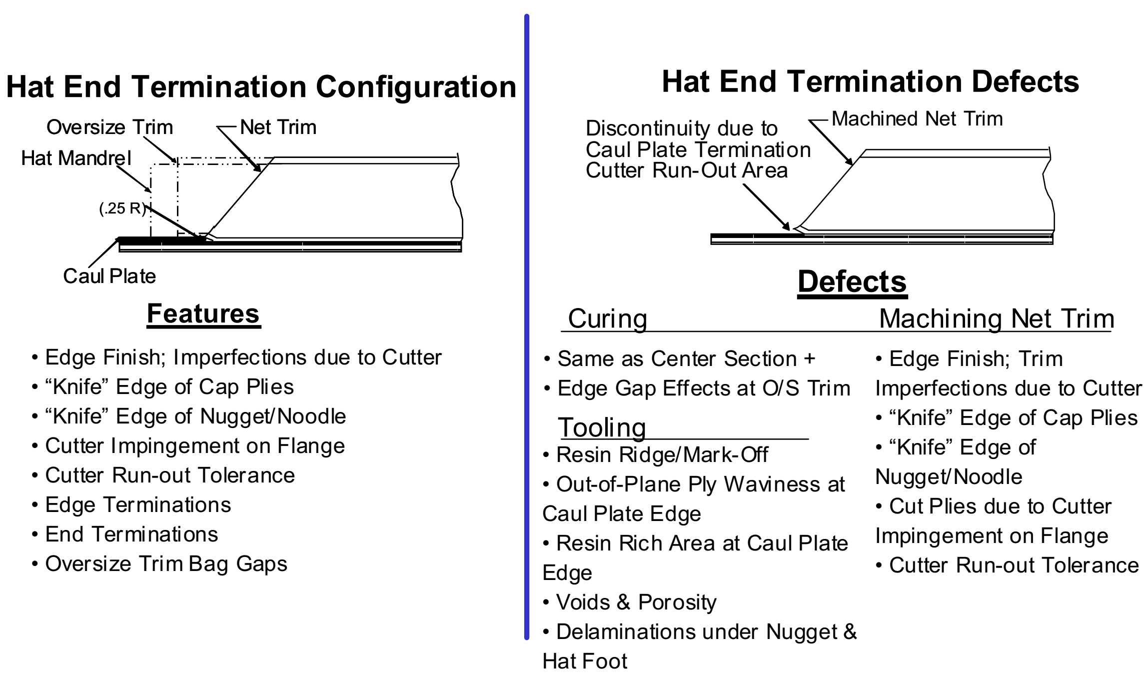



**Figure 12-57. Revised Hat End Termination with Caul Plate**

# 13. AIM-C Structures Methodology

This chapter is comprised of four sections. Section 13.1 outlines the general methodology used for the insertion of a new composite material. When a specific AIM-C tool exists to aid this objective it is identified. Section 13.2 discusses the various AIM-C system tools that support generation of preliminary design values. These tools are restricted to those that provide laminate level strength data. Section 13.3 discusses the actual generation of firm design allowables - design allowables being different from preliminary design values. Section 13.4 discusses the Structural Design Process.

## 13.1 General Methodology to Obtain Preliminary Structural Design Values Using the AIM-C Tool

One may have either a new program in which design values for a new or unused resin/ fiber system is being contemplated or a specific problem which need to be solved in which a new fiber/resin system holds some promise. The steps that follow outline a process or a methodology that may be used in order to obtain preliminary design values using the AIM-C system. When a specific task can be accomplished by the AIM-C system, the AIM-C tool is identified. Once the preliminary design values are obtained it is up to the judgment of the structural engineer in consultation with other design, manufacturing, and processing professionals to use these values directly or to apply a factor(s) to them.

1. **Objective:** Obtain preliminary lamina properties (modulus, etc) so that finite element models of the structure can be built for preliminary analysis. Lamina properties are also needed to predict laminate allowables. Traditionally, lamina properties are obtained from test. However, AIM-C Tools are available to generate these properties given resin and fiber properties.
   TASKS
   1. Enter known data into AIM-C System.
   2. Get material info from Materials (fiber & resin) module.
   3. Check airframe requirements (temperature range, environment, etc).
   4. Run Lamina module to get predicted lamina properties.
   5. Pass lamina properties to IPT's and other AIM-C modules.
   6. Identify additional resin, fiber and prepreg data needed to increase confidence level in predictions for next cycle of allowables predictions (Item 5)

2. **Objective:** Generate preliminary laminate allowables (UNT, UNC, FHT, FHC, OHC, BRG, CSAI) based on nominal parameters. These preliminary allowables will be used to size the structure. Need to include the effects of environment and design features (open vs filled, countersink, hole size, edge distance, etc). Again, this data would all come structural testing. However, AIM-C tools are available to generate some of these properties. Specifically unnotched and open hole tension and compression data (UNT, UNC, OHC, OHT) may be generated for a range of

laminates using the AIMC tool. Some test data is required. At a minimum lamina testing at 10 and 90 degree fiber orientations are required in order to obtain data for the Strain Invariant Failure Theory (SIFT) Method (Template 10). In addition, the point stress method used to generate strength data using Template 21 requires lamina strength data obtained from testing at 0 degree and 90 degree fiber orientations and requires testing of an open hole laminate. The laminate lay up may be common lay up desired for the application but it is best to not use one strongly dominated by +/- 45 degree plies.

TASKS
1. Enter known data into AIM-C System.
2. Get needed info from lamina module.
3. Run Laminate Module or Templates 21 or 10 to get predicted laminate carpet plot data.

**3.** Preliminary size the part using data generated in previous steps. An AIM-C tool exists for a specific class of structural problem that is the sizing of a hat stiffened panel (Templates 14, 16, and 17).

**4.** Determine impact of selected materials (components variability, etc.), processes (cure cycle window, etc.), and producibility features (i.e. tooling, part configuration, etc.) on design allowables. Design allowables may need to be refined based on proposed processing, tooling, effects of defects, etc.

**5.** Pilot batch of material available

First batch of material fabricated using proposed nominal production parameters but on a pilot line.

**6.** Lamina and laminate tests, including environment, of pilot batch. Number of tests are variable. The objective of these tests is to determine batch variability. This data will be used for extensive structural configuration and sizing exercises by structural designers and engineers.

**7.** EMD Go ahead

Official start of the Engineering Manufacturing Develop phase. Integrated product teams launch into intense design phase.

**8.** Update preliminary allowables with pilot batch data

Update previously estimated allowables based on pilot batch data. These allowables will now be available for Concept Layout (CLO). Again, this data will be used for extensive structural configuration and sizing exercises by structural designers and engineers.

**9.** Production qualification material batches.
The number of batches and testing must be coordinated with Certifying Agency.

**10.** CLO – Concept Layout
The IPT produces the concept.

**11.** ALO – Assembly Layout
The IPT produces the initial assembly documentation.

**12.** BTP – Build To Packages and normal redesign/refinement effort based on coordination with manufacturing

**13.** Predict in-plane laminate allowables (UNT, UNC, FHT, FHC, OHC, BRG, CSAI). Include environmental impacts.

This task is completed at the beginning of the ALO phase to minimize the amount of redesign because of allowables changes downstream. Need to refine the design allowables based on proposed processing, tooling, effects of defects, etc.

TASKS:
1. Run structures module to update design allowables based on MP2 input.
2. Run durability module to determine impact of fatigue (based on preliminary spectrum)
3. Run materials module to determine impact of fluid resistance, etc.
4. Release updated allowables to IPT's

**14.** Allowables validation tests (coupon tests)

Validate predicted design allowables from the AIM-C system. Need to do these tests with the production qualification material.

TASKS:
1. Select critical tests to perform first based on risks (cost, schedule, technical) identified by what we know.
2. Tests coupons should be fabricated by the shop that will fabricate the production parts. Use the selected production processes to build in the predicted MP2 parts.
3. Choose proper test methods, test labs, etc.

**15.** Effects of defects (coupon/element tests)

Based on identified expected defects, determine via tests impact on design allowables. Performed earlier enough in program that design changes can be made to increase robustness and minimize cost.

**16.** Element Tests, including fatigue

Test critical joints and splices, including fatigue tests. Include defects as required.

**17.** Allowables modifications, as dictated by tests

Continuously evaluate predicted allowables vs. test data. Update the allowables when differences are identified between prediction and test. Complete this phase before BTP phase is complete.

## 13.2 Determination of Laminate Strength and Stiffness Properties using AIM-C Tools

The calculation of laminate strength and stiffness properties can be accomplished using AIM-C templates 21 and 10.

**Template 21 General non-SIFT analysis of laminated Coupons**
Usage Scenario: analysis of laminated coupons, using either a classic point stress or ISAAC analyses, to accurately predict laminate failure including variability.

The template has the ability to predict unnotched or open hole tension or compression strengths. The user is given the option of entering constituent or lamina level properties. The template interfaces with RDCS allowing variability studies and uncertainty analysis. This template provides the capability to compare different methods, failure criteria, laminate types, etc. The generality of the template allows quick "what-if" studies for proposed materials.

**Template 10: Generation of Data for Carpet Plots using the Strain Invariant Failure Theory (SIFT) Method**

This template uses the SIFT technique to determine final failure stresses and strains for a fixed set of laminates of sufficient quantity to generate carpet plots. The routine does not generate the plot, only the data that to be used by the user to generate the plot. In addition the user may input their own set of layups or simply input a single layup. The default layups are shown below as well as results for open hole tension and compression for an IM7/977-3 coupon test simulation. The coupon size for this simulation was 12.0 inches by 1.50 inches with a 0.25 inch diameter hole located at the coupon centerline.

The data in Figure 13-1 can be plotted into traditional looking carpet plots as shown in Figures 13-2 and 13-3.

| | | | | Strength [ksi] | |
|---|---|---|---|---|---|
| Layup ID | % 0 Deg Plies | % +/- 45 Deg Plies | % 90 Deg Plies | OHC | OHT |
| 1 | 20 | 80 | 0 | -38,623 | 65,319 |
| 2 | 20 | 60 | 20 | -50,625 | 71,918 |
| 3 | 20 | 40 | 40 | -51,277 | 71,040 |
| 4 | 20 | 20 | 60 | -47,543 | 62,915 |
| 5 | 20 | 0 | 80 | -38,652 | 49,548 |
| 6 | 40 | 60 | 0 | -62,145 | 100,269 |
| 7 | 40 | 40 | 20 | -77,553 | 102,031 |
| 8 | 40 | 20 | 40 | -75,761 | 94,191 |
| 9 | 40 | 0 | 60 | -67,005 | 87,272 |
| 10 | 60 | 40 | 0 | -83,100 | 125,136 |
| 11 | 60 | 20 | 20 | -95,964 | 131,863 |
| 12 | 60 | 0 | 40 | -86,543 | 118,670 |
| 13 | 80 | 20 | 0 | -102,432 | 141,819 |
| 14 | 80 | 0 | 20 | -104,645 | 146,353 |

**Figure 13-1 Open Hole Coupon Simulation Laminate Designations and Results**

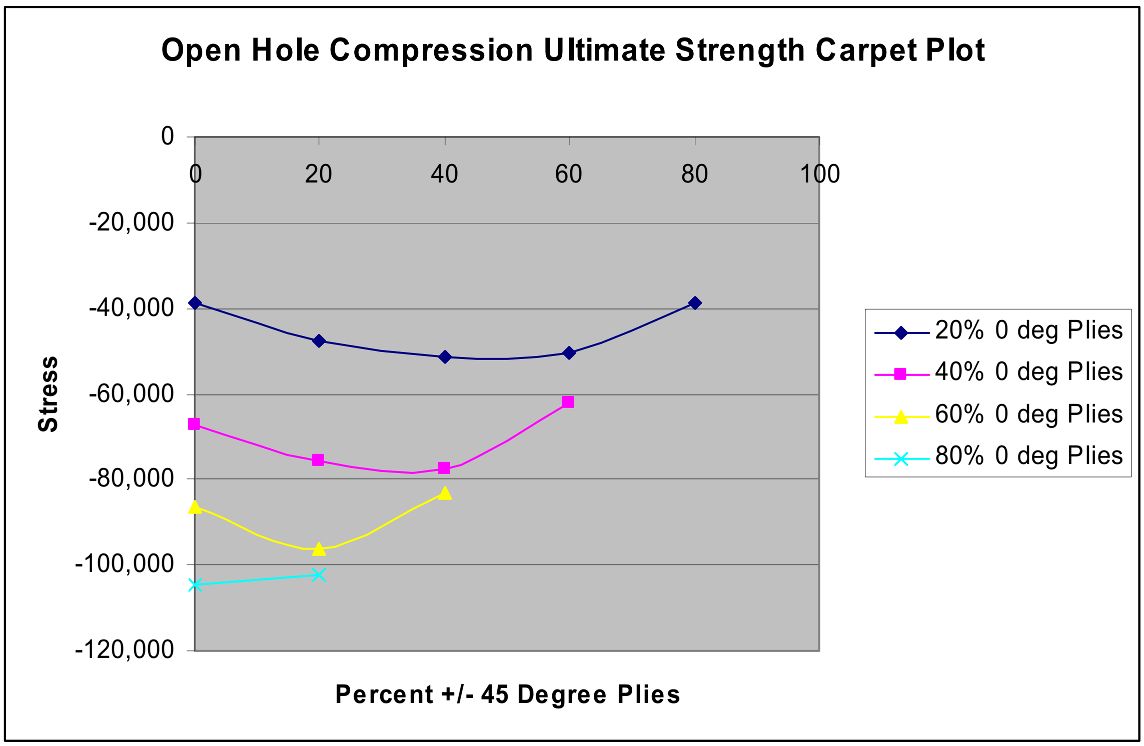



**Figure 13-2 Open Hole Compression Strength Carpet Plot**

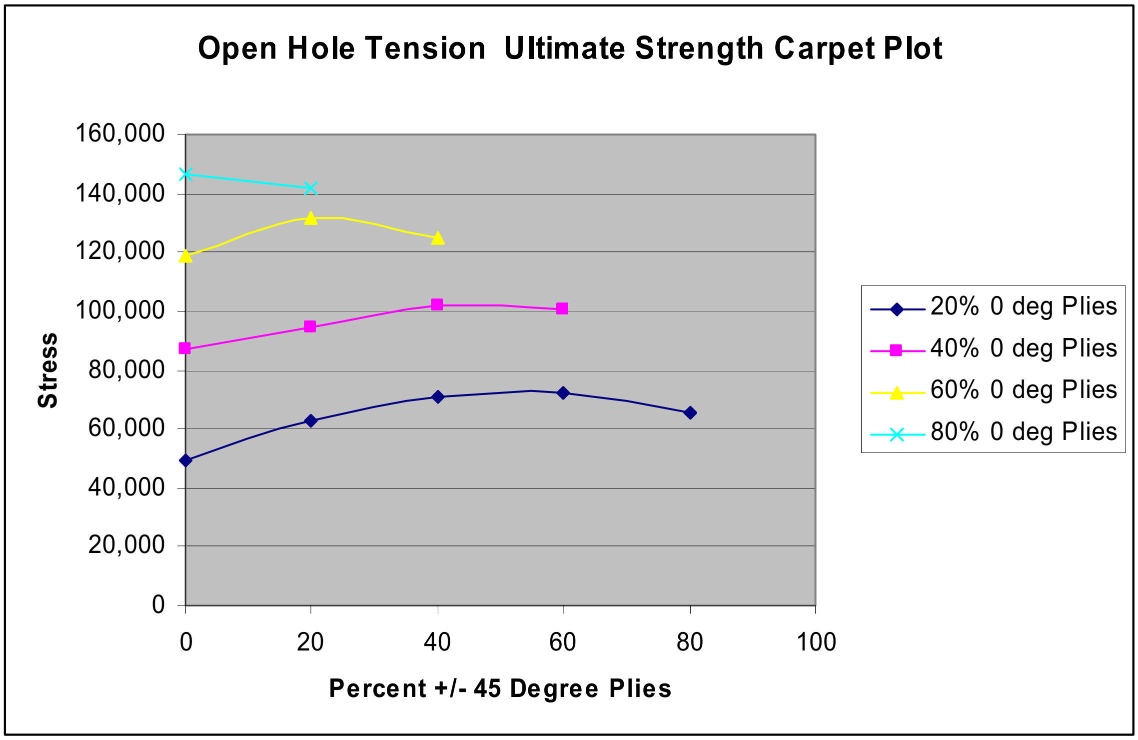



**Figure 13-3 Open Hole Tension Strength Carpet Plot**

## 13.3 Generation of Firm Design Allowables

This section contains the test methods for determining the structural mechanical properties of laminates and the methodology to develop allowables. The following laminate tests are outlined.

- Laminate Unnotched Tension
- Laminate Unnotched Compression
- Laminate Open/Filled Hole Tension Test
- Laminate Open/Filled Hole Compression Test
- Laminate Interlaminar Shear Test
- Laminate Pin Bearing Test
- Laminate Compression Strength After Impact (CSAI) Test
- Laminate Flexure Test
- Laminate Interlaminar Tension Test
- Bearing Bypass/Interaction Test

For open hole and filled hole tension and open and filled hole compression testing, gross section width is defined as the width of the specimen including the hole (i.e. the specimen width without the hole diameter subtracted).

**Structural (Laminate) Unnotched Tension Test**

The objective of this test method is to determine the unnotched tensile strength and modulus of different lay-ups of tape and cloth laminates.  A flat rectangular specimen may be used or one with a very gentle radius which provides a minimal stress concentration between the gripped region and the test region. It is recommended to use at least one 0° axial strain gage on one side of the specimen. Both sides may be instrumented to determine if the specimen is experiencing bending stresses.

**Laminate Unnotched Compression Test**

The objective of this test method is to determine the unnotched compressive strength and modulus of different lay-ups of crossplied tape and cloth laminates.  Each specimen should have back-to-back 0° axial strain gages.  A lateral stabilization fixture is required to ensure that the specimen does not fail by buckling.

**Laminate Open/Filled Hole Tension Test**

The objective of this test method is to determine the open/filled hole tension strengths and moduli of different lay-ups of crossplied tape and cloth laminates.  The specimen geometry may be identical to that used for unnotched testing provided adequate edge margin exists. Each specimen should have at minimum a single 0° axial strain gage placed on the side without the countersink.

### Laminate Open/Filled Hole Compression Test

The objective of this test method is to determine the open/filled hole compression strengths and moduli of different lay-ups of crossplied tape and cloth laminates. The specimen geometry may be identical to that used for laminate open/filled hole tension testing. Back-to-back 0° axial strain gages are required on all compression specimens. A lateral stabilization fixture is required to ensure that the specimen does not fail by buckling.

### Laminate Interlaminar Shear Test

The objective of this test method is to determine the interlaminar shear strengths of crossplied laminates. A typical configuration is shown in Figure 13-4.

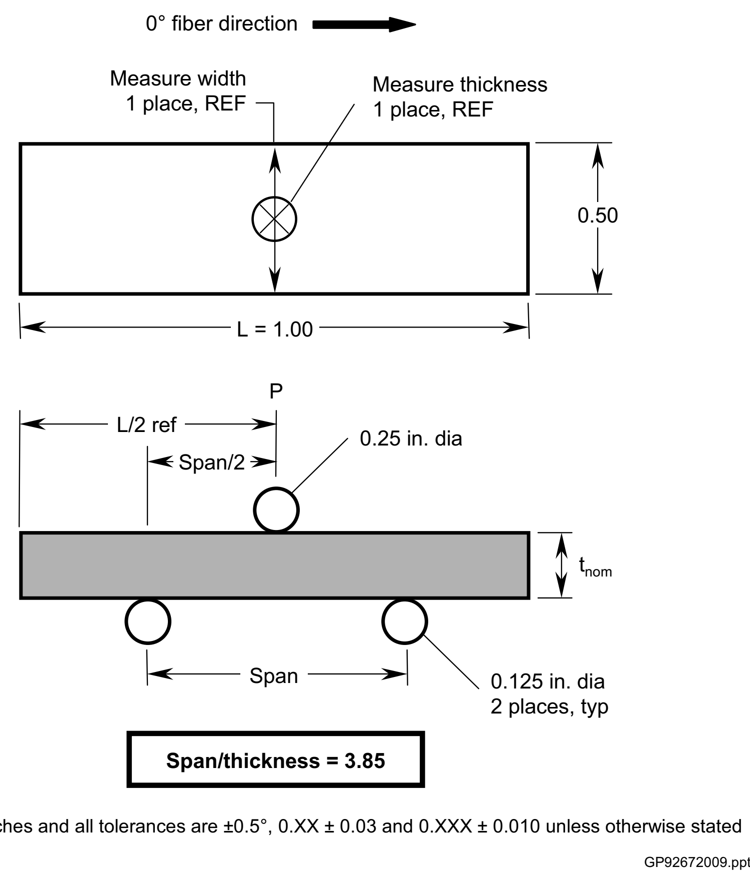
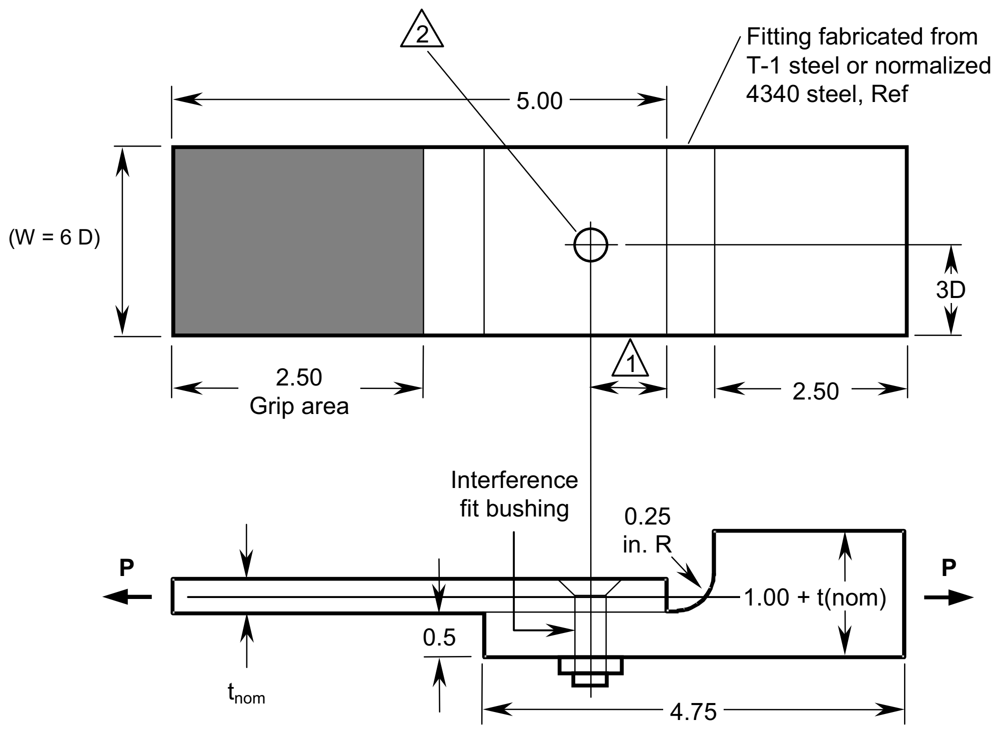



**Figure 13-4 Interlaminar Shear Test Configuration**

### Laminate Pin Bearing Test

The objective of this test method is to determine the static pin bearing strengths of cloth and tape laminates. Typical specimen geometry is shown in Figure 13-5. The reference to TWD, refers to the Test Work Description which could be prepared differently depending on the problem statement and conformance plan. These specimens do not require strain gages. A pin-bearing test fixture is required.




Notes:

1 The edge distance will be per TWD.

2 Hole diameter per TWD.

3 For pin bearing tests, to 10 in-lbs over run on torque.

4 All dimensions are in inches and all tolerances are ±0.5°, 0.XX ± 0.03 and 0.XX ± 0.010 unless otherwise stated

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**Figure 13-0-5 Bearing Test Configuration**

## Compression Strength after Impact (CSAI) Test

The objective of this test method is to determine the compressive residual static strength of composite panels with low velocity impact damage (LVID). Typical specimen geometry is shown in Figure 13-6. Back-to-back strain gages should be used.

Several trial impact specimens from each configuration should be impacted at various impact energy levels to determine the impact energy level required to produce clearly visible damage at a distance of 5 feet. The trial impact specimens will be impacted in 2 locations per specimen. Due to the lack of a standard for impact testing, the exact number of trial impact specimens required cannot be established with any degree of certainty both technically and programmatically.

After each impact, measure the dent depth of the impact and perform a pulse-echo A-scan or through transmission scan around the damaged and document damage size and location. The dent depth shall be recorded to the nearest 0.001 inch. The required impact depth is 0.01 to 0.02 inches.

Impact all the test specimens in its center at the critical impact energy level determined by the trial impacts. The window should be large enough not to clamp on delaminated areas, but small enough to prevent local laminate buckling (note: delaminations should be still able to buckle). The impact procedures outline above in the trial impact section shall be followed. Attach strain gages and employ the necessary strain recording equipment. The lateral support plates shall have a window large enough so that the damage area is not constrained.

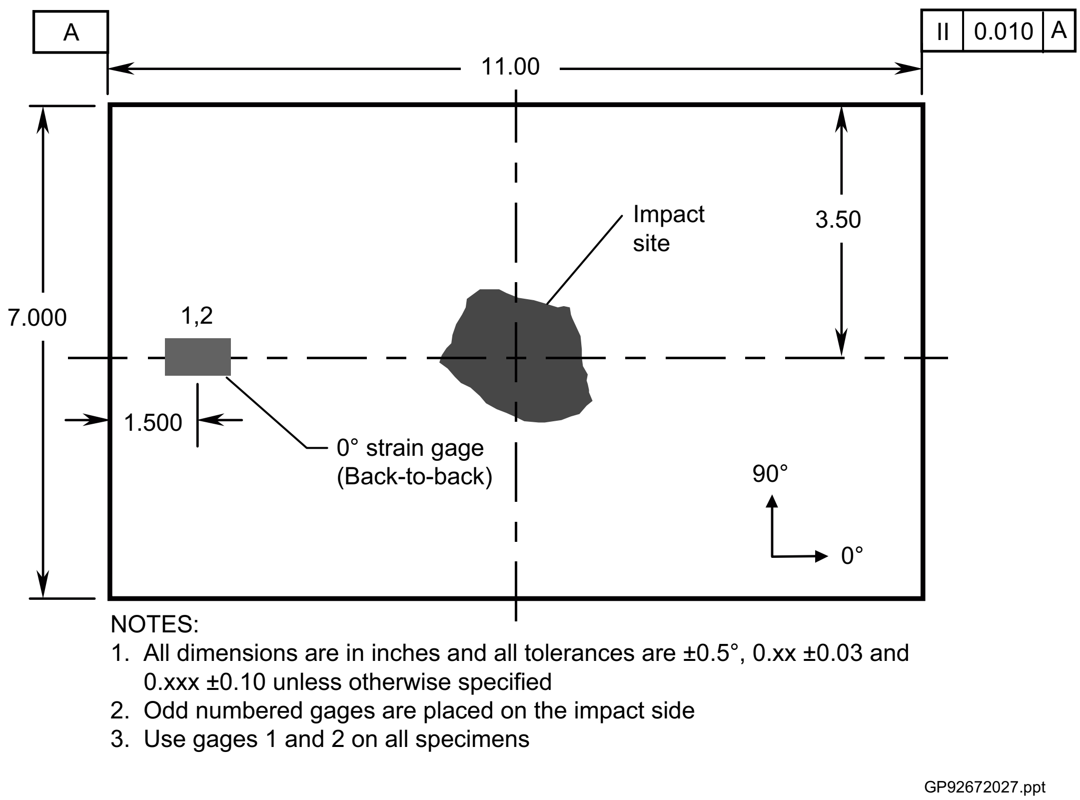


**Figure 13-6 Compression Strength After Impact Test Configuration**

## Laminate Unnotched Flexure Test

The objective of this test method is to determine the flexural strengths of unnotched composite laminates. Typical specimen geometry is shown below. Each specimen requires one set of back-to-back axial strain gages and a displacement transducer. A four-point bending test fixture is required which is illustrated in Figure 13-7.

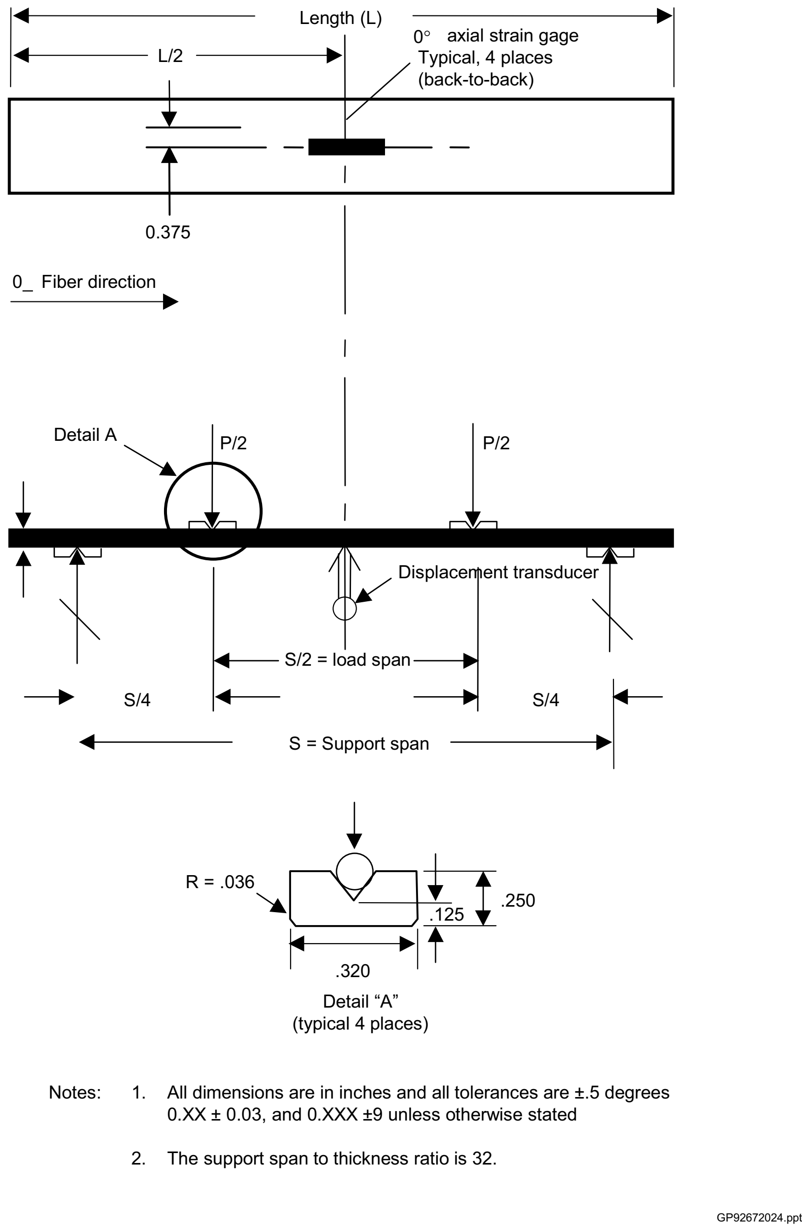


**Figure 13-7 Laminate Flexure Test Specimen**

## Laminate Interlaminar Tension Test

The objective of this test method is to determine the interlaminar tension strength of cross plied laminates. Specimen geometry is shown in Figure 13-8. The specimens do not require any strain gages. (Lfail= momemt arm at failure. Mfail=P(L-Δ).)

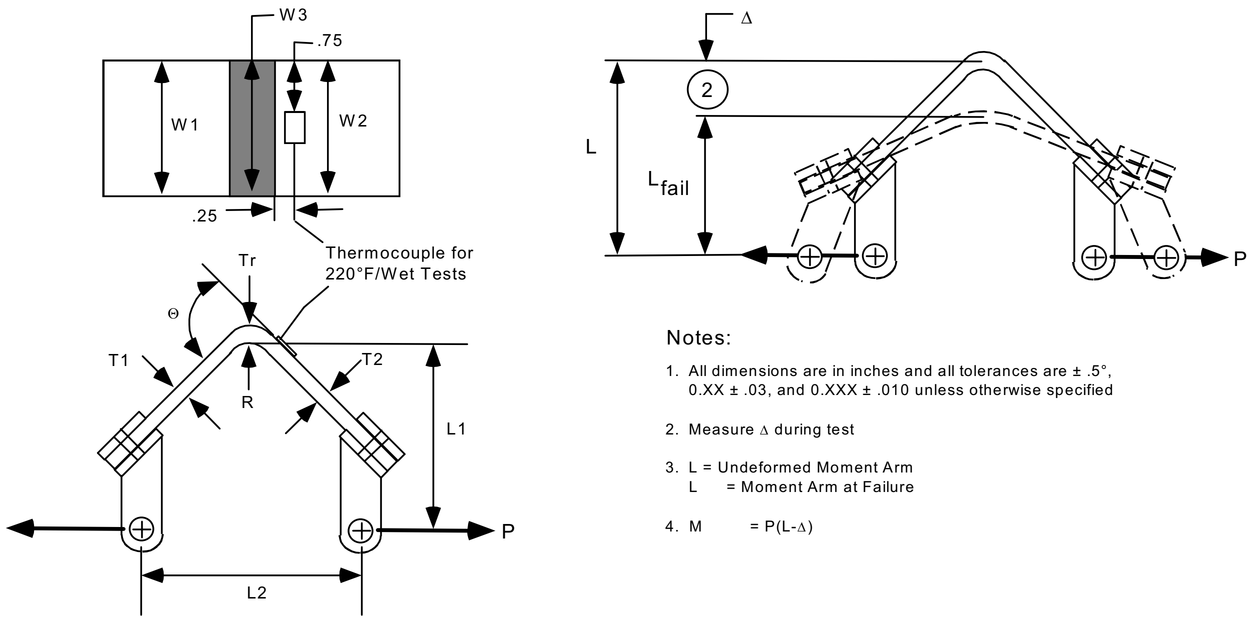


**Figure 13-8 Interlaminar Tension Specimen**

## Bearing/Bypass Interaction Test

The objective of this test method is to determine the static bearing/bypass strengths of cloth and tape laminates. The typical specimen geometry is shown in Figure 13-9. (All units are in inches and all tolerances are +/- 0.5%, 0.XX +/- 0.03 or 0.XXX +/- 0.010 unless otherwise specified.) Each specimen requires back to back axial strain gages. A bearing/bypass test fixture is required. Bearing load ($P_B$) is applied independently of the tension load ($P_T$). It should be noted that the bearing load, $P_B$, is not equal to the load in the strain link but is rather a function of the load in the strain link and the fixture geometry. Apply the initial tensile load ($P_{T1}$). This load should be equal to the applied bearing load $P_B$. Apply the bearing load ($P_B$) at the fastener hole, $P_B = P_{T1}$. While holding the bearing load ($P_B$) constant, increase the tension load, $P_{T1}$, to failure.

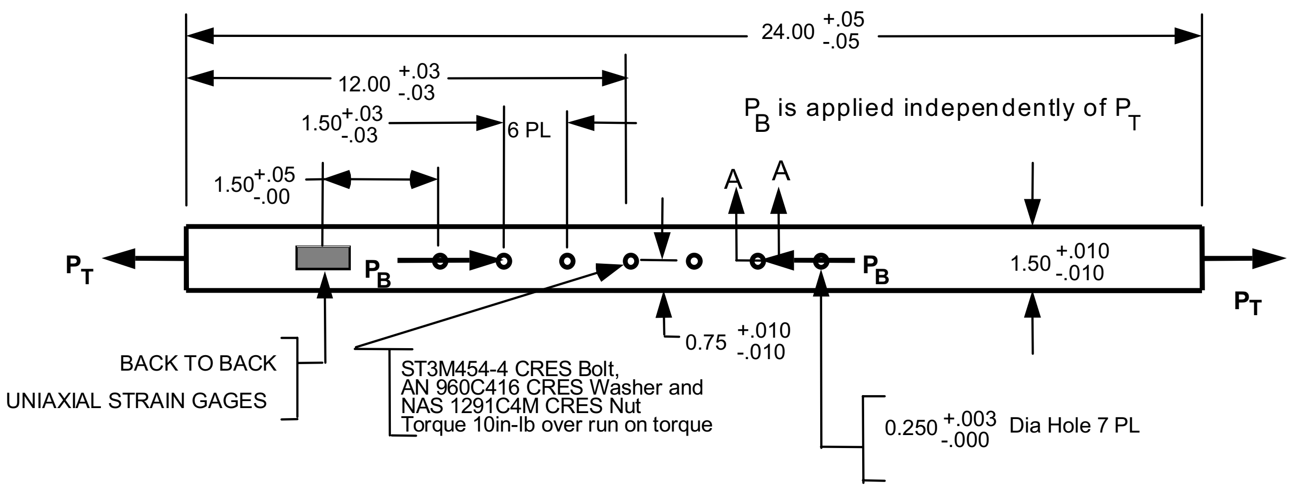


**Figure 13-9 Bearing/Bypass Interaction Test Setup**

### *Data Reduction Methodology for Allowables*

This section discusses the methodology employed to reduce the test data to generate design allowables. This design allowable approach uses test coupons from representative laminate families. The test configurations are representative of actual aircraft structure; that is, holes, fasteners, etc. are included in the coupons.

It is necessary when developing design allowables to consider how the structural analyst will use the allowables to ensure the structural integrity of the aircraft structural components. The structural analyst typically makes the following assumptions:

1. Finite element and stress analysis assumes the material exhibits a linear elastic behavior.

2. Only one set of lamina elastic constants per environmental condition represents all laminate families.

3. Nominal (theoretical) laminate thicknesses are used in the analysis instead of actual, cured thicknesses.

## Tension and Compression Strain Allowables

The end result of a strength analysis is to accurately predict the strength of the part. In determining strain allowables to ensure that the structural part strength is accurately predicted, the following methodology is used:

1. Determine lamina stiffness properties except $E_1$.

2. $E_1$ is a best-fit value based on data from a variety of laminates. Classical lamination theory analyses are conducted until an $E_1$ value is found to best predict the laminate moduli measured during test.

3. Determine a failing strain using the best fit analytical laminate extensional stiffness (same as that used by the analyst) and the nominal failing stress. This ensures that the laminate strength will be correctly predicted during analysis.

4. Determine design allowable strains by reducing the test average failure strains with a B-Basis statistical factor. The B-Basis design allowable implies that composite structure will have this strength or higher 90 percent of the time with 95 percent confidence.

5. Employ the best-fit moduli in the finite element models.

The first step in developing design allowables is to determine the best-fit moduli. The best-fit elastic moduli are determined from a combination of lamina test data and laminate open/filled hole test data. All stiffness properties are determined from the best-fit line of the nominal stress-strain curves from 1000 to 3000 μ-in./in. extensional strain (2000 to 6000 μ-in./in. shear strain), as shown in the figure below This strain range was selected for stiffness determination because a majority of the composite structure does not exceed 3000 μ-in./in. for most flight conditions. The goal for stiffness properties is to most accurately predict deflections for actual flight loads.

Lamina tests are used to establish the lamina stiffness properties $E_2$, $G_{12}$, and $\nu_{12}$. Lamina tests can predict these properties with sufficient accuracy, since these lamina properties can be in error by a significant amount and have little effect on the predicted laminate stiffness of a fiber dominated laminate. History and test data developed on the F/A-18 E/F, however, have shown that using 0° moduli from lamina tests in conjunction with classical lamination plate theory, tends to over predict the laminate stiffness. For this reason, the lamina 0° fiber direction stiffness, $E_1$, as determined from lamina tests, is employed in material acceptance tests but is not used in design. The value of $E_1$ used in design is instead "backed out" of multidirectional laminate test data.

To determine $E_1$, the values of $E_2$, $G_{12}$, and $\nu_{12}$ from the lamina tests and an assumed value of $E_1$ are input into a classical lamination plate theory analysis to predict the laminate extensional modulus, $E_x$. This analytically predicted $E_x$ is then compared to the $E_x$ measured in tests. A new value of $E_1$ is then assumed and the analysis is repeated in an interactive procedure until the analytical $E_x$ is the same as the measured $E_x$. This procedure is performed for all laminates, loading types, and environmental conditions. Typically, the "backed out" $E_1$, is 1) lower than the $E_1$ measured in a lamina test, and 2) varies in value depending upon the percentage of 0° plies in the laminate. The "backed out" $E_1$ tends to increase in magnitude as the percentage of 0° plies in the laminate increases, which explains why the lamina test value of $E_1$ is too high to use in design.

To simplify analysis, one value of $E_1$ is desired for a given load type and environment to predict the laminate stiffness properties for all laminate families. The value of $E_1$ chosen is from a laminate containing 30% to 35% 0° plies. This $E_1$ is the middle value from a range of laminates that contains 20% to 50% 0° plies. Figure 13-10 shows typically expected trends of measured laminate modulus versus analytical modulus when $E_1$ is chosen using this method. As shown, the moduli of "soft" laminates are slightly over predicted while the moduli of "hard" laminates are slightly under predicted.

The goal of the structural analyst is to accurately predict laminate strength, not strain at failure. As illustrated in Figures 13-11 and 13-12, the stress-strain behavior of a laminate as it is loaded to failure is not necessarily linear-elastic, as is assumed in analysis. Due to this inelastic behavior, the predicted laminate strength could be over predicted if the measured failure strain is used with the analytical laminate modulus, as shown in Figure 13-13. To eliminate the potential to over predict laminate strength when designing with strains, all test failure stresses are divided by the analytical laminate modulus to derive analytical failure strains for use in analysis. As illustrated in Figure 13-, by using this methodology the laminate strength will be accurately predicted, but the analytically predicted failure strain may or may not be the same as the actual measured failure strain.

When interpreting full-scale test success criteria, the difference between analytical stiffness and laminate test data must be considered to accurately predict measured failure strains.

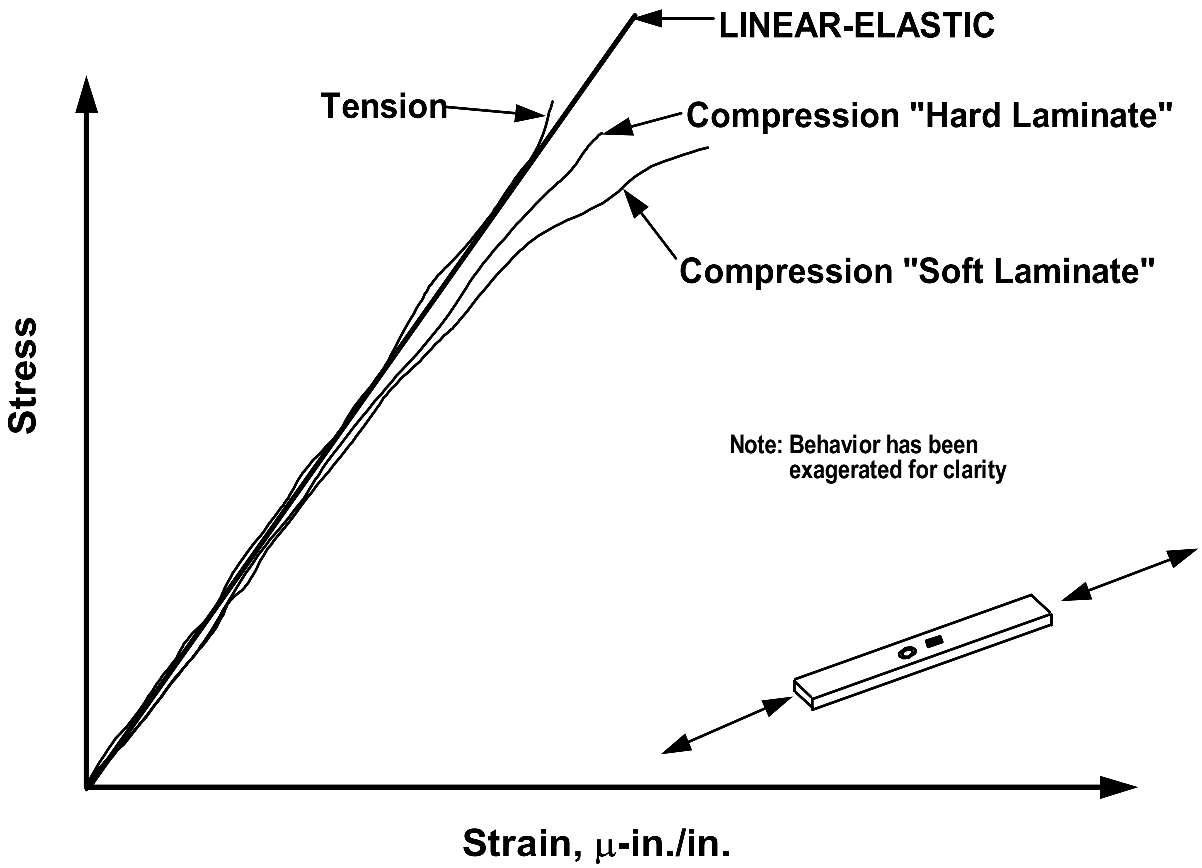


**Figure 13-10 Typically Observed Types of Stress-Strain Behavior for Composite**

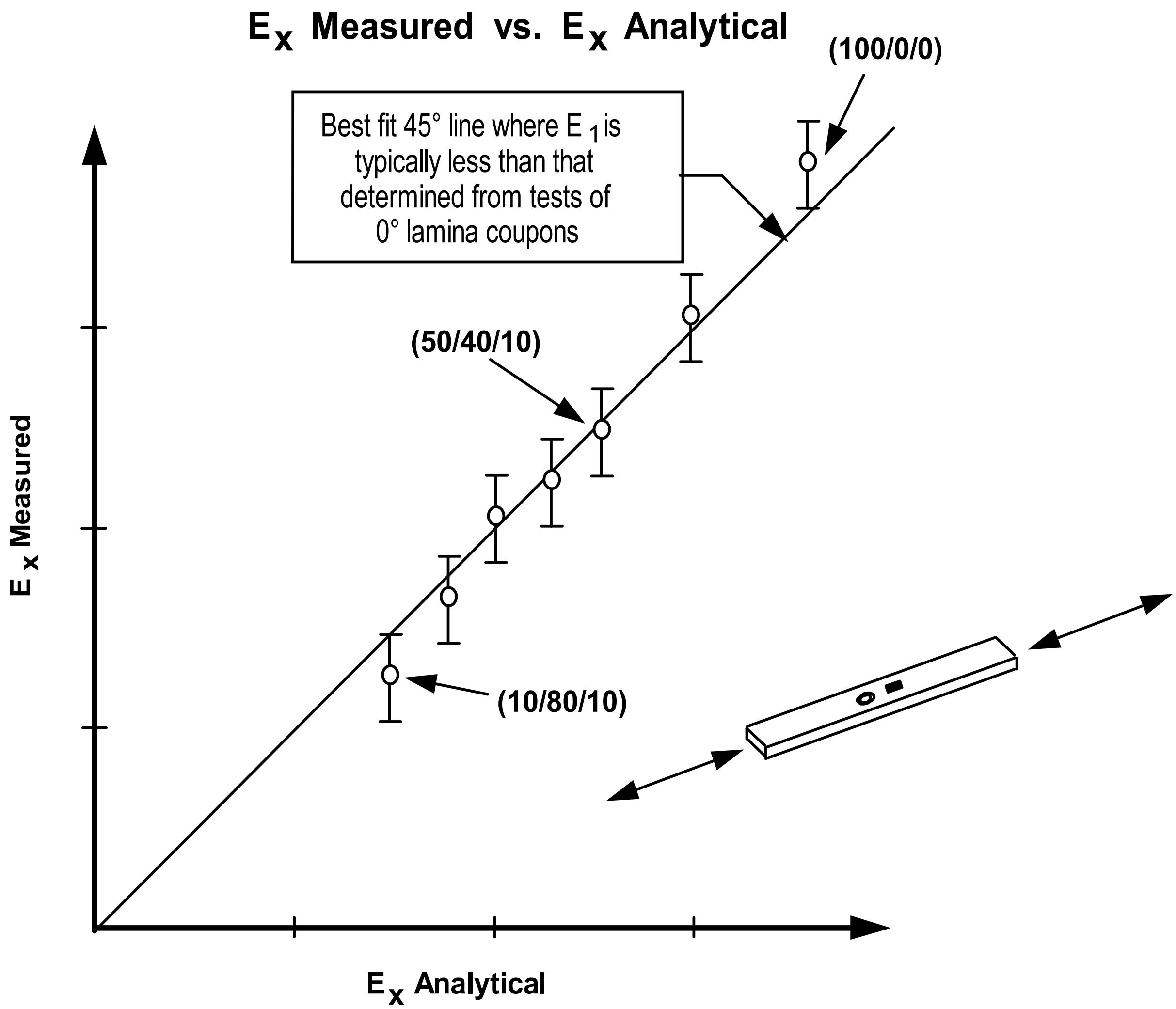


**Figure 13-10 Typical Trends of Ex Measured Versus Ex Analytical**

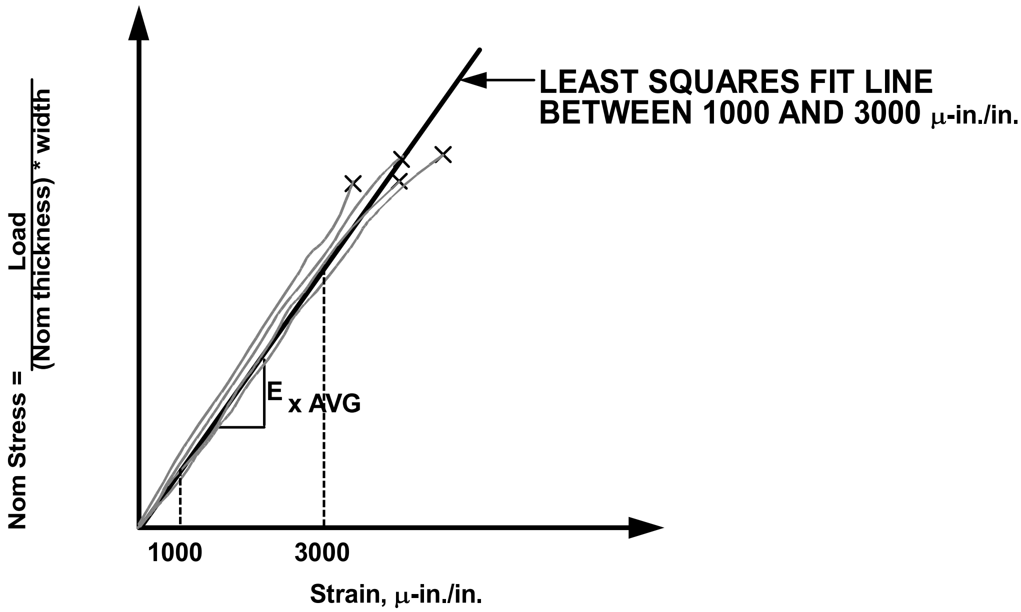


**Figure 13-12 Laminate Average Initial Modulus Used for Design**

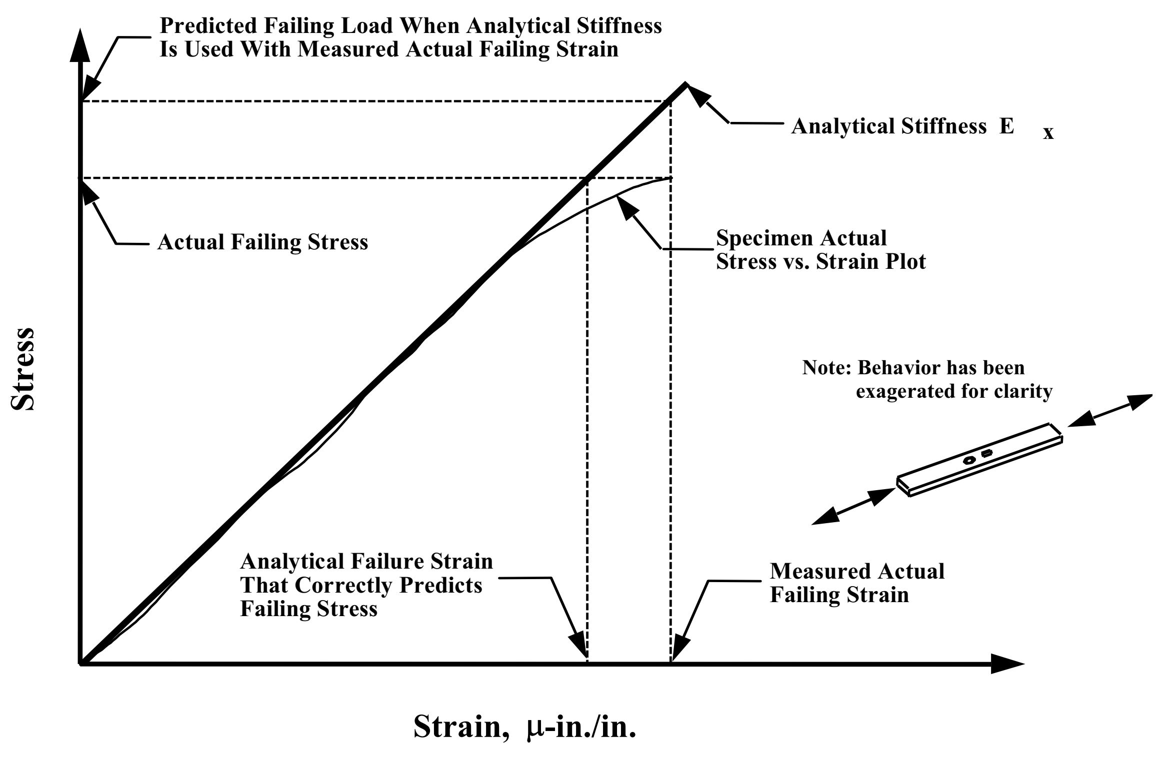


**Figure 13-13 Analytical Stiffness Used with Analytical Failure Strains to Correctly Predict Laminate Strength**

## Pin Bearing Allowables

Pin bearing strength test data is reduced into allowable design data using the methodology of *MIL-HDBK-17E*. The ultimate bearing failure load is defined as the maximum load obtained during a pin bearing test. The bearing yield load is defined as a 4% hole elongation. The design ultimate bearing load was defined as either the ultimate failing load in the test or 1.5 times the test bearing yield load, whichever is smaller. In calculating bearing stress, the nominal thickness and nominal hole diameter are used in the bearing stress equation:

$$F_{br} = \frac{P_{ult}}{Dt}$$

| | | | |
|---|---|---|---|
| where | $F_{br}$ | = | Ultimate bearing stress |
| | $P_{ult}$ | = | Ultimate bearing load |
| | D | = | Nominal hole diameter |
| | t | = | Nominal laminate thickness |

Similarly, the bearing yield stress, $F_{bry}$, can be calculated using the above equation and substituting the bearing yield load, $P_{yield}$, for $P_{ult}$. B-Basis pin bearing allowables are determined using the regression analysis method.

## Interlaminar Shear Allowables

The first step in reducing interlaminar shear test data into design allowables is to verify the failure mode is interlaminar shear. The correct interlaminar shear failure mode is illustrated in Figure 13-14. Specimens that show cracks and delaminations near the outer surfaces actually failed in flexure. Test data from interlaminar shear specimens that experienced a flexure failure mode are not used in developing interlaminar shear stress allowables. Interlaminar shear stresses are calculated from the test data using the isotropic beam theory equation:

$$F_{ils} = \frac{V}{bt}$$

| | | | |
|---|---|---|---|
| where: | $F_{ILS}$ | = | Interlaminar shear stress |
| | V | = | Out-of-plane shear load in the laminate (P/2) |
| | b | = | Actual specimen width |
| | t | = | Nominal specimen thickness |

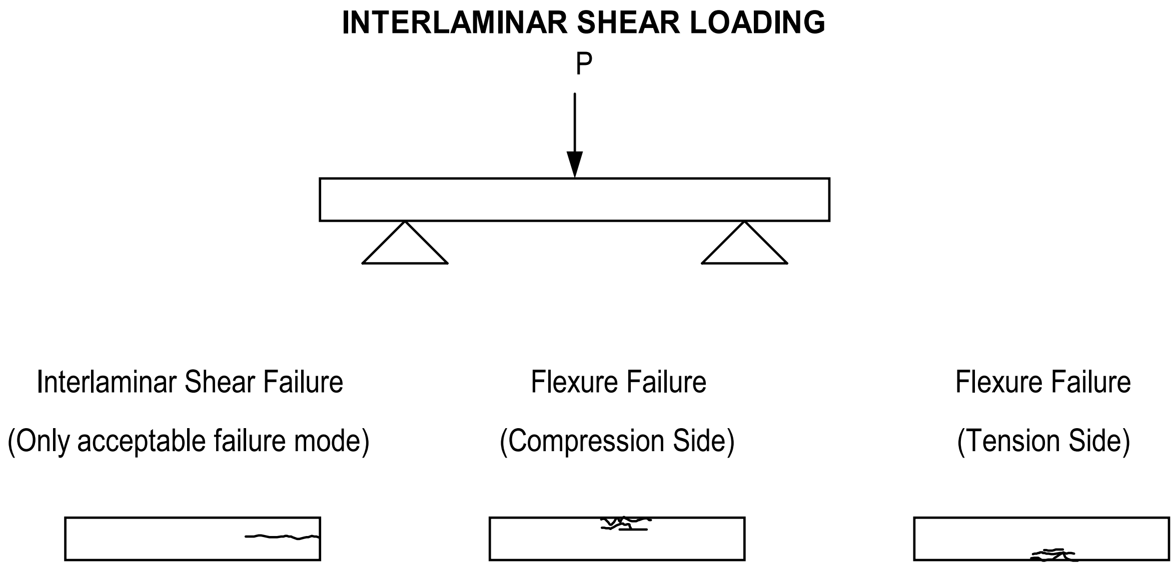


**Figure 13-14 Interlaminar Shear Failure Mode Versus Flexure Failure Mode for Interlaminar Shear Test Specimen**

In material acceptance tests, interlaminar shear stresses are typically calculated using actual specimen thickness instead of nominal thickness. Actual thickness interlaminar shear calculations are more representative of the true resin interlaminar strength. However, the aircraft is designed using nominal thicknesses. Thus, for design purposes, interlaminar shear stress allowables are based on nominal thickness.

### Interlaminar Tension Allowables

The interlaminar tension (ILT) specimen and fixture shown in Figure 13-15 are designed to isolate the maximum interlaminar tensile stress at the center of the curved region. The ILT stress must be computed by hand or via compute program. The interlaminar tensile stress is determined by summing the radial stress induced by the end load and moment. In material acceptance tests, interlaminar stresses are typically calculated using actual specimen thickness instead of nominal thickness. Actual thickness interlaminar tension calculations are more representative of the true resin interlaminar strength. However, the aircraft is designed using nominal thicknesses. Thus, for design purposes, interlaminar tension stress allowables are based on nominal thickness. In addition, using the same analogy, the nominal radius is used in the calculation of the ILT stress.

As a result, the actual moment arm at failure is critical to predicting the ultimate ILT stress. As the specimen is loaded, the moment arm is reduced, thus lowering the actual ILT stress at failure. It is not desirable to use the initial moment arm in the computation of the ILT stress because this over predicts the actual failure ILT stress of the specimen. The reduced moment arm is determined by measuring the lateral displacement of the radius.

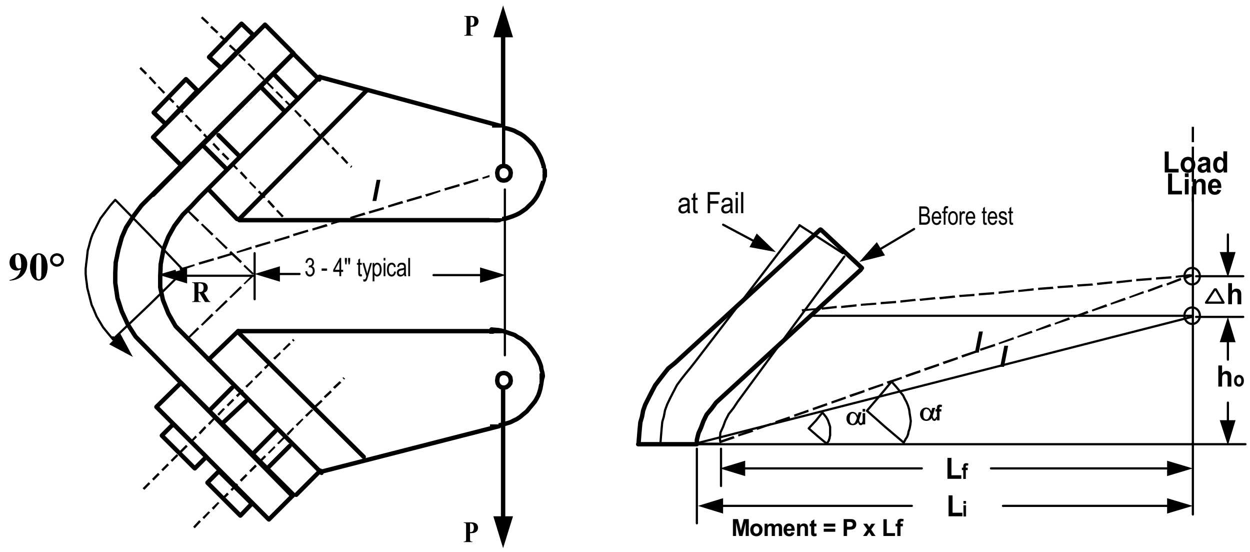


**Figure 13-15 Interlaminar Tension Specimen with Reduced Bending Moment Arm**

## Allowables Development Methods

### *B-Basis Development Methodology*

Composite design allowables are B-Basis values, as a minimum. A B-Basis design allowable, as defined by *MIL-HDBK-5*, is the value, which at least 90 percent of the mechanical property population of values is expected to equal or exceed, with a confidence level of 95 percent.

Design allowables are calculated using one of two procedures described in *MIL HDBK-5*. One procedure is the direct computation of B-Basis allowables from a normally distributed population of a single material property. The other method determines B-Basis allowables by linear regression analysis of a single material property as a function of another parameter.

The direct computation method determines B-Basis allowables for one value of the material property. To calculate the B-Basis allowable for this case, the following equation from *MIL-HDBK-5E* was used:

$$B = X - k_B S$$

where B = B-Basis allowable for the material property
X = Mean (average)
$k_B$ = One side tolerance limit factor, from *MIL HDBK-5E*, Table 9.6.4.1
P = 0.90, 95% confidence and *n* degrees of freedom
S = Sample standard deviation, from *MIL HDBK-5E*, Section 9.2.2.

When a test is run on a set of specimens at two or more different values of the independent variable, the linear regression B-Basis allowables method of *MIL HDBK-5E*, Section 9.2.11, can be applied. For this analysis, the method of least squares is used to best fit a line through the data.
This line is given by:

$$Yo = a + bXo$$

where Yo = The dependent variable
Xo = The independent variable

$$b = \frac{S_{xy}}{S_{xx}}$$

$$a = \frac{\sum y - b\sum x}{n}$$

x = Individual values of the independent variable
y = Individual values of the dependent variable

n = Number of data points used in the regression

A B-Basis allowable can then be determined from the best-fit line using the following equations:

$$B = Y_o - k_B S_y \sqrt{1 + \frac{1}{n} + \frac{\left[X_o - \frac{\sum x}{n}\right]^2}{S_{xx}}}$$

where B = B-Basis allowable for a given value Xo
Yo = Value of the dependent variable for a given value of Xo
$k_B$ = One side tolerance limit factor, from *MIL HDBK-5E*, Table 9.6.4.1, for

P = 0.90, 95% confidence, and n-1 degrees of freedom
Xo = Value of the independent variable
n = Number of data points used in the regression
x = Individual values of the independent variable
$S_y$ = Sample standard deviation

$$S_y = \sqrt{\frac{S_{yy} - \frac{(S_{xy})^2}{S_{xx}}}{(n-2)}}$$

$$S_{xx} = \sum x^2 - \frac{\left(\sum x\right)^2}{n}$$

$$S_{yy} = \sum y^2 - \frac{\left(\sum y\right)^2}{n}$$

$$S_{xy} = \sum xy - \frac{\left(\sum x\right)\left(\sum y\right)}{n}$$

### *Statistical Tests for Data Normality*

The Chi-Square test is used to determine if the data set comes from a normally distributed population. The data must pass this test in order to use the B–Basis methodology discussed above.

To determine if the mechanical property is from a population with a normal distribution, a Chi-Square goodness of fit test is performed on each population. First, the theoretical distribution is divided into several equal slices or intervals centered about the mean. The observed frequencies for these intervals are determined from the test data sample. In the Chi-Square test, the observed frequency distribution is compared to the corresponding values of an expected, or theoretical, distribution.

The Chi-Square statistic, obtained from the above equation, is compared to the 0.95 fractile chi-square for k - m degrees of freedom, where k is the number of terms in the formula for $c_2$ and m is the number of quantities, obtained from the observed data, that are needed to calculate the expected values. Generally, the number of specimens and the sample standard deviation are used to calculate the expected values, so m = 2.

### *Data Pooling*

Data sets can be combined to increase the population for B-basis calculations. With larger data samples there is increased confidence that the sample variance adequately approximates the population variance. Accordingly, the $k_b$ value decreases with larger data samples. Smaller $k_b$ values give higher B-basis design allowables and lighter weight airframe designs. In general these data must represent the same material, layup, test, etc., before they can be pooled. The data should also come from the same population as can be checked with a t-test.

Some data can be pooled even if the tests were not identical in every way. For example, data sets of the same laminate layup, width to diameter ratio, test temperature, and moisture content can be combined if each data value is divided by the average failure strain at that particular temperature and moisture content. This normalized data can be combined with normalized data from the other test conditions to form a larger pool. The standard deviation of the larger sample is then obtained and used to compute the statistical knockdown factor.

### *Batch-to-Batch Variation*

Composite materials are made in separate batches, so it is possible to encounter batch-to-batch variations in the composite's properties. In fact, this is often the case, although a good, robust manufacturing process will minimize the phenomenon. The goal of all approaches is to determine design allowables at the beginning of the design process that account for any expected batch-to-batch variations.

The simplest and most cost-effective approach is to pool all data together as if no batch-to-batch variation exists and then perform goodness-of-fit tests on the pooled data. Batch-to-batch variability will then be built into the B-basis values. However, this cannot be guaranteed. Engineering judgment must be used to evaluate if the test data has the expected distribution based on the historical performance of similar materials. Important test data are collected from several batches of material to include this batch-to-batch variability and data pooling techniques as shown above are used to include the variability in other tests. During production, acceptance testing is performed on each batch of material to ensure it meets certain minimum requirements so that any excessive batch-to-batch variability is caught before the material is used in production.

Even when all batches of pooled data together pass a goodness-of-fit test for a chosen distribution, however, it does not ensure that batch-to-batch variability is insignificant. Further, one cannot guarantee that B-basis values of structured data computed after pooling and fitting a distribution are always conservative.

## 13.4 Structural Design Process

### Design Goals

In a typical design effort, the primary focus is on

1. meeting the mean structural performance requirements and design constraints
2. meeting the weight target
3. meeting producibility and cost requirements

In the past, this has often been done in a sequential manner, i.e., first find a design that works, then tailor the design extensively to reduce the weight, and finally, pass the design "over the fence" to manufacturing and develop tooling and processing techniques to reduce the cost. It is ASSUMED that the Structure will be consistently built to print.

Even in an IPT environment, where this job is done concurrently with input from all disciplines, the approach is similar. The Structures organization typically defines an initial design and then discussions ensue about how to balance performance, weight, producibility and cost requirements. The primary blind-spots in this approach are: (1) the focus is normally on mean performance, with very little consideration of robustness to defects or material/geometry variation, (2) it is assumed that a defect-free structure can be consistently built, and (3) very little data is available for the Structures and Manufacturing representatives to objectively discuss the effects of potential design and manufacturing trade-offs. As a result, the success of the effort is highly dependent on the experience and knowledge of the IPT members and the available tools and knowledge about the particular concept.

One of the key differences in the AIM-C Design Selection Methodology is the early consideration of design robustness to variation and defects. Another is the availability of a tool set to rapidly assess the criticality of various parameters related to the design, be they geometric parameters or parameters associated with manufacturing effects.

## The Design and Selection Process

Structure, be it a detailed part or a complex assembly must meet certain operating objectives if it is to provide satisfactory service. Broken down it a simplistic statement, the basic design philosophy is to create the highest quality product that is feasible, using the best available materials and design and manufacturing techniques. This very broad statement must be considered throughout the design process.

In order to decrease the size of the design space without unduly limiting it is to begin the design process by consulting a "Requirements" or "Design Requirements and Objectives" document. This document is assembled prior to the design of a commercial or military aircraft or platform and includes among other things static and dynamic load factors, margin of safety requirements, criteria to cover buckling and crippling, joint design, fastening requirements, and minimum gage requirements.

With internal and external loads and design criteria in hand the structures engineer may begin the design process. For illustrative purposes a design of a hat stiffened panel will be used as a design example. The following paragraphs detail the design process from this point and discuss how the designer can meet the requirement of "creating the highest quality product that is feasible, using the best available materials and design and manufacturing techniques."

The design process was broken down into the following steps;

(1) Selection of an initial starting point or initial design concept
(2) First Shell Model FEM Runs – Critical Regions and Stability
(3) Initial Cure Cycle and Tooling Selection
(4) Alternate Concepts – Elimination of Critical Defects
(5) Determination of important variables
(6) Interaction with manufacturing
(7) Selection of Tooling Approach
(8) Local Model or Detailed FEM Studies
(9) Defect Sensitivity Studies

**Selection of an Initial Starting Point or Initial Design Concept**

Perhaps this is the most important step in the process. Often in the design process it is this initial design concept that is used. For this design example a hat stiffened panel was assigned and not "selected." Other designs could have been blade, "J", "I" stiffened or sandwich panel.

To properly perform this study one must accurately assess each design at a level that gives reasonable results and captures trends but also at a level that allows a relatively quick assessment of each concept. Often at this stage a designer may rely upon past experience or may consult company design practices that will give guidance.

**First Shell Model FEM Runs – Critical Regions and Stability**

In this step shell finite element models are created and reviewed. In all situations involving finite element modeling the designer must look at results with skepticism. Shell element finite element models give accurate results only in regions that are stress concentration free. In addition, any regions where shells intersect at any angle other than zero, the shell results are suspect and other means must be used to determine the state of strain. One must always be aware of the method by which results are obtained in the finite element model. Are results averaged at nodal locations? What domain is used if results are averaged or a maximum number is reported by the finite element code? A myriad of questions must be answered.

Figure 13-16 shows the results of a shell finite element of an initial hat concept. At this load level gross area strains throughout most of the skin are evident. It can be determined that strains in the top of the hat section are quite low. The analyst should also determine if the modeling technique is appropriate. Would those low strains in the stiffener crown increase if a nonlinear analysis is performed? It appears the stiffener run out has the highest strains although that's somewhat difficult to determine. At this point the analyst should look for discontinuities and attempt to rationalize the results of the model. In addition it is always helpful to plot displacements and to animate the displacements, again to determine if the model is behaving as it should. This linear model is sufficient for initial sizing and for trade studies but is inadequate or at least regions of it are inadequate for final strength determinations.

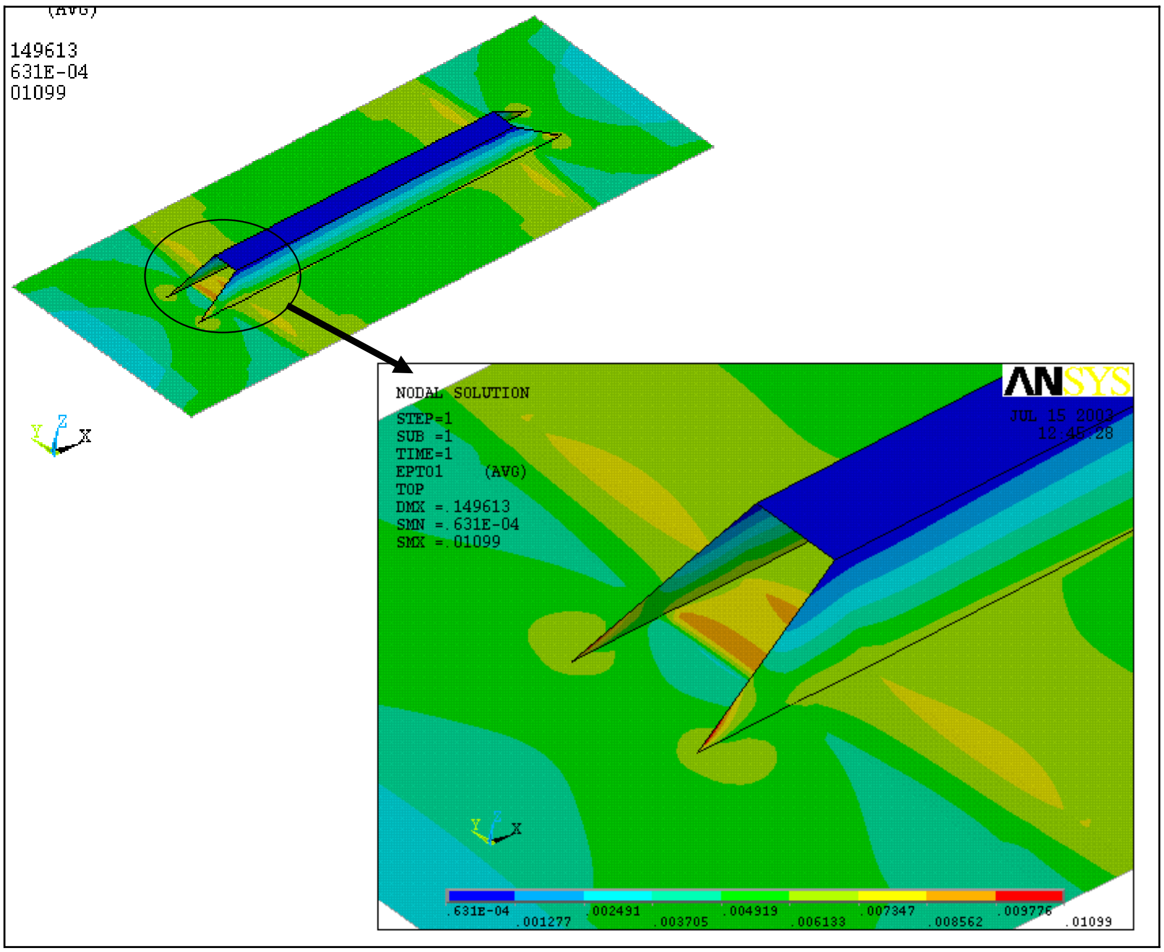


**Figure 13-16 Shell Finite Element Model**

## Initial Cure Cycle and Tooling Selection

With a firm concept defined which includes basic component thickness to a reasonable level of certainty and with knowledge of other basic geometrical parameters the design should be examined to determine appropriate cure cycle and tooling concepts. This step may eliminate some possible variations in downstream design iterations or may lead the design down a different path or variation of the design based on producibility or cost considerations. This exercise is generally beyond the responsibilities of the structures engineer. In depth knowledge of materials and processes is required to accurately determine appropriate methods and interpretation of results of this exercise. Consult the Materials and Process Development and Producibility Sections of this document for further detailed discussion of cure cycle and tooling analysis and selection.

**Alternate Concepts – Elimination of Critical Defects**

Upon completing the previous steps the design has gained maturity. This does not mean the design cannot be modified. On the contrary, now that the design is determined to be viable, efforts may be expended to make the design better with a high degree of certainty of benefit from these efforts. Many designs have a few critical details that determine overall part strength. If one can eliminate a critical detail – actually eliminate it, one can increase the overall part or assembly strength, or make the part more durable or damage tolerant or perhaps make the part or assembly more easily produced. The hat stiffened panel offers a good example of elimination of a critical detail.

Traditionally the termination of the stiffener foot or flange has been a problem area, often delaminating due to the abrupt stiffness change and requiring the addition of fasteners or requiring fracture based analysis for substantiation. This analysis assumes a defect or delamination at the stiffener termination. Analysis is performed to determine load level at which the crack grows. A large amount of effort and cost is expended attempting to minimize the chance of delamination by tailoring the stiffener flange termination. The cost is highest on the production side by requiring detailed and exacting ply ramp terminations at this location. Figure 13-17 shows this detail and a concept that enables elimination of it.

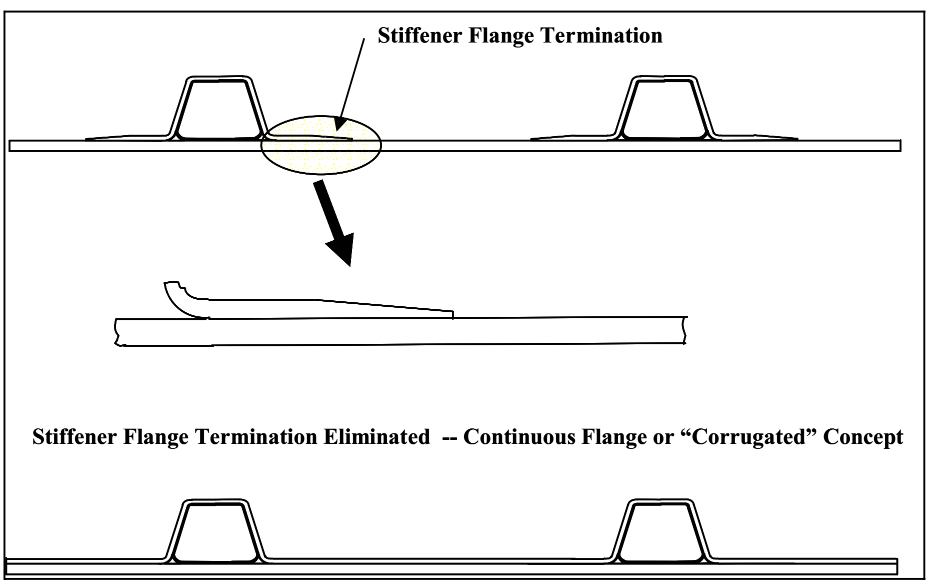


**Figure 13-17 Stiffener Flange Termination**

For illustrative purposes several of the studies that were done for design of the AIM-C Phase 1 Hat Stiffened Panel Demonstration/Validation are discussed.

Study 8: Corrugated Stiffener/Skin Configuration Study

Due to the relatively small bay width the stiffener foot termination occurs relatively close to the middle of the bay as shown by the sketch below. A concept whereby the stiffener feet common to the skin are extended to meet the adjacent stiffener foot is the focus of this study. The stiffener and wrap detail for a multi stiffener bay assembly would resemble a corrugated sheet, Figure 13-18.

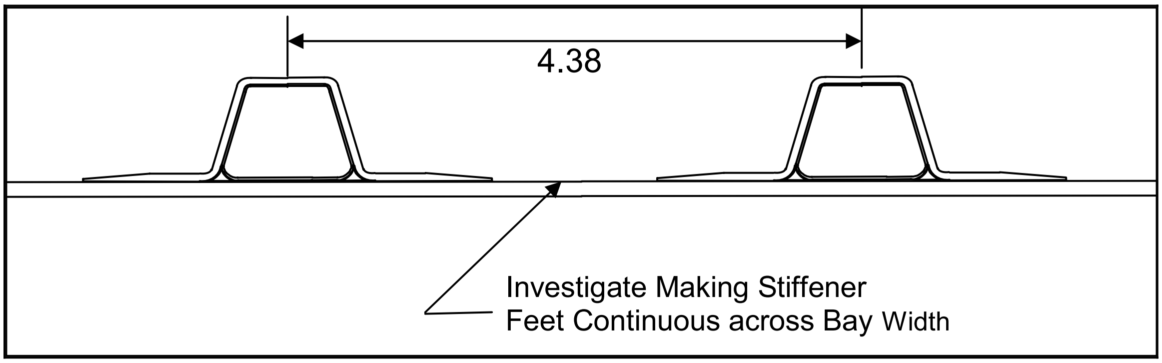


**Figure 13-18 Corrugated Study Concept**

This can offer advantages of elimination of stress concentrations at the stiffener foot termination, and the elimination of manufacturing defects at the foot. In addition ply waviness at the foot termination, which has been problematic on other stiffened assemblies can be eliminated. The continuous inner skin and outer skin is not new. It is a common arrangement in superplastic/diffusion bonded assemblies. If this concept proves to be weight competitive it can offer a very simple assembly sequence. The inner skin may be easily located on the outer skin by way of tooling tabs. This concept seems to be very simple and therefore relatively easy to assemble.

This study will compare this concept to the conventional concept and determine its weight impact. Determination of the structural efficiency of each concept will also be determined.

Three configurations were studied

1. Separate stiffeners co bonded or cocured to skin
2. Corrugated Stiffener cobonded or cocured to skin
3. Same as 2. Except integral skin plank removed. The skin plank is a local reinforcement in the skin which consist of plies added to the skin below the stiffener

Figure 13-19 details the stain levels in each of the configurations.

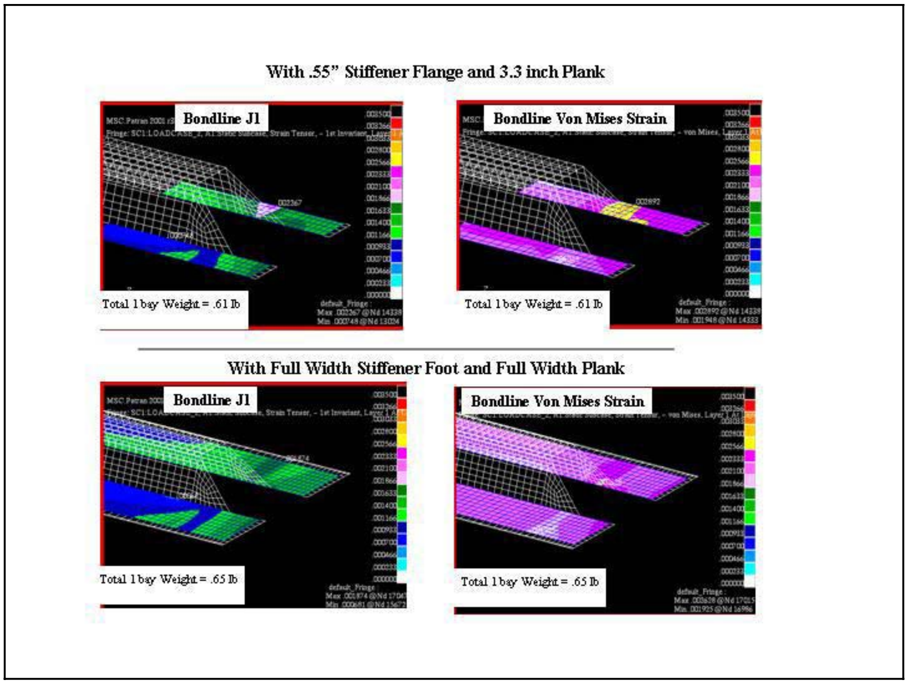


**Figure 13-19 Bond Line Strains**

Figure 13-19 shows the bond line strains (the strains at the interface of the stiffener flange and the skin) for an assembly with 0.55 inch long stiffener feet and for an assembly with continuous feet. Please note that only a single stiffener bay is shown. Note the strain level in the bond line decreases as the full width stiffener flange is used. The weight of the assembly however also increases.

Figure 13-20 shows the stiffener strains for an assembly with 0.55 inch long stiffener feet and for an assembly with continuous feet. Please note that only a single stiffener bay is shown. Note the strain level in the stiffener decreases as the full width stiffener flange is used. The weight of the assembly however also increases

Figure 13-21 shows the skin strains for an assembly with 0.55 inch long stiffener feet and for an assembly with continuous feet. Please note that only a single stiffener bay is shown. Note the strain level in the skin decreases as the full width stiffener flange is used. The weight of the assembly however also increases

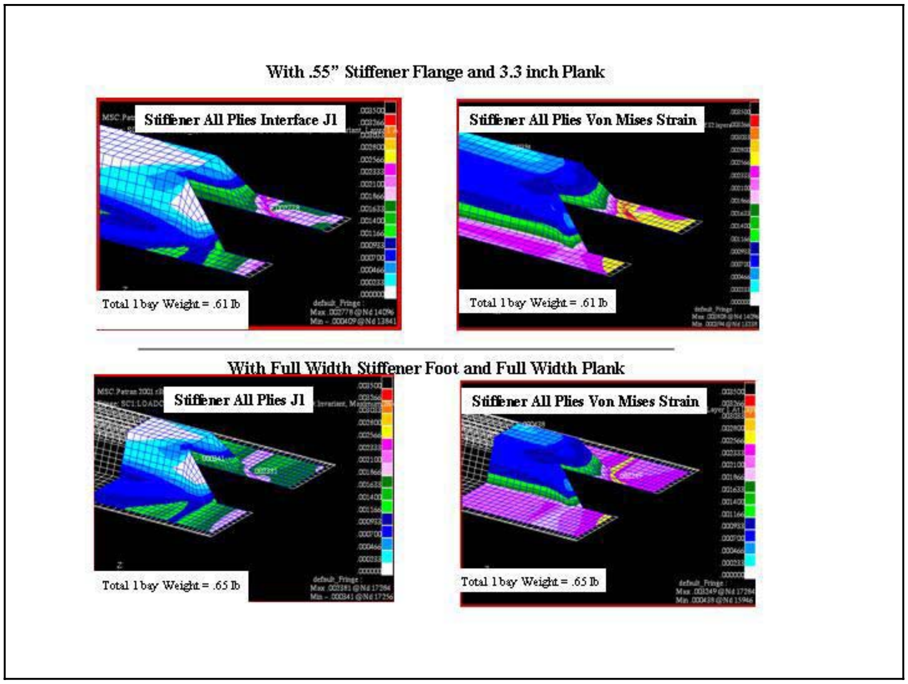


**Figure 13-20 Stiffener Strains**

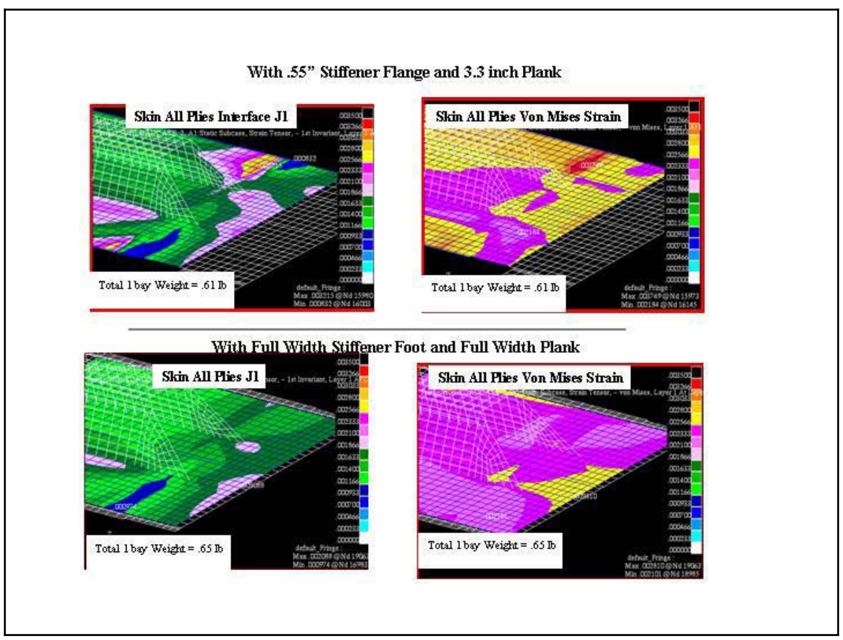


**Figure 13-21 Skin Strains**

The preceding figures compare the strains for two different assemblies. One with stiffener feet of 0.55 inches and the other with continuous stiffener feet across the bay width. Both assemblies utilized a skin with four 0 degree plank plies located at the skin centerline. The next set of figures will investigate to effect of removing the plank plies thereby reducing the stiffness of the skin.

Figure 13-22 shows the bond line strains for assemblies with full width stiffener feet – the corrugated concept with and without plank plies in the skin. As the skin stiffness is decreased the bond line strains increase. But, of course, the assembly weight decreases as the plank plies are removed

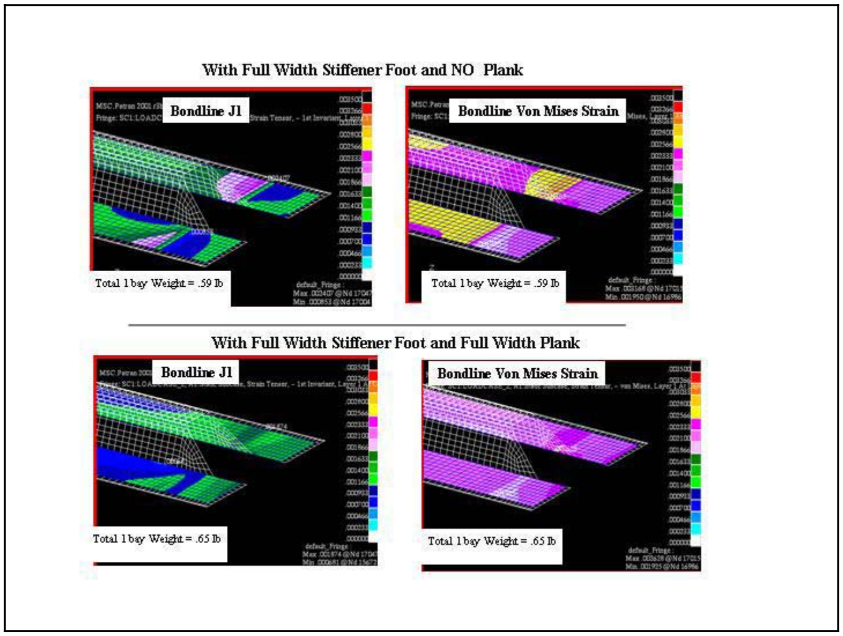


**Figure 13-22 Bond Line Strains**

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Figure 13-23 shows the stiffener strains for assemblies with full width stiffener feet – the corrugated concept with and without plank plies in the skin. As the skin stiffness is decreased the stiffener strains increase. But, of course, the assembly weight decreases as the plank plies are removed.

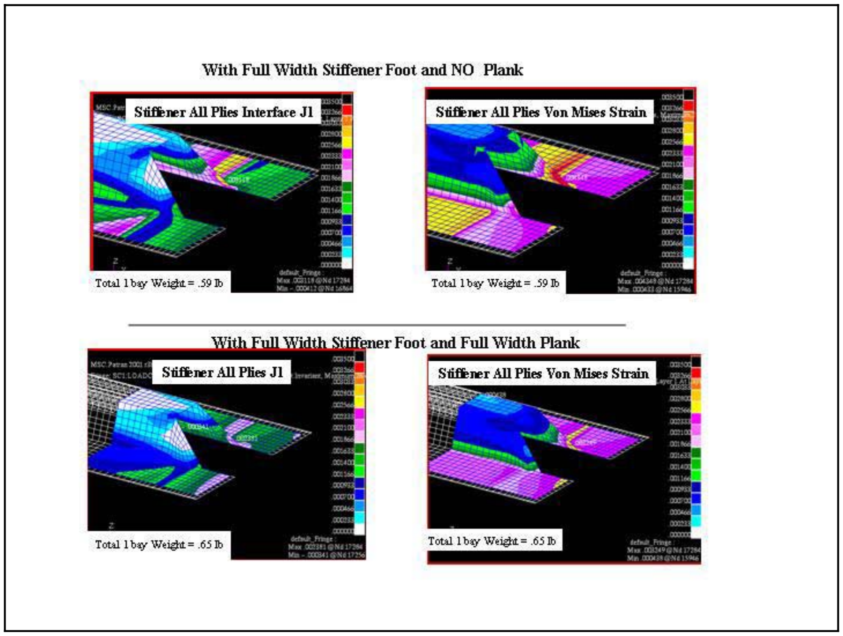



**Figure 13-23 Stiffener Strains**

Figure 13-24 shows the skin strains for assemblies with full width stiffener feet – the corrugated concept with and without plank plies in the skin. As the skin stiffness is decreased the stiffener strains increase. But, of course, the assembly weight decreases as the plank plies are removed

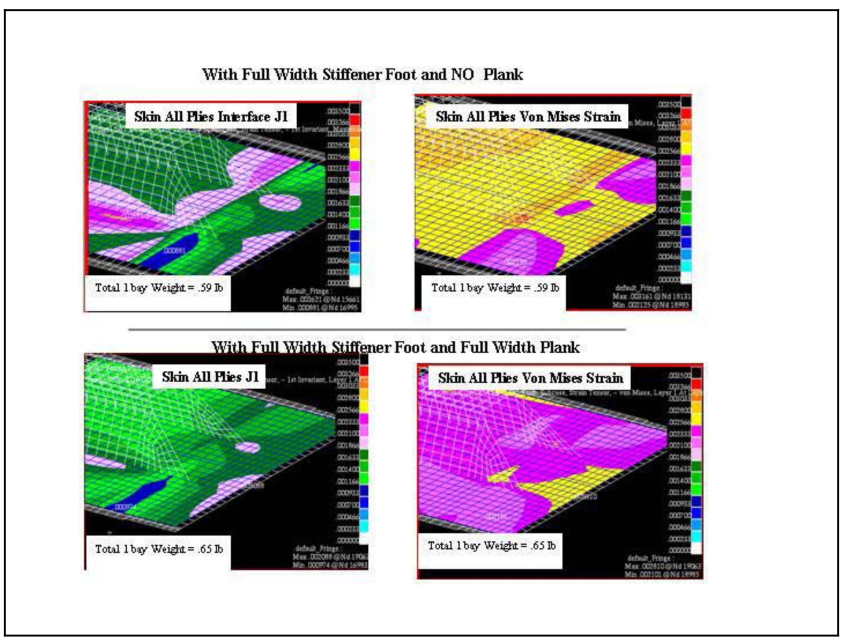



**Figure 13-24 Skin Strains**

In all cases it was of course shown that strains can increase or decrease as a function of the material thickness – nothing profound about that. How does one determine what design is most appropriate? For this design a concept of structural index was introduced, Figure 13-25. In this case the structural index is defined simply as the strain level multiplied by the assembly weight. One could argue that the exponents should be something other than one for these products but for the sake of this study this simple relationship was used. The structural index for each of the configurations at strain levels seen by each component is given in the figure below. A lower structural index is an indication of a more weight efficient design. Please note in all cases the corrugated design with integral plank plies over 100% of skin has the lowest structural index and is therefore the most weight efficient design.

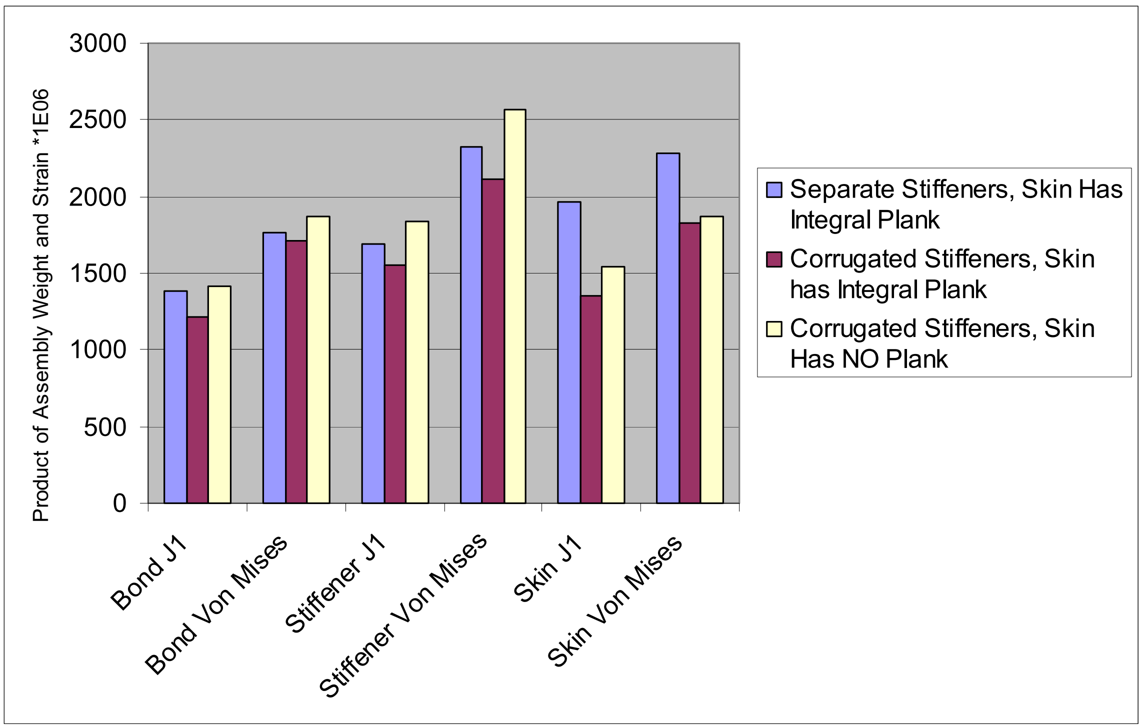



**Figure 13-25 Structural Index for Each Configuration (Lower is Better)**

The result of this study suggests the corrugated concept is the most weight efficient design studied if plank plies will be utilized for 100% of the skin unlike the existing design which utilized plank plies over approximately 75% of the skin area. The assembly will therefore be made up from a single corrugated hat/ inner skin cobonded to a procured outer skin – both of relatively simple geometry. This design was examined to determine producibility with the corrugated concept shown to be easier to assemble than having separate hats bonded to the skin.

In conclusion, it was determined that the critical stiffener flange termination could be eliminated.

**Determination of Important Variables**
While it is relatively easy to anticipate the effect of some geometrical parameters on the strength attributes of a detail or assembly it is important to quantify these effects. Some parameters will have profound effects on strength, others will have negligible effect. On the other hand parameters that are unimportant from a strength standpoint may have profound influence on cost and or producibility. If one finds a parameter that is unimportant to strength but is very important to producibility the design parameter may be set by manufacturing and not by structures.  It is important to determine the effect of as many parameters as feasible in order to make informed decisions. In an effort to further illustrate these points a study that was performed during the design of the hat stiffened panel is shown here.

Study 7: Stiffener Parameters - Analysis of Variations

In an effort to determine the effect of varying stiffener geometric parameters of height, width and run out or termination angle a full factorial study was done where each of these parameters was varied over a reasonable range. The input parameters are summarized in the table below. It is important to note that the run out angle is not set directly. Rather it is determined by the two parameters H_st, the height of the stiffener and the parameter " once the stiffener height is set, the parameter "run out" which is the distance over which the stiffener crown and webs go from full height to zero. With three independent variables 27 runs separate runs were needed for a full factorial study.

The effect of each variable and the effect of combinations of independent variables, Figure 13-26 is discussed.

**Geometric Constants and Other Default Settings**

| | |
|---|---|
| w_st - Stiffener width across flat | **VARY** |
| H_st - Stiffener height | **VARY** |
| Lstiff - Stiffener Flange Length | **VARY** |
| L_st_ramp - Stiffener Flange Ramp | 0.2 |
| alpha - Stiffener Leg Angle | 15 |
| r1 - Stiffener Upper Radius | 0.25 |
| r2 - Lower Radius | 0.25 |
| w_p - Plank Width | 3.3 |
| adim - Stiffener Bay Size | 4.38 |
| wpad - Edge Pad Skin Perimeter | 0.08 |
| wpl_l - Plank Ramp | 0.2 |
| bdim - Stiffener Spacing | 12.5 |
| mdim - Mid Stiffener Length | 8.14 |
| runout - Runout Length | **dependent** |
| stiff2framegap - Stiffener to to Frame Gap | 0.2 |
| stiff2framefastener - Stiffener to Frame Fastener | 0.57 |
| a_0 - initial crack length | 0.08 |
| frame_spacing | 14.7 |
| frame_flange_gage | 0.125 |
| framewidth | 0.53 |
| extend_plank_and_feet 1== Extend Thru Frame | 1 |
| plank_integral 1= Plank Integral to Skin | 1 |
| mesh_size | 0.15 |

**Components**

| Component | Stacking Sequence T=Tape F=Fabric | t |
|---|---|---|
| Skin | [45 -45 0 90 45 -45 0 45 -45]s All IM7 Tape | 0.0936 |
| Plank | [0]4 All IM7 Tape | 0.0208 |
| | Skin + Plank Thickness | 0.1144 |
| Skin at Frame | [45 -45 0 90 45 -45 0 45 -45 0 0 90 0 ]s 0 All | 0.1404 |
| Stiffener | [45]3 AS4 Fabric | 0.0420 |
| Crown | [45F 0T 0T 0T 45F 0T 0T 0T 45F] Tape=IM7 | 0.0732 |
| Wrap | [0 F 45 F] AS4 Fabric | 0.0280 |

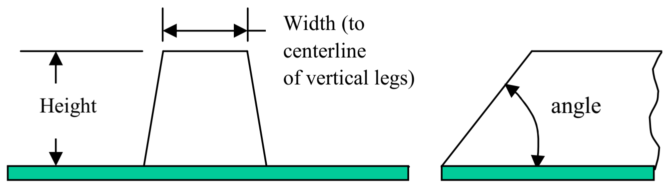



**Figure 13-26 Geometric Constraints and Other Default Settings**

Fore-Aft Tension dominated load case

- $N_{transvese}$ = 360 lb/in (+)==tension in skin
- $N_{fore/aft}$ =2610 lb/in (+)==tension in skin
- $N_{xy}$ = -1680 lb/in
- Pressure = 4.5 psi (+)==tension in skin compression is stiffener crown

Bond Line Strains

The bond line strains are very important in the determination of the strength of the hat stiffened panel assembly. Past experience has shown delaminations upon assembly and under load are typical and common problems. While the global model by no means has the ability to accurately predict strains in this region it does have the ability to accurately determine trends. The results of the full factorial study are shown in Figure 13-27.

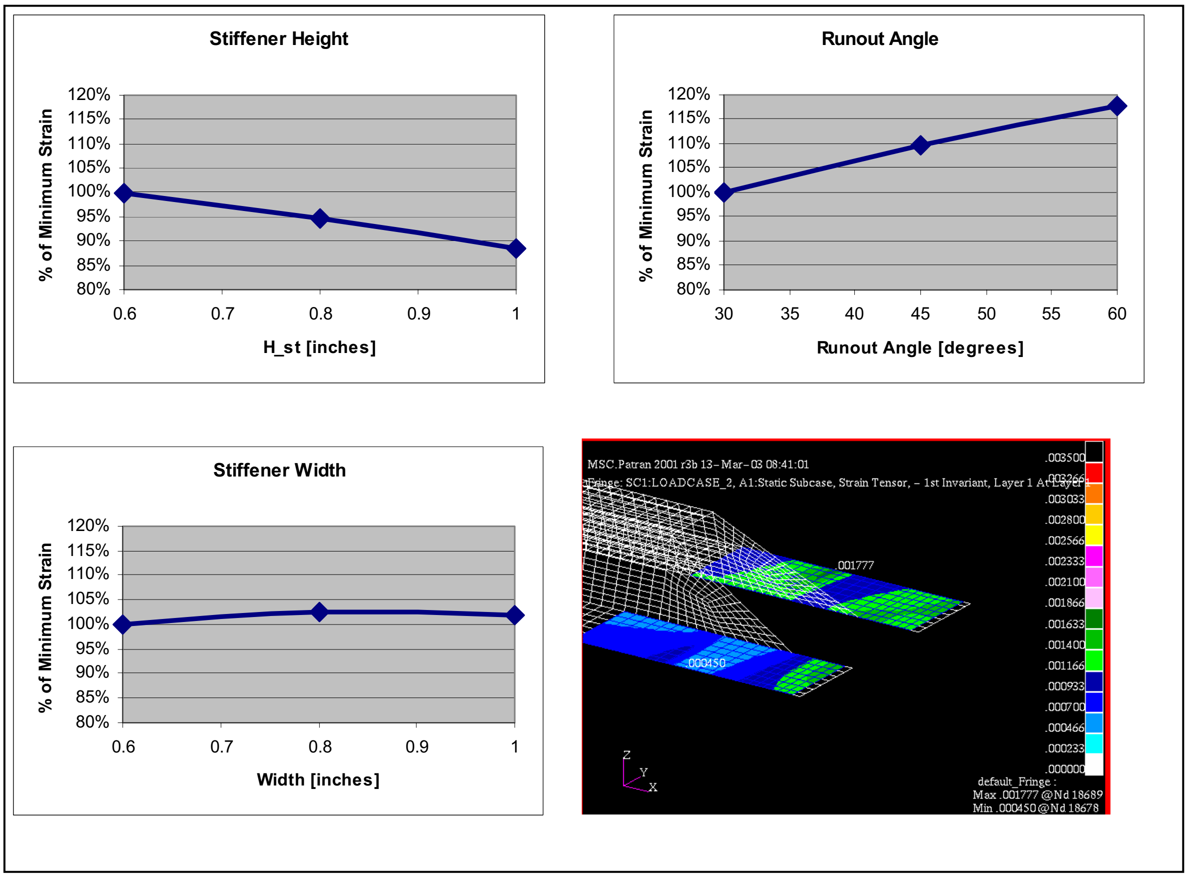



**Figure 13-27 Relative Bond Line Strains**

Figure 13-27 shows the effect of a single parameter on the bond line strains. These curves were generated by averaging the results from two of the three study parameters and showing the range of the third parameter and its dependent variable, in this case J1 or the first invariant of strain in the bond line. These curves show the strains in the bond line trending downward as the height of the stiffener is increased and as the run out angle is decreased. The effect of the width of the stiffener is relatively minor.

What parameters are the largest contributors to bond line strains? Figure 13-28 shows the relative strengths of each parameter and the effect of parameter combining on the bond line strains.

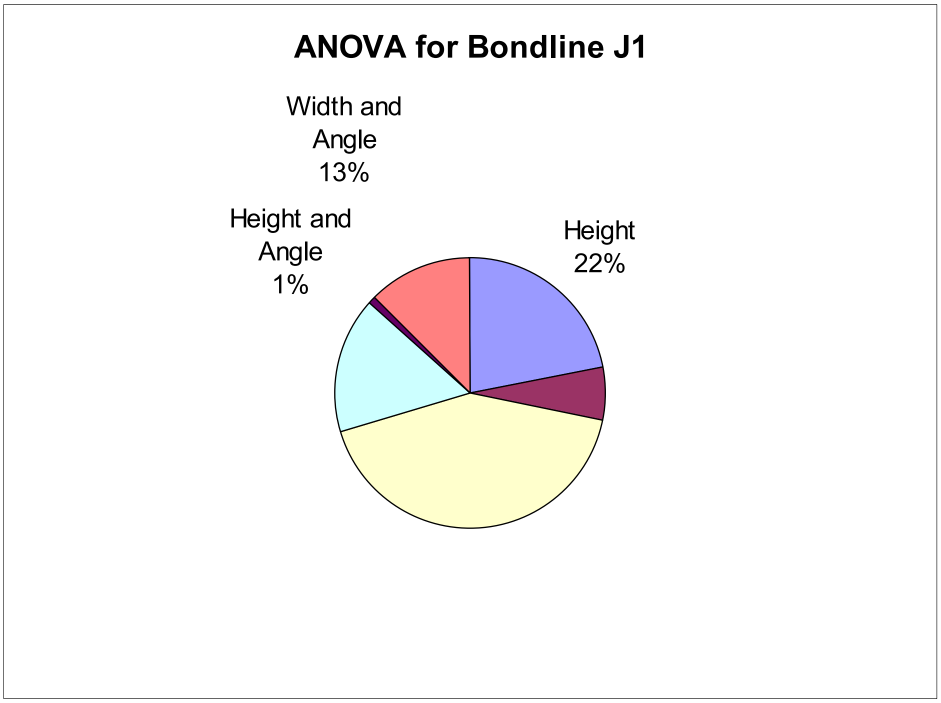



**Figure 13-28 Relative Influence of Each Parameter on Bond Line J1**

Within the limits of this study, bond line strains were most heavily influenced by the run out angle followed by the height of the stiffener. The width of the stiffener is of relatively minor importance. This study therefore suggests running out the stiffener at a relatively low angle in the range of 30 degrees or so.

Figure 13-29 plots the two strongest influencing parameters as a response surface. This figure strongly shows the influence of stiffener height and run out angle on bond line strains.

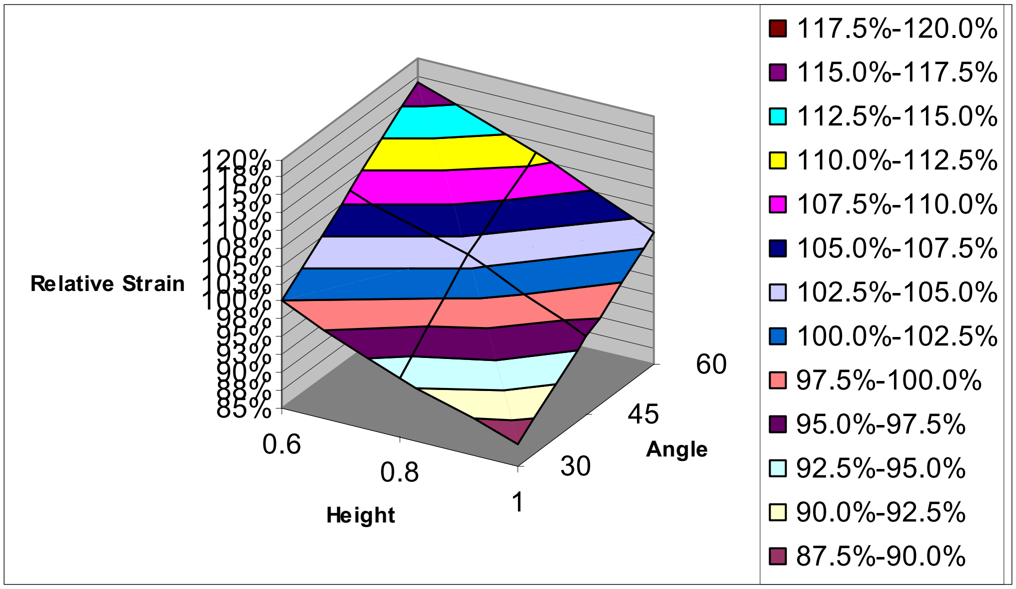



**Figure 13-29 Influence Stiffener Height and Run Out Angle on Bond Line J1**

What has not been considered in this study is the effect that the above parameters have on the buckling capability of the assembly. Very shallow run out angles will decrease the buckling capability. This study, like all others cannot be used as an ends. Other failure modes must also be considered. However the very strong influence of run out angle and stiffener height as they affect bond line strains must not be ignored and must be weighted very heavily on the determination of the final design configuration.

Stiffener Strains

The stiffener strains are probably of less importance from an assembly strength determination viewpoint than bond line strains. Stiffeners function to add buckling capability to the skin and are generally not highly stressed in most applications. They are not however unimportant. Inattention to any component in an assembly can render the assembly incapable of carrying design loads or of being highly sensitive to design imperfections. No assembly is stronger than its weakest member. The stiffener strains from the full factorial study are shown in Figure 13-30.

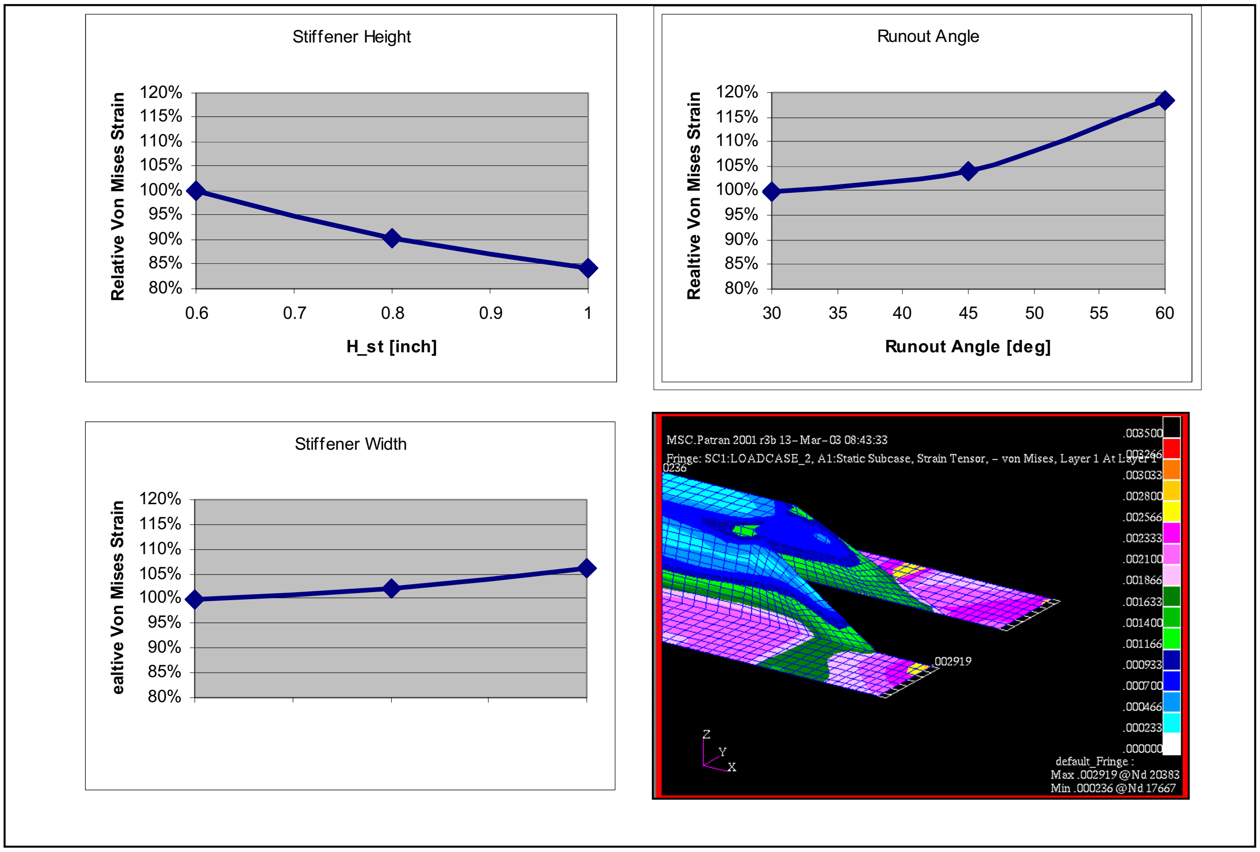



**Figure 13-30 Relative Stiffener Von Mises Strain**

These curves show the strains in the stiffener trending downward as the height of the stiffener and width are increased and as the run out angle is decreased. These are similar trends as those shown at the bond line. What parameters are the largest contributors to stiffener strains? Figure 13-31 shows the relative strengths of each parameter and the effect of parameter combining on the stiffener strains.

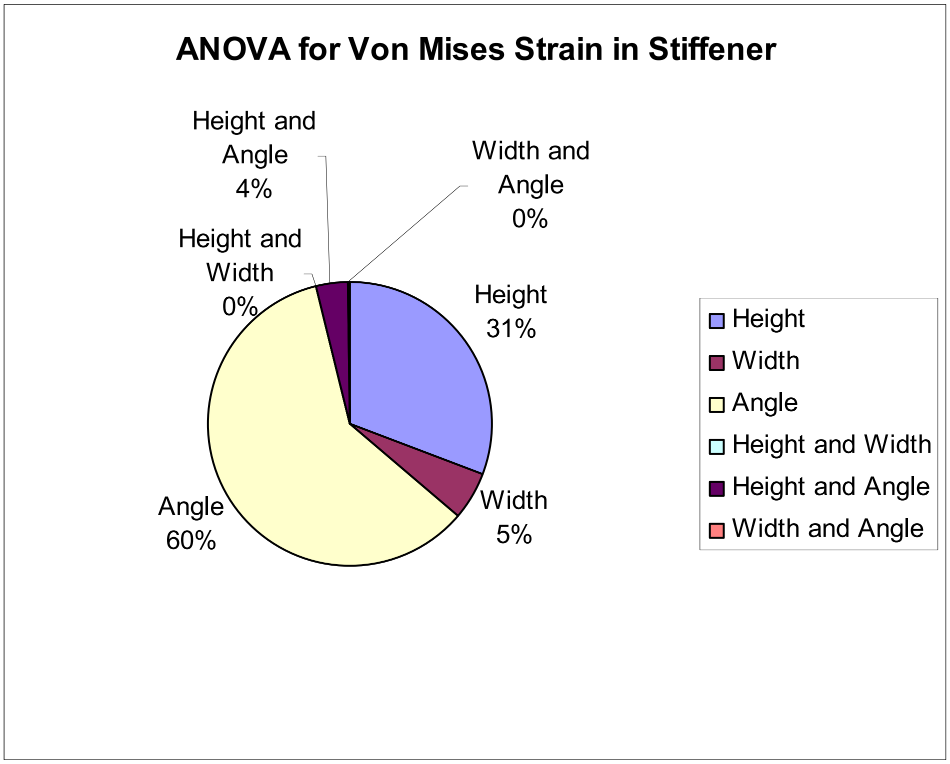



**Figure 13-31 Relative Influence of Each Parameter on Von Mises Strain in Stiffener**

Within the limits of this study, stiffener strains were most heavily influenced by the run out angle followed by the height of the stiffener. The width of the stiffener is of relatively minor importance. Again, as with the previous bond line study, this study therefore suggests running out the stiffener at a relatively low angle. Say in the range of 30 degrees or so.

Figure 13-32 plots the two strongest influencing parameters as a response surface: the influence of stiffener height and run out angle on the stiffener strains. Also shown in the figure is given a run out angle, one can see the effect of the stiffener height. For instance, one can see that for a 30 degree run out angle strain reduction is most pronounced as the stiffener height is increased from 0.60 inches to 0.80 inches. As the stiffener height increases from 0.80 to 1.0 inches the benefits are less pronounced. This strongly suggest a stiffener height of approximately 0.80 inches for a 30 degree run out is optimal.

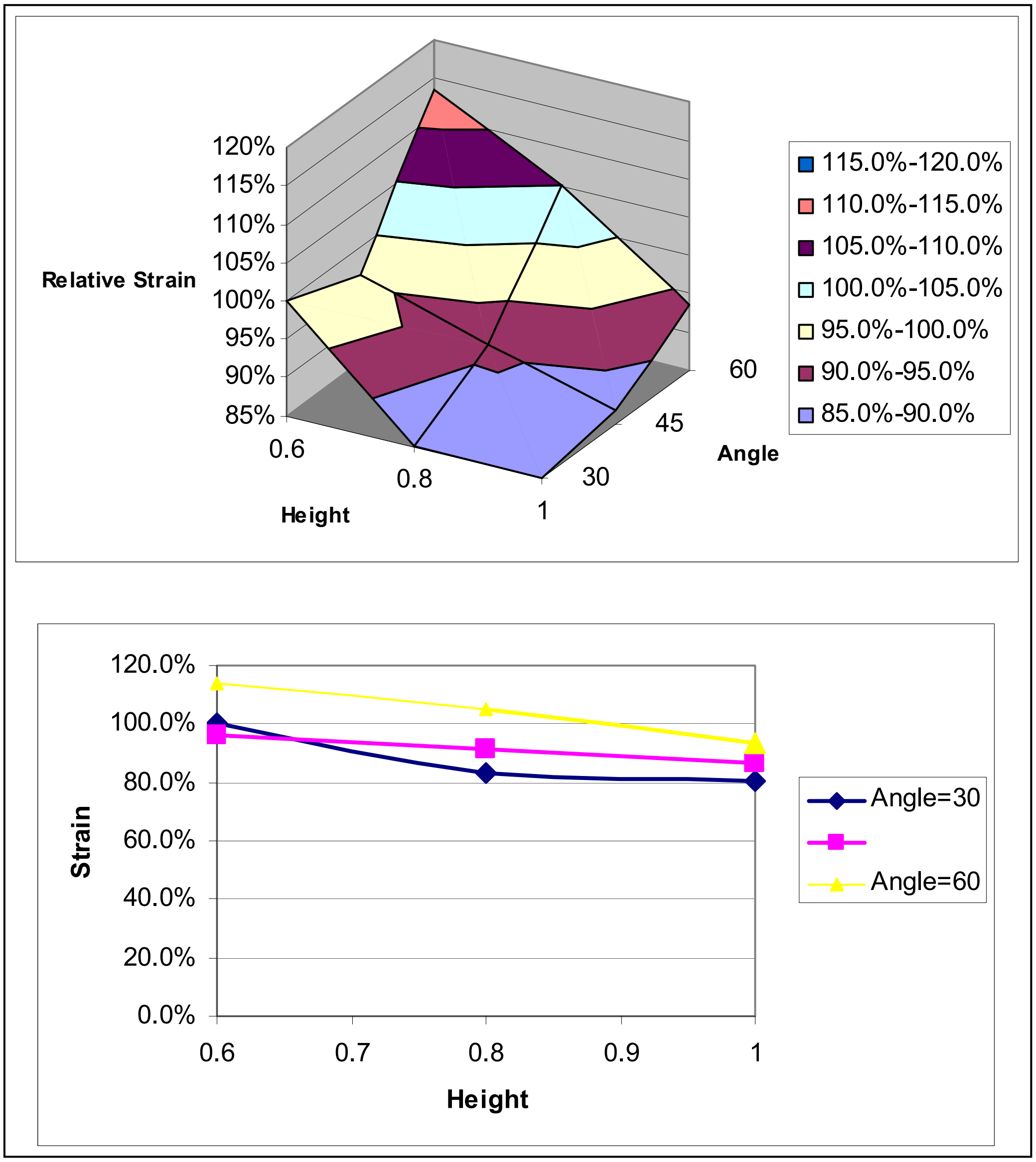



**Figure 13-32 Influence of Stiffener Height and Run Out Angle on Stiffener Strain**

Skin Strains

The strains in the skin near the frame interface and stiffener run out are of particular concern due to their relatively high level. All configurations show a marked increase in strain level at this location as loads are transferred from the stiffener into the skin and frame. Because the stiffener crown and webs terminate, a very high stiffness change results as one passes from the full height stiffener through the run out and eventually into the frame interface. This is an inherent problem in all configurations of this sort. The skin strains from the full factorial study are shown in Figure 13-33.

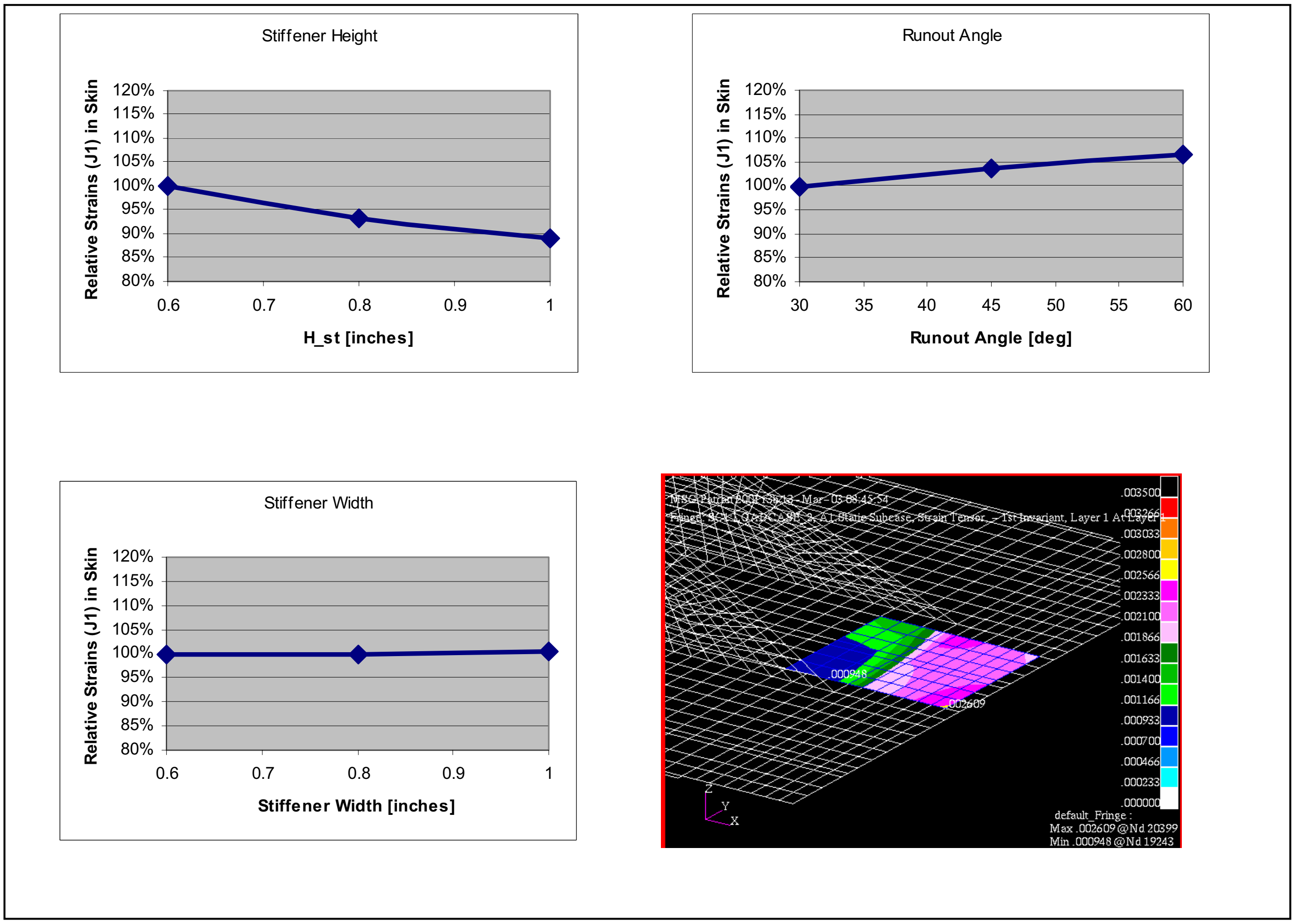



**Figure 13-33 Relative Skin Von Mises Strain**

These curves show the strains in the skin trending downward as the height of the stiffener is increased and as the run out angle is decreased. Stiffener width has little affect. These are similar trends as those shown at the bond line. What parameters are the largest contributors to skin? Figure 13-34 shows the relative strengths of each parameter and the effect of parameter combining on the skin strains. The plot shows the height of the stiffener is by far the most important parameter influencing the strains in the skin at the stiffener run out. Again, the reader is cautioned that the results are for a set of unchanged skin, stiffener, and wrap thicknesses, material, and stacking sequence groups. In no way does this study discount those very important parameters. This study simply shows the effect of stiffener geometric parameters for a fixed set of skin, stiffener, and wrap thickness, material and stacking sequence parameters and can be used to identify and quantify contributions from the parameters that were varied.

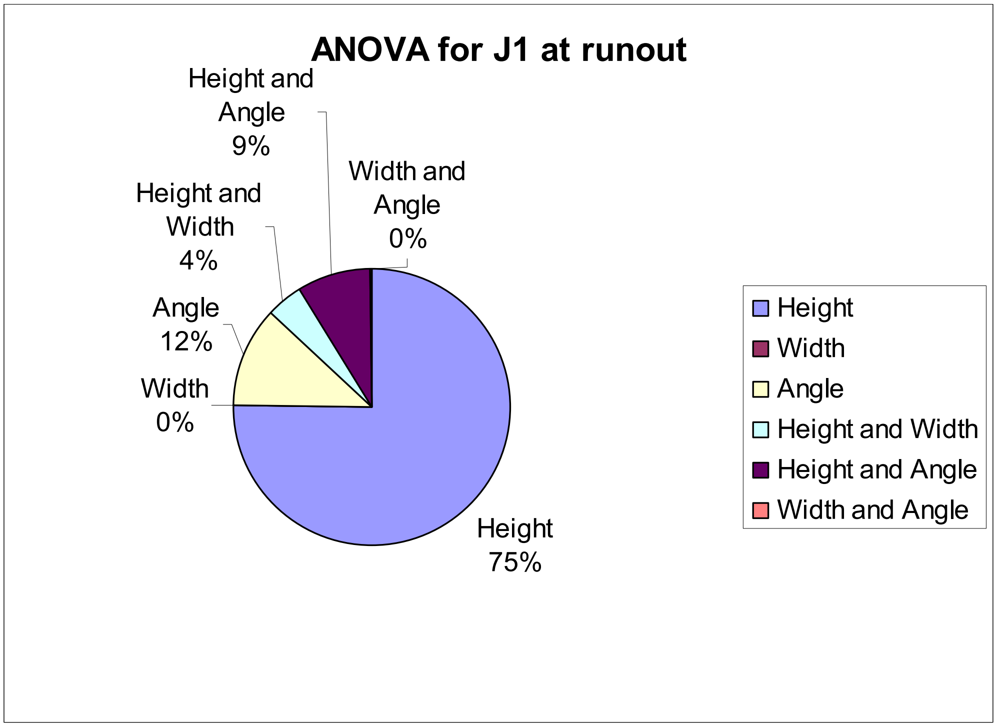



**Figure 13-34 Relative Influence of Each Parameter on J1 in Skin at Stiffener Run Out**

Within the limits of this study, skin strains were most heavily influenced by the height of the stiffener with taller stiffeners yielding lower skin strains. The width of the stiffener is of relatively minor importance.

Figure 13-35 plots the two strongest influencing parameters as a response surface. This figure strongly shows the influence of stiffener height and run out angle on the skin strains.

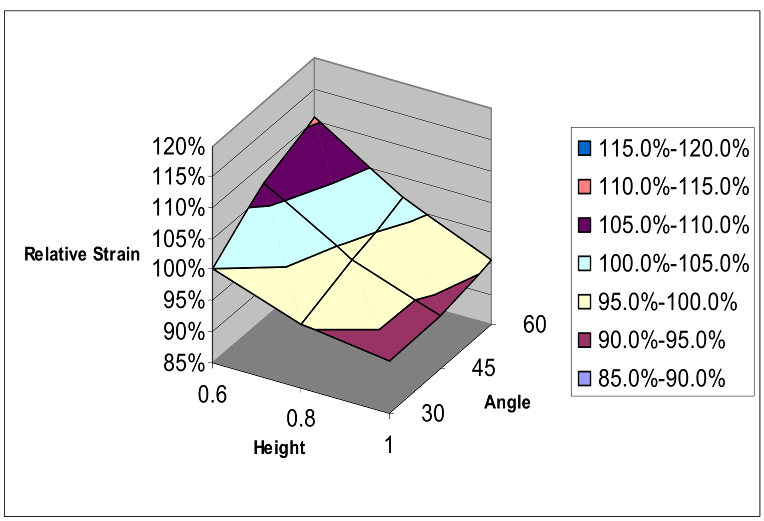



**Figure 13-35 Influence of Stiffener Height and Run Out Angle on Skin Strains**

The conclusions drawn from this study tended to strongly drive the design concept for the hat stiffened panel. The run out angle was set to 30 degrees which without exception will tend to lower the strains in all components. Buckling capability will be assessed in another study. Stiffener height was firmed up more as the result of this study. In addition it was determined the original design used a very appropriate hat height. The final design of the hat stiffened panel was set to 0.85 inches – only slightly higher than the previous design.

**Interaction with Manufacturing**

On going coordination with manufacturing allows important information to freely pass between manufacturing and the design group decreasing the possibility of unpleasant surprises upon drawing release.

**Selection of Tooling Approach**

At this point in the design process the final configuration is very close to being fully defined. A final tooling approach may now be determined. Due to the continuous interaction between the design group and manufacturing this decision has been ongoing and need only be formalized at this point.

**Local Model or Detailed FEM Studies**

As discussed earlier, there are regions of the shell finite element model that are inadequate for the determination of strength. This section details the use of solid fem submodels used to deal with this.

Figure 13-36 shows a solid finite element model (FEM) laid over the shell model. The detailed solid model must be built using the proper coordinates such that it interfaces exactly with the shell model. A two step solution process is used. The first step is the solution of the shell model. Step two takes the displacements from the shell model and applies them to the solid model at the shell model to shell model interface.

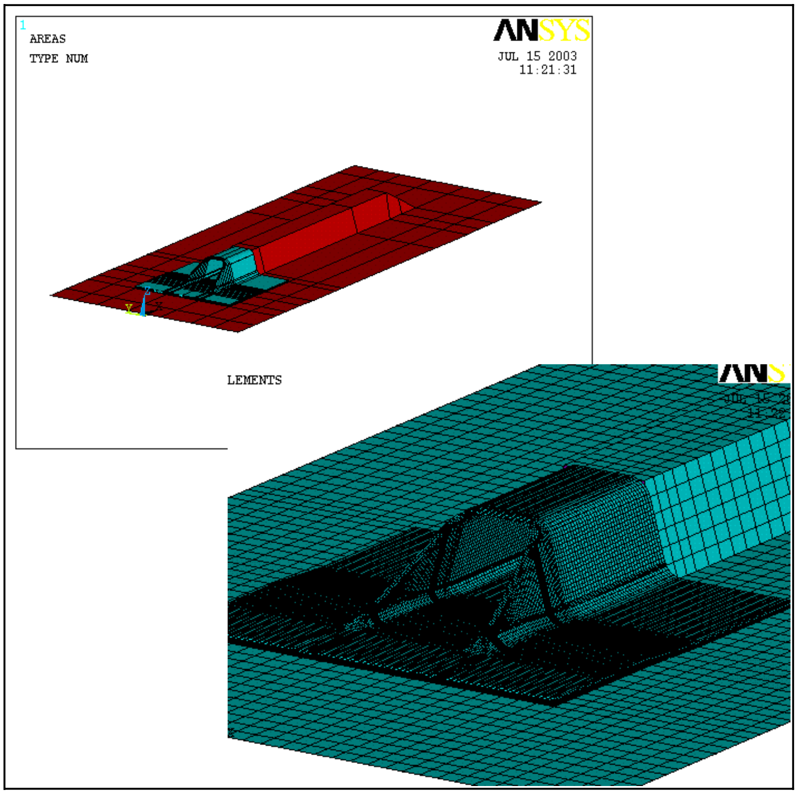



**Figure 13-36 Shell Model and Detailed Solid Submodel**

Why go to the effort of building the detailed solid model? Figure 13-37 shows in gray the regions of the solid model that exhibit strains that are higher than the shell model. They are, as expected, in regions where the stiffener intersects the skin. This region is not well modeled in the shell model but is in the solid model. This region also is the critical region in the assembly. It is therefore very important to perform some kind of submodeling to determine the actual state of strain in this critical region.

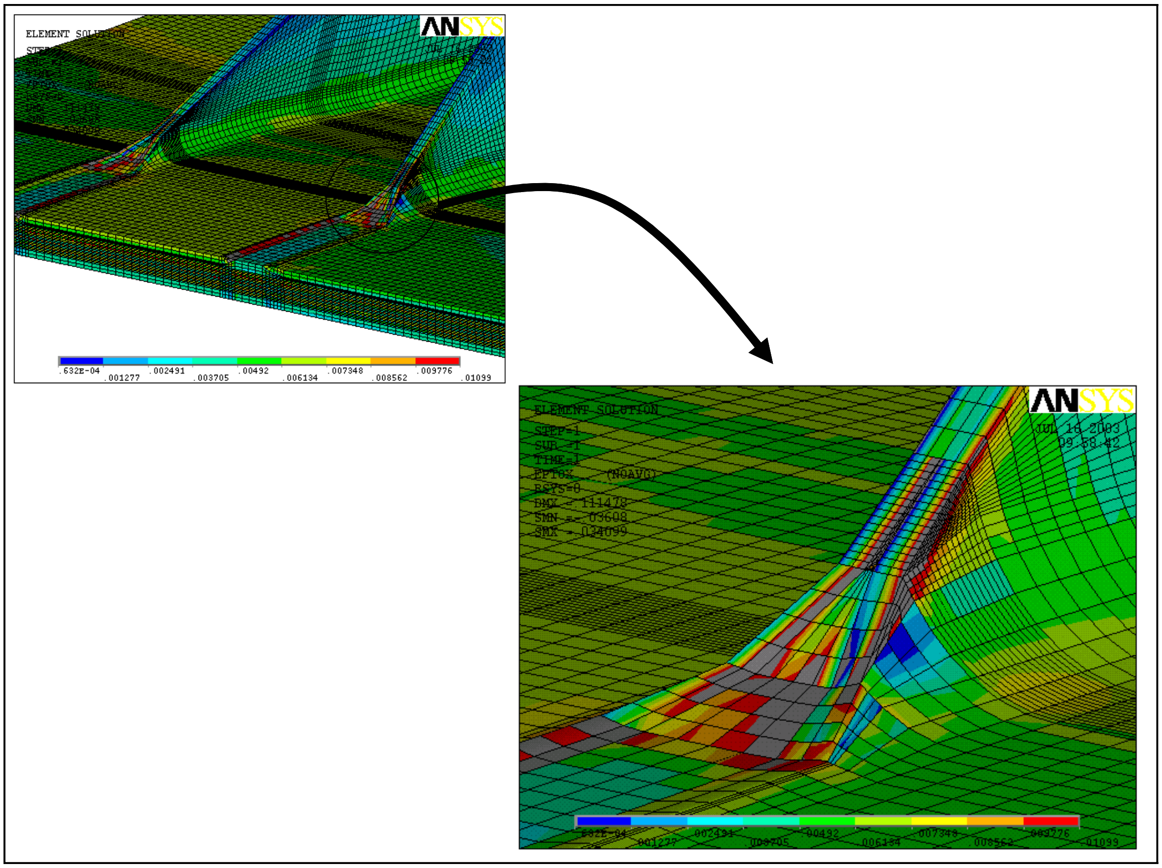



**Figure 13-37 Detailed FEM Regions shown in Gray are at a Higher Strain than what was Shown in the Shell Model.**

### Defect Sensitivity Studies

In a manner similar to the determination of various geometrical parameters on strength studies should be performed using fracture based methods on the effect of defects in various regions of the design. Many parallels may be drawn with the final objective to be insensitive or relatively insensitive to defects in order to have a robust design.

### Lessons Learned

There were a number of lessons learned encountered by the integrated technology/product team in the AIM-C Phase 1 hat stiffened panel demonstration/validation.

The AIM-C methodology and tools facilitated *integration* of the integrated technology/product team.  The team *did use* existing knowledge, analyses, and test to develop the successful design.  Processing and producibility assessment *were able* to keep pace with the product definition development and incorporate concerns or preferred approaches. The team repeatedly noted that this methodology/tools set greatly improved the upfront incorporation of these build improvements.

The methodology, including the IPT, multi-scale modeling, global/local solid modeling and the Strain Invariant Failure Theory *did result* in a superior design and good predictions in a projected 60% of the time of the baseline case.

Improving failure predictions on the design *early* in the development is very important. The team completed the Build-To-Package (BTP) in April. The BTP release initiates the build and test of the parts. The best available failure predictions were used. The failure predictions changed dramatically when updated analytical tools became available. In October, the predictions were coming in for tension initiation with 200% improvement over the April predictions,  tension final failure 100% improvement over the April predictions, and shear final failure 12% improvement over the April predictions. This was a significant improvement over the baseline and therefore good news. Unfortunately, the test specimens and test fixtures had been built to the BTP and therefore sized to validate much lower load level predictions. Despite significant efforts to reinforce the load introduction area of the specimens and fixtures, the off-axis testing failed in the load introduction fasteners. The improved failure predictions would have allowed the team to avoid these issues.

The team decided that it would be valuable to test the same geometry specimens in similar fixtures to those used in the baseline. This would ease and improve the correlation to baseline results. Not surprisingly, the baseline definition had insufficient margin for the 200% improvement in load-carrying capability realized in October. A lesson learned is to *greatly oversize specimens and load introduction structure* to accommodate a very large change in test requirements.

Take care when planning the *thickness of frame tie-in* with the specimen to allow for modifications if doublers are needed.

Be sure to use an adequately *large margin* (like roughly 2x and not just 20%) when performing test specimen and fixture sizing.

Intec has now developed a capability to use hydraulic grips for testing. This approach is proving to be a good alternative to fastening, as was done on the baseline.

The use of third party reviews is very helpful. Uninvolved experts can often help find issues that need to be addressed.

When determining specimen configuration for off-axis testing, *consider both the configuration of the specimen and the fixture*.  For example, a 10 deg off-axis test can have a fixture design to introduce the 10 deg off-axis or the specimen can be configured for 10 deg off-axis.

Methodologies and tools for *uncertainty management* are discussed in Section 9.  Use of these concepts and tools was very helpful in the development of a successful design and in drawing out issues from the multifunctional team.

## Conclusion

Remember that applying the tools is only part of the answer. The other part is giving adequate consideration to elimination of defects in critical regions and achieving design robustness. These considerations must be kept in mind during interpretation of results from all steps. Most important is to consider the limitations of each of the tools that are being used. For all designs where actual stress or strains are needed at any region at or near a stress concentration detailed solid finite element modeling is generally required. This process is generally time consuming and is purely a function of the software tool being used, the finite element modeler's approach and of course is subject to interpretation. The bottom line is that the exact determination of strains in anything but the simplest shape and loading condition is a difficult problem not handled well by all general purpose finite element codes.

# 14. Durability of Composites

Durability is the prediction of the time it takes for flaws to begin to initiate in nominal structure. Durability is primarily an economic issue affecting the inspection intervals, repair costs, and service life of a structure.

Explanation: For mechanical damage, Durability generally refers to the initiation of cracks/damage (or initial growth of damage from small undetectable flaws) in an as-manufactured structure. Also included in the definition of Durability is the initiation of irreversible material property degradation, which may result from long-term environmental exposure. The initiation of multiple small cracks (or small amounts of irreversible property degradation) is unlikely to be a safety concern until the damage progresses significantly; however, it is certainly an economic one. Once damage or degradation is detected, the structure must be repaired to restore Ultimate Load capability. Frequent and/or costly inspections may also be required to monitor the structure and assure that damage is found and repaired prior to compromising the safety of the aircraft. If such inspections and repairs prove technically or economically infeasible, the aircraft has reached the end of its service life.

To show the distinction between durability and damage tolerance, the definition of damage tolerance is provided as the prediction of damage growth (after initiation) and residual strength of structure with large cracks or other damage. Damage Tolerance is primarily a flight safety consideration – ensuring that the structure can continue to carry regulatory loads with damage or degradation due to any likely sources. Sources may include growing fatigue damage (already initiated), impacts, in-service discrete damage events (e.g., engine bursts), or any other likely source.

Note: Damage is typically localized to known locations, though interaction between multiple damage sites is possible. Regulatory load level generally depends on the level of detectability. For example, large discrete source damages are known about immediately, so usually come with a "get-home" load requirement, whereas threshold-of-visibility impact damage can't reliably be found by visual inspection, so it typically comes with an Ultimate Load requirement (unless you inspect for it with more sensitive NDI).

## 14.1 Durability Methodology in General

This durability methodology augments existing practices, where an experienced designer relies on experience and intuition. The methodology provides such a designer with relevant information and a suite of software tools. The tools are available through the Durability section of the AIM-C System. These tools give an increased quantitative capability to assist in making decisions regarding design options and testing. Furthermore, the Durability tools allow the designer to extract more relevant information from a given test program once it is completed. Overall, the Durability Methodology is comprised of four pieces: (1) a list of issues to prompt the designer on durability issues, (2) a convenient library of models and data that can be used to provide quantitative estimates of durability performance, (3) guidelines on test matrices, including the available models and methods for accelerated testing, and (4) guidelines on the interpretation of analysis and test data and its application to the target design. These four methodology components can be thought of as sequential steps in a durability program, that when taken together, will prevent many of the mistakes which can significantly hamper a materials insertion effort.

Background - The durability of composites is a broad and at times vexing topic, more so than for more homogeneous materials such as metal alloys or polymers. In contrast to these materials where typically only one or at most two mechanisms are relevant at any one time, for composites it is possible for multiple mechanisms and their interactions to affect the economic lifetime of a part. Usually only one or two load/environmental cases are really critical. The trick is to identify these critical cases at an early stage and to ensure that adequate testing is performed to ensure that there are no "surprises" awaiting the design team at a later stage in the design process. Although there are opportunities to perform accelerated testing, some level of real-time testing is always likely to be required. Given that this testing is of a long duration and therefore high cost and long lead-time, it is critical that the most relevant tests are specified at an early stage in the program and that unnecessary tests are avoided. The current procedure for accounting for durability in the design process is to entrust it to experienced designers/program managers who call on their experience and intuition to identify the most likely durability issues and to specify test programs to probe them.

The durability of composites has received considerable attention over the past 20 years and a significant number of useful models have been developed for key processes associated with durability. Examples include moisture diffusion, thermal diffusion, chemical and physical aging, creep, fatigue delamination and off-axis ply crack growth and property (usually stiffness) reduction due to damage and degradation. These models tend to have predictive capabilities that capture trends successfully, but are not capable of achieving highly accurate predictions. Furthermore, there is a general lack of models for the interaction between damage/degradation mechanisms (creation of fast moisture diffusion paths due to cracking, combined off-axis ply cracking and delamination, effects of hygrothermo-mechanical cycling). These deficiencies in the modeling capability lead to the conclusion that it is probably not worthwhile aiming for a fully integrated modeling framework. The concatenation of modeling errors once several models are combined would be likely to mask even gross trends in behavior. Furthermore, the likelihood of un-modeled interactions between damage/degradation modes within an integrated "black box" model could provide a user with a false sense of confidence, which would result in durability surprises of the type that we are aiming to avoid. Given these considerations, the most promising approach is one in which the AIM-C Durability tools augment the existing practice of an experienced designer relying on experience and intuition. The intention is to provide such a designer with an increased quantitative capability to assist him or her in making decisions regarding design choices and the associated testing.

Furthermore, the tools allow the designer to extract more relevant information from the test program once it is completed.

Approach - In order to meet these goals a fourfold approach is proposed: (1) Provision of a check list of questions to prompt the designer on durability issues, (2) A library of available models and data that can be used to provide quantitative estimates of durability performance, (3) Guidelines on the development of test matrices including the available models/methods for accelerated testing, and (4) Guidelines for the interpretation of test data and its application to the target design. These four components of the durability methodology could be thought of as four steps in a process.

**A checklist:** This would augment the designer's experience base and intuition regarding the likely durability limiting factors. It could be as simple as a list of questions: "have you thought about…" to a more structured decision tree directly linked into the models in step 2. Questions might be divided into several basic categories, such as "material", "geometry", "loads and environments" and then subdivided so as to identify the key features within each and then their interactions. The output of this step would be to identify possible issues whose severity could then be quantified by application of the models in step 2.

The ultimate intention of this component of the methodology is to provide a series of questions or "prompts" to a designer/durability assessor to guide her towards the appropriate literature, models and test methods (catalogued in the following sections). This information would be contained within a database, which would allow the linking of durability factors and an assessment of the durability issues and the potential means to address them. A diagram outlining the intended information flow capability is shown in Figure 14-1.

The embodiment of this check list would be either a stand alone searchable data base or a web-based linked hypertext tool. This tool will not be developed under Phase 1 of AIM-C. The appendix to this section serves as a living document cataloguing the elements contained in each of the components of the tool.

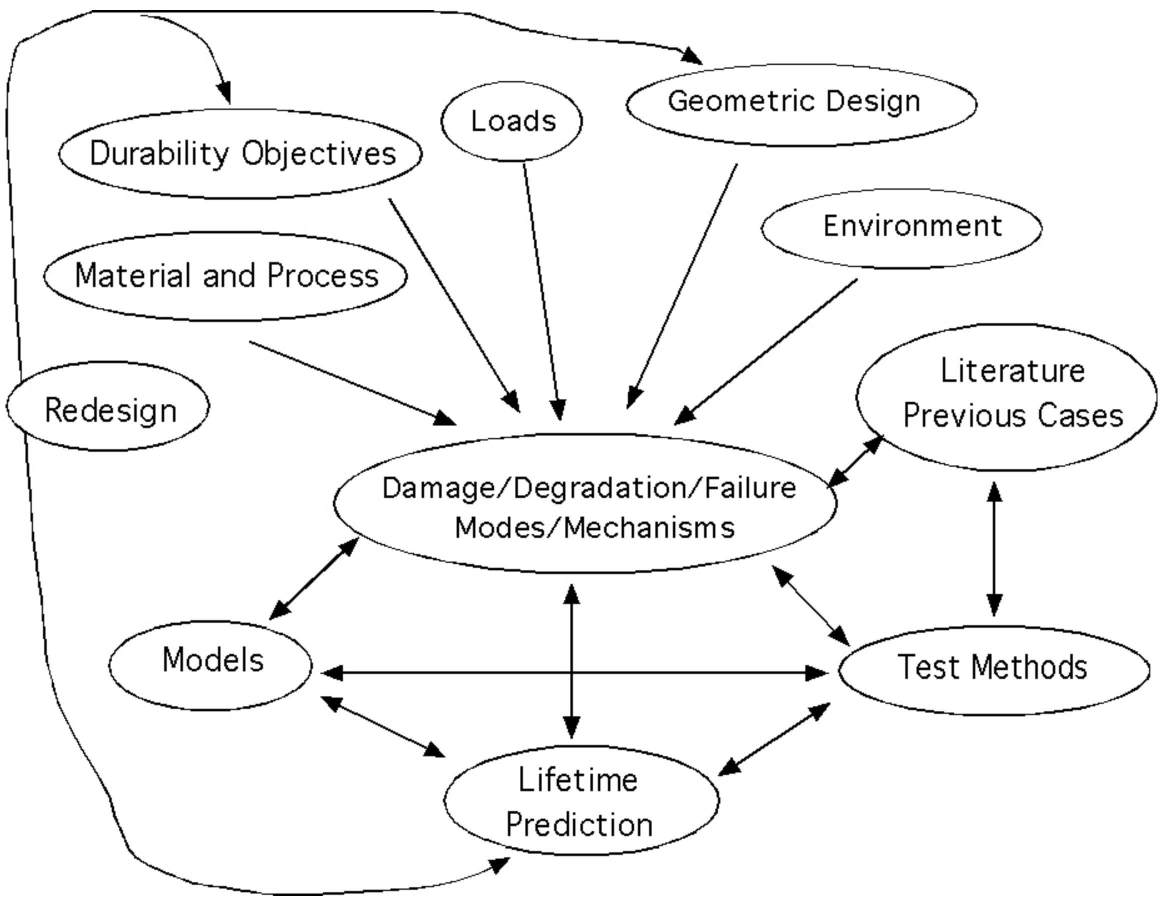



**Figure 14-1. Information flow chart for the durability methodology**

**A library of models and data:** Once the candidate durability issues have been evaluated in step 1 (or possibly in parallel with step 1), the designer would call on existing models and test data from previous programs to evaluate the likely severity of these conditions. Models that are envisioned to be used here include those physically-based models for moisture and thermal diffusion and their effect on hygrothermal stresses, fatigue crack growth models for delaminations and adhesive joints, models for physical and chemical aging, models for intralaminar cracking, models for stiffness reduction due to damage and degradation. In cases where only the raw test data is available, purely empirical models would be offered to fit the data. These models (empirical and physically-based) would allow the designer to evaluate whether there was likely to be a durability concern given the material choices, geometric design, loading and environmental conditions and the desired economic lifetime, and what the critical conditions and locations might be. This knowledge could then either be applied directly to redesign or to allow the comparison of design choices, or towards specifying the test matrix.

This will be cross-referenced from the remainder of the AIM-C durability module. Currently this consists of the following elements:

Super MicMac
Durasoft
ISAAC
HSR tools
Delamination Fatigue - supplement to Structures fracture methods

Additional models can be added as they become available, subject to validation and integration requirements.

The models should be exercised so as to identify the likely responses of the candidate design to the anticipated load and environmental factors. Key conditions or combinations of conditions that are likely to exceed or come closest to compromising the durability design objectives should be identified together with the corresponding failure modes. Factors that are predicted to have little or no affect should also be identified, so that they can be eliminated from the test matrix, or from the loading/environmental testing when spectrum loading is applied. Examples include geometric details that add manufacturing complexity but do not affect durability, low load cycles, components of hot/cold - dry/wet cycles that do not affect damage/degradation.

**Guidelines for specifying a test matrix:** Once steps 1) and 2) have identified the most likely key durability issues, the test matrix should be specified to probe these issues. In particular it should be targeted towards "known unknowns" i.e. conditions which are suspected of possibly determining the overall durability, but which have not been encountered in previous test programs. The model library and previous test data should be available to help guide the form of the test matrix, and in particular to identify possible accelerated test methods and to identify potential interactions between damage/degradation modes that would need to be captured by the testing. It is anticipated that the majority of the tests will consist of generic tests on generic geometries and loading conditions that capture the key features of the actual design under consideration.

The intentions behind the test matrix are twofold. Firstly, the test matrix should be guided by and be complementary to the modeling effort outlined in (2) above. The most severe loading cases predicted by the models should be applied to assess the validity of the prediction by the model and that the designed structure will indeed meet the durability design objectives. The second objective is to provide assurance against cases where there are gaps in the modeling capability, or previous experience that a particular loading or environmental factor has been problematic. Where possible accelerated testing will be used on simplified, but representative geometries. These simplifications and accelerations should be guided by the modeling in (2) above. Assuming that the test results are in reasonable agreement with the model predictions, it can generally be assumed that the remaining predictions by the models are also sufficiently accurate for design purposes.

It is anticipated that for large, primary structure a full scale fatigue test article will also be manufactured and tested and the testing of this can be guided by the modeling effort and the results fed back into the model validation.

The following test methods are currently available and documented within AIM-C. Other test methods will be added in due course.

Time-Temperature superposition
Delamination fatigue
Matrix/adhesive fracture with environmental factors
HSR accelerated test methods

**Interpretation of test data:** Once the testing is underway, it is important that maximum use be made of the data obtained. This is both for the particular design under consideration and also so that the data obtained can be applied to future designs, so as to expand the library of models and data in step 2. For the immediate purposes of the design under consideration, key tasks in this step include: verifying the mechanisms assumed in steps 2 and 3, tuning/calibrating the models used so that they can be applied to the actual design, developing local (ad hoc) models to capture interactions between mechanisms, and application of the models/data to the actual design. For the longer term, these results must be fed back into the modeling/data library so that they are available for future designs.

Again, it is very important that maximum use be made of the test results generated in (3) above. Durability testing is time consuming and expensive, and so it is imperative that the greatest possible benefit be derived from such tests. In addition to the macroscopic predictions of mechanical response, e.g. cycles to failure, stiffness reduction with cycles and residual strength after cycling, it is very important that the predicted damage and degradation modes be verified wherever possible. All of the models recommended in (2) base their predictions of durability response on knowledge of physical mechanisms. As shown in Figure 14-1 this is at the core of the durability methodology. In cases where a model successfully predicts the macroscopic mechanical response, it is also important that it is verified that the underlying damage/degradation processes and their extent are also correctly predicted. If this prediction is not correct, then it is likely that the model cannot be successfully transferred to other cases. Equally, in cases where a poor prediction of the test data is achieved, identification of the underlying damage modes can provide important information that can be used to refine the models.

Methods for observing damage/degradation can be divided into two parts:

1. In situ observations during tests. This necessitates the use of non-destructive methods. The following methods may be considered: Infra red or acoustic imaging, application of acoustic emission sensors, use of local strain gauges to measure local stiffness reduction, use of Lamb-wave sensors to triangulate damage, monitoring of overall frequency response, use of replicate techniques

where free edges are available, use of stress-sensitive paints or white coatings to help reveal the presence of cracks.

2. Post-mortem tests. Once the desired number of cycles has been applied, or failure has occurred, then more intrusive observational techniques can be applied. These include: C-Scan, X-ray inspection with penetrants, cross-sectioning and polishing and microscopy. Local micro or nano-indentation may be used to detect degradation. From large test articles, specimens may be cut out to perform local mechanical tests to assess local residual strength. Specimens can be excised for chemical analysis (SIMS, Auger, FTIR) or thermal/mechanical analysis (DMTA, DSC, TGA).

Information resulting from these observations include: presence of intraply cracks, delaminations, fiber microbuckles, tensile fracture of fibers, local chemical degradation, changes in glass transition temperature, moisture content, changes in matrix hardness, changes in other local mechanical, physical or chemical properties.

In all cases the key point is that the understanding of the failure modes be captured. Where models exist, this data can be fed back into them to improve the validation. Where models do not exist, an understanding of the relevant damage/degradation modes can be highly instrumental in allowing for the development of modeling capabilities.

Links to the rest of the AIM-C System - The durability tools and their accompanying methodology are linked to the rest of the AIM-C System. In particular, the links to the structures' module are important for the transfer of the global structural geometry, loads and environment. In addition, at a more local level, point stresses, geometrical details, and material/lay-up details will be needed by both. In addition, durability damage/degradation criteria may make direct use of analytical tools from within the structures module. These include the use of the structures' fracture mechanics methods to calculate strain energy release rates, which can then be applied to moisture/temperature modified critical strain energy release rates or to calculate fatigue crack growth rates. Similarly, the use of stress-based methods, such as SIFT, can be expanded to include effects of damage/degradation. Also, the effect of damage/degradation on local stiffness can be propagated through the structures module analysis tools in order to assess the critical levels of damage/degradation.

In addition, there will be interaction with the producibility module, particularly with regard to durability issues associated with processing-induced stresses and also the effects of defects.

Specifics - In the preceding sections, models have been reviewed that might allow progression and iteration within the design process. Models do exist, at the scales below that of the laminate (coupon), that have some utility for predicting fatigue damage propagation. Success has been achieved for individual damage modes such as bridged matrix cracking in MMC's and CMC's and off-axis ply cracking and delamination in PMC's. However, as yet these models are not sufficient to allow prediction, *a priori*, of the fatigue response at higher structural levels that are likely to be of interest in design or maintenance applications. Even an ostensibly simple case such as the growth of damage at a notch and its effect on residual strength has only been modeled with limited success in a handful of material systems and test conditions. In particular, relatively little attention has been devoted to modeling the interactions between damage modes which typically govern the response at this level. This is chiefly because such damage is truly three-dimensional and it is often not considered worthwhile to construct a three-dimensional model, with the belief that it could evolve in parallel with the current empirical approach to fatigue in composites.

Concluding Remarks – The AIM-C durability methodology advocates the development of mechanism-based models for characterizing durability of composite structures. Many of the models currently available for individual damage mechanisms are based on fatigue crack growth relationships that can be experimentally calibrated and used to predict damage growth rates, as a function of microstructural, geometric and loading parameters. There has been less success in predicting the growth of multiple interacting damage modes that typically govern the durability at the structural level, although some models do exist, and similar modeling approaches might be applied to other materials and structural configurations. The foreseeable capability of such modeling is unlikely to be able to fully support detailed structural design, however an intelligent application of the approach may reduce the reliance on test programs to an extent that could improve the overall cost effectiveness of the design process.

## 14.2 AIM-C Durability Methodology Applied to Hat-Stiffened Panel Demonstration Case

The four steps of the AIM-C durability methodology are applied to the hat-stiffened panel demonstration problem below. The listings under each step are included as examples but are not necessarily definitive design guidelines.

1. Checklist of durability issues
   - What are the locations where mechanically induced (*i.e.* fatigue) damage is most likely to initiate?
     - Free edges
     - Plank/skin interface
     - Skin/hat interface (including adhesive)
     - Noodle
     - Fasteners
   - What are acceptable levels of damage at these locations?
     - None
     - Microcracking initiation
     - Microcracking initiation that creates a delamination, but no delamination propagation
     - Microcracking initiation that creates a delamination with subcritical delamination propagation

- What are the effects of temperature and moisture on the development of damage at these locations?
  - Accelerated or delayed microcrack initiation
  - Accelerated or delayed delamination propagation
- How does damage affect structural behavior?
  - Decreased stiffness
  - Failure
- How do temperature, moisture, and aging affect structural behavior (assuming no damage)?
  - Accelerate decrease in stiffness and onset of failure

2. Library of models and data
   - Data
     - Properties as a function of temperature and moisture
     - Fatigue behavior of structural details at various temperature and moisture levels
     - Aging behavior
   - Models
     - SIFT durability
     - Moisture diffusion
     - Microcracking in off-axis plies
     - Fatigue crack initiation and propagation
     - Physical or chemical aging
     - Stiffness reduction from damage and degradation
   - Analysis methodology for skin/hat interface
     - Choose acceptable level of damage to determine cumulative fatigue life
     - Determine cycles to microcracking initiation
       - Calculated maximum principal transverse tensile stress compared with transverse tension fatigue life (Minguet and O'Brien)
     - Determine cycles to delamination onset
       - Compare strain energy release rate with threshold fatigue data
     - Predict delamination propagation and examine effect on structural behavior
       - Use crack growth law and determine structural stiffness based on propagated crack
     - Examine effect of temperature and moisture on damage development
       - Use modified crack growth law based on environmental conditions

3. Guidelines for specifying a test matrix
   - General tests
     - Stringer flange/skin tests
     - Material characterization at various temperature and moisture conditions
   - Model Calibration Tests
     - Fatigue crack growth of delaminations
     - Transverse tensile fatigue testing
   - Accelerated Testing
     - Viscoelastic resin tests

- Validation Tests
    - Hat stiffened panel fatigue test

4. Interpretation of test data
    - Verify assumed mechanisms/behavior
        - Crack initiation locations and propagation behavior
    - Tuning/calibrating models
        - Crack growth laws
        - Modified crack growth laws for environmental conditions
    - Develop local models to capture interactions between mechanisms
        - Interaction of damage at several locations

## 14.3 AIM-C Durability Methodology Example

The problem statement is: "I have a new application that takes an existing "AIM" material into a different environment. How does one generate a carpet plot that takes into account all the durability issues of interest for a particular application? In other words, the structures carpet plot is for a RTD, pristine material. How would that carpet plot change after exposure to environments including temperature, cyclic loading, moisture, etc? See Figure 14-2.

- Methodology for the determination of carpet plots that include durability effects
- Four step durability methodology would be implemented in the AIM-C system
    - Checklist of questions/issues
    - Library of models and data
    - Guidelines for specifying a test matrix (including accelerated testing)
    - Interpretation of analysis and test data
- Methodology is generic such that it can be applied to fracture results, etc.
    - Same process would be used, but different input data and models required
- Multiple "tools" available. The one used depends on the answers to the questions along the way

**Figure 14-2. AIM-C Durability Methodology Example**

Figure 14-3 shows the AIM-C Main Menu/Home. There are a few different ways to reach the durability page from this location. The most obvious way is to select the word durability and/or the picture of the open-hole test coupons. Another way to reach the durability page is through the analysis template pull down menu as shown in Figure 14-4. A third way is through the process guidelines pull down menu.

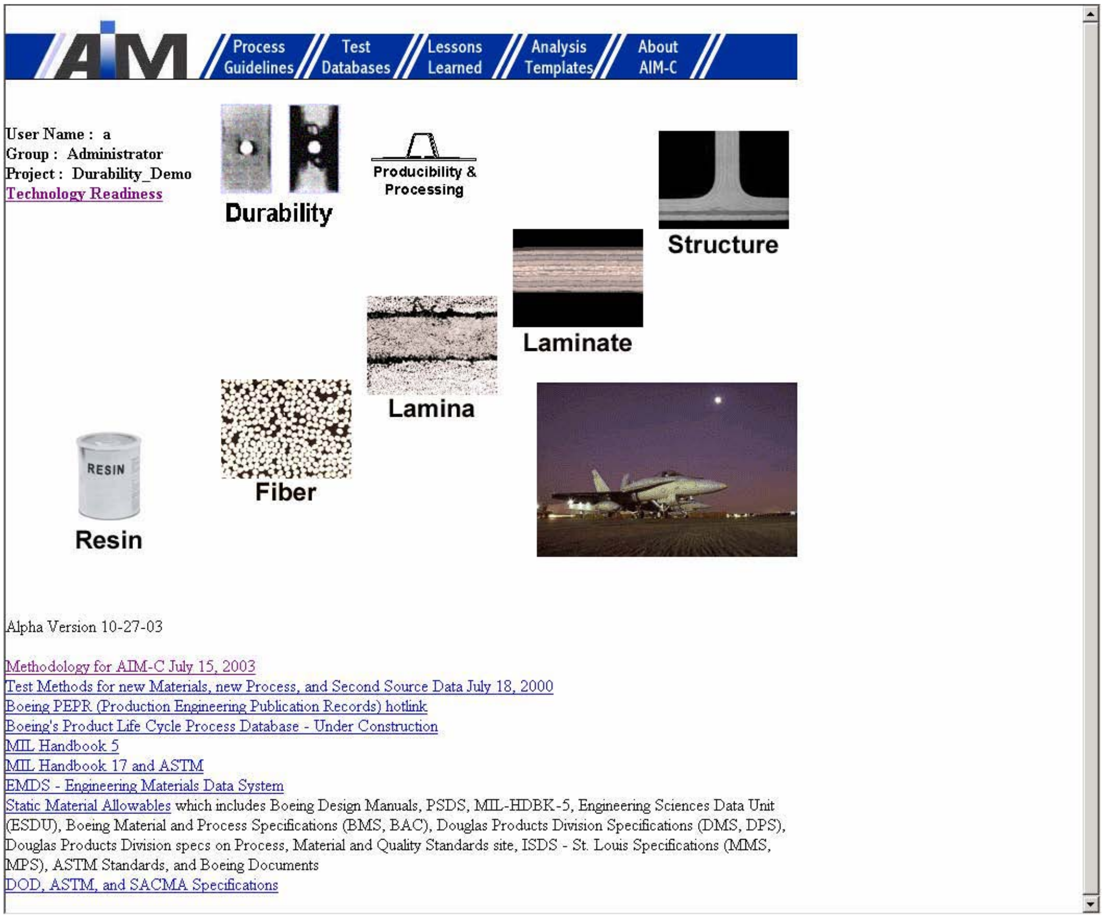



**Figure 14-3. The AIM-C System Home Page**

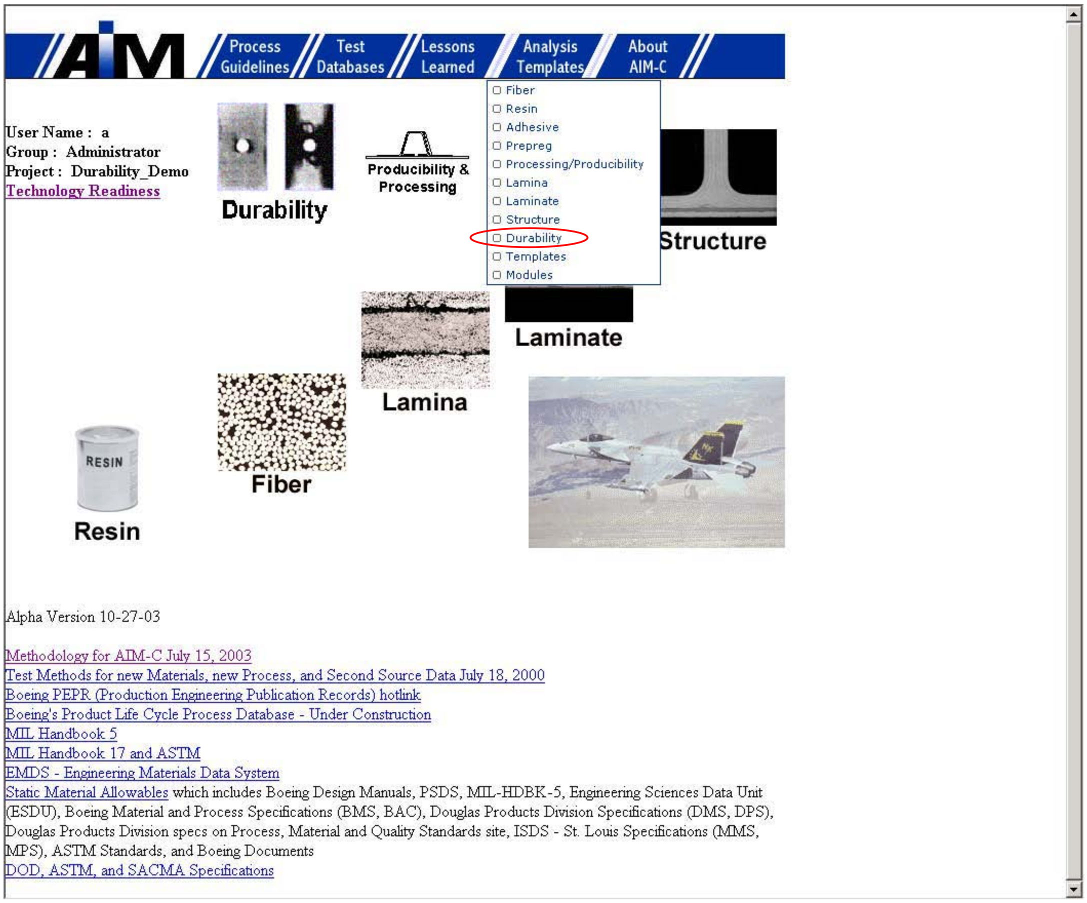
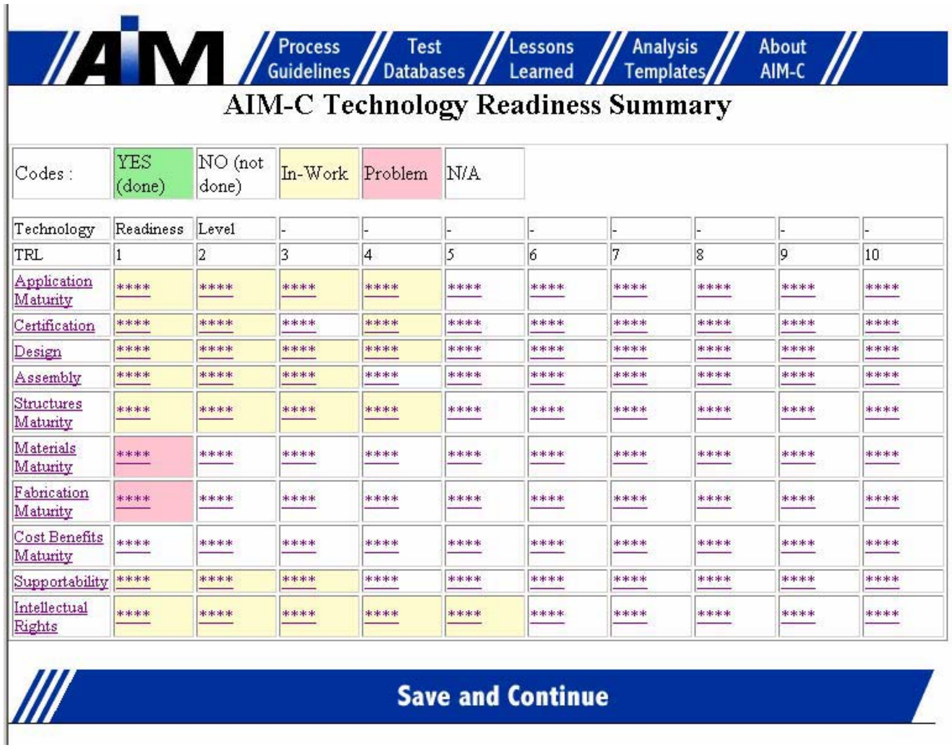



**Figure 14-4. The AIM-C System Analysis Template Menu**

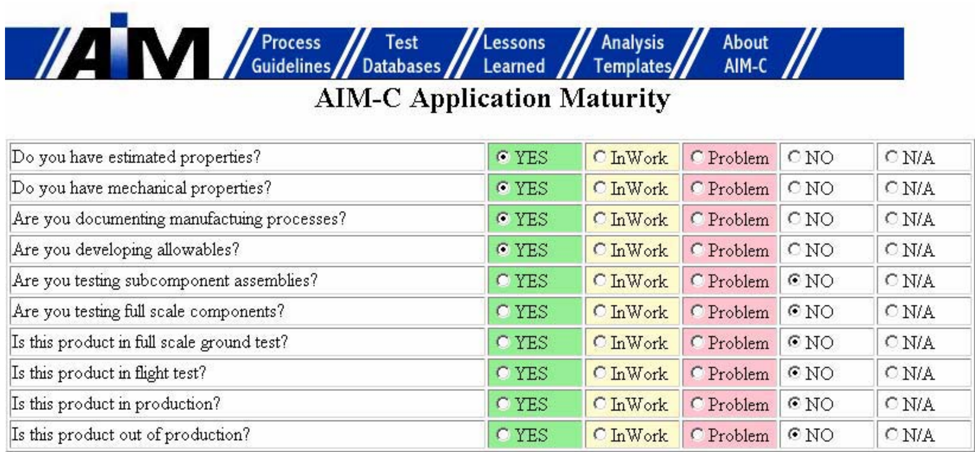
The overall AIM-C methodology follows a process that begins at the technology readiness level (TRL) and proceeds to the XRL and down to the worksheet level. This path is illustrated by this example problem. Figure 14-5 shows the top-level technology readiness level of the system software. The next level down can be reached by selecting any of the items in the first column of the TRL chart. If the user selects application maturity, he is taken to the menu shown in Figure 14-6. Similar menus exist for each of the remaining items in this column, such as structures maturity, materials maturity, etc. As the user progresses further down into the system, specific answers to questions related to the application would indicate what types of durability issues might be of interest. For example, the application requirements might specify the upper and lower use temperatures, etc. The answers to these questions should prompt the user to go to the durability assessment page.




| Codes : | YES (done) | NO (not done) | In-Work | Problem | N/A |
|---|---|---|---|---|---|

| Technology | Readiness | Level | - | - | - | - | - | - | - | - |
|---|---|---|---|---|---|---|---|---|---|---|
| TRL | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Application Maturity | **** | **** | **** | **** | **** | **** | **** | **** | **** | **** |
| Certification | **** | **** | **** | **** | **** | **** | **** | **** | **** | **** |
| Design | **** | **** | **** | **** | **** | **** | **** | **** | **** | **** |
| Assembly | **** | **** | **** | **** | **** | **** | **** | **** | **** | **** |
| Structures Maturity | **** | **** | **** | **** | **** | **** | **** | **** | **** | **** |
| Materials Maturity | **** | **** | **** | **** | **** | **** | **** | **** | **** | **** |
| Fabrication Maturity | **** | **** | **** | **** | **** | **** | **** | **** | **** | **** |
| Cost Benefits Maturity | **** | **** | **** | **** | **** | **** | **** | **** | **** | **** |
| Supportability | **** | **** | **** | **** | **** | **** | **** | **** | **** | **** |
| Intellectual Rights | **** | **** | **** | **** | **** | **** | **** | **** | **** | **** |

**Figure 14-5. AIM-C Technology Readiness Summary Page**




| | | | | | |
|---|---|---|---|---|---|
| Do you have estimated properties? | YES | InWork | Problem | NO | N/A |
| Do you have mechanical properties? | YES | InWork | Problem | NO | N/A |
| Are you documenting manufactuing processes? | YES | InWork | Problem | NO | N/A |
| Are you developing allowables? | YES | InWork | Problem | NO | N/A |
| Are you testing subcomponent assemblies? | YES | InWork | Problem | NO | N/A |
| Are you testing full scale components? | YES | InWork | Problem | NO | N/A |
| Is this product in full scale ground test? | YES | InWork | Problem | NO | N/A |
| Is this product in flight test? | YES | InWork | Problem | NO | N/A |
| Is this product in production? | YES | InWork | Problem | NO | N/A |
| Is this product out of production? | YES | InWork | Problem | NO | N/A |

**Figure 14-6. The AIM-C System Application Maturity Page**

Figure 14-7 shows the durability home page, aligned with the four-step durability methodology process. Also on this page is a direct link to the Durability xRL conformance planning check sheet and a link to an example showing the durability methodology applied to the hat stiffened panel design problem. Each of the items on the durability home page allow further interrogation, as will be demonstrated by the current carpet plot example.

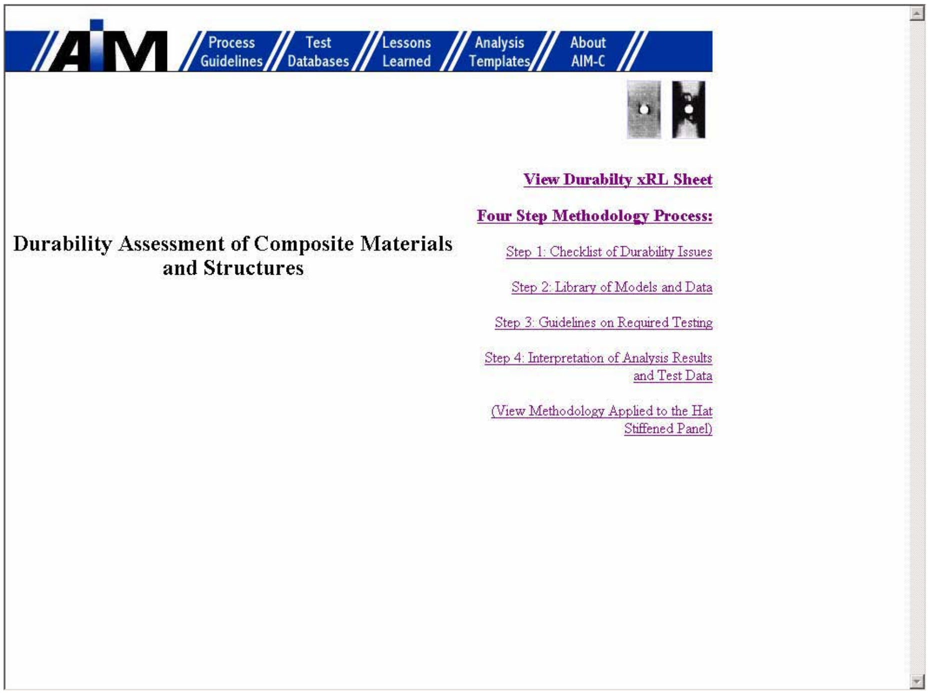
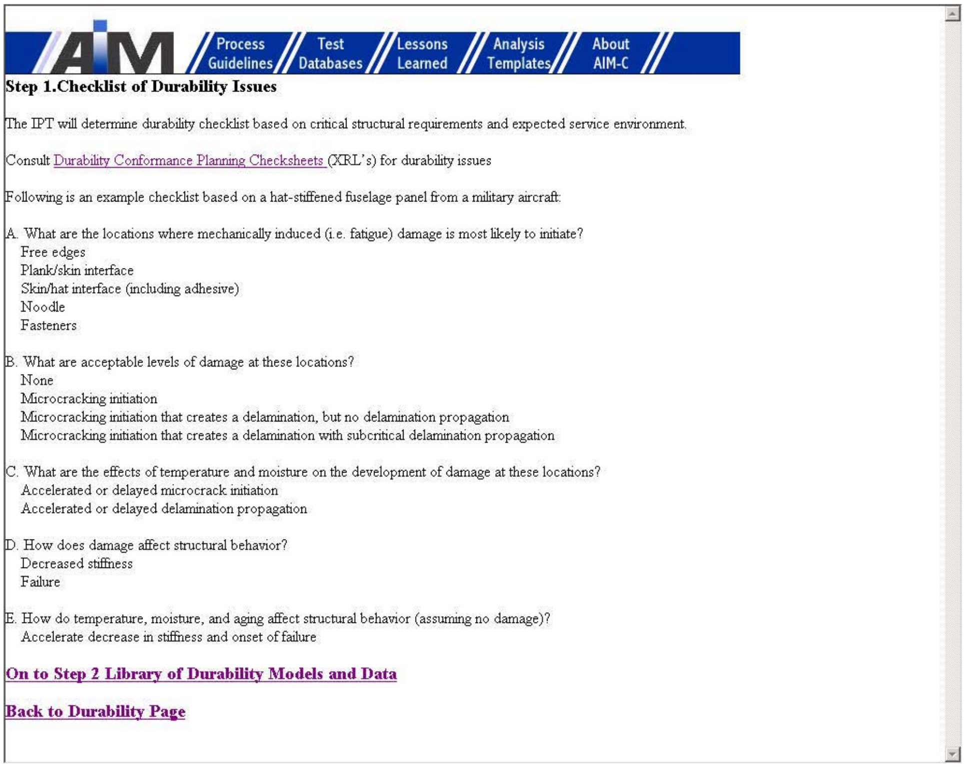



**Figure 14-7. The AIM-C System Durability Assessment "Home Page"**

Figure 14-8 illustrates step 1 of the durability methodology – the checklist of issues. After the durability issues are identified, the user proceeds to step 2 of the methodology via the link at the bottom of the page (see Figure 14-8). The page for step 2 is shown in Figure 14-9. This provides a list and description of all the durability analysis tools available in the system. For this carpet plot example, the user selects the link to the Super Mic-Mac spreadsheets and manuals. Selecting this link brings the user to the page shown in Figure 14-10.



AIM Process Guidelines Test Databases Lessons Learned Analysis Templates About AIM-C

**Step 1.Checklist of Durability Issues**

The IPT will determine durability checklist based on critical structural requirements and expected service environment.

Consult Durability Conformance Planning Checksheets (XRL's) for durability issues

Following is an example checklist based on a hat-stiffened fuselage panel from a military aircraft:

A. What are the locations where mechanically induced (i.e. fatigue) damage is most likely to initiate?
Free edges
Plank/skin interface
Skin/hat interface (including adhesive)
Noodle
Fasteners

B. What are acceptable levels of damage at these locations?
None
Microcracking initiation
Microcracking initiation that creates a delamination, but no delamination propagation
Microcracking initiation that creates a delamination with subcritical delamination propagation

C. What are the effects of temperature and moisture on the development of damage at these locations?
Accelerated or delayed microcrack initiation
Accelerated or delayed delamination propagation

D. How does damage affect structural behavior?
Decreased stiffness
Failure

E. How do temperature, moisture, and aging affect structural behavior (assuming no damage)?
Accelerate decrease in stiffness and onset of failure

**On to Step 2 Library of Durability Models and Data**

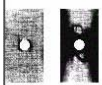
**Back to Durability Page**

**Figure 14-8. Durability Methodology Step 1 - Checklist**

Process Guidelines | Test Databases | Lessons Learned | Analysis Templates | About AIM-C

# Durability

**Step 2. Library of Durability Models and Data**



Consult Durability Conformance Planning Checksheets (XRL's) for durability issues

**These Spreadsheets are not controlled databases. They will not be saved by this system software.**

Thermal Degradation SpreadSheet V 1.0.0 3-07-03
Degradation Theory Manual
Thermal Degradation Data Set
This will select, implement, and develop models that relate the effects of environmental exposure to the change in structural performance. This includes determining the life of the product to first detectable damage that can affect the strength of the part if usage continues or alternately the residual strength at the end of the service life. Beyond this, a methodology for implementation of the modules and the application of heuristics are also being developed in support of the AIM vision of reducing the time to insert materials. The thermal degradation of polymer systems is highly temperature dependent and involves many different chemical reactions. The type of chemical reaction depends on environmental factors, such as pressure, concentration of oxygen, moisture, and diffusion characteristics. The environmental factors will govern not only the rate of reaction, but the type of reactions that happen. Our work thus far has focused on thermal effects; without oxygen or moisture, thus temperature is the only accelerating factor. The approach taken here builds on methods and analysis taken from the HSCT program and from the literature.

SuperMicMac SpreadSheets and Manuals (Stanford University) V 1.0.1 7-31-03
The program runs on Microsoft Excel and is composed of several worksheets some shown and some hidden. Most of the calculation is real-time, meaning the calculation is performed instantly every time any input is changed. Additional features such as the interactive guide, analysis of multiple and spectrum load cases, parameter study, and carpet plot can be performed by pressing appropriate buttons on the worksheet. The purpose of this program is to provide the engineers and designers an integrated durability analysis tool that can predict the long-term stiffness and strength of composite laminates at wide ranges of temperature and moisture conditions. These predictions will facilitate the material selection, ply orientation optimization, and reduction of time-consuming durability tests.

Delamination Tool Spreadsheet (MIT) V 1.1.0 9-01-03
Delamination Tool Manual
The Delamination Durability Tool allows for durability analyses of composite structures that are likely to develop delaminations in critical locations. It takes tables of information from the structures module model and material data and calculates the number of cycles to the initiation of matrix cracking, delamination onset (beginning of crack propagation from a delamination), and propagation of a crack to a specified length. While it is not expected that the predictions will exactly predict the number of cycles to a specific event, the Tool is extremely useful at determining which mechanisms dominate under particular loading regimes and the magnitude of the time that these mechanisms can be expected to occur.

DURASOFT Download (MIT) V 1.0.0 8-01-03
DURASOFT Manual (MIT)
MicroCracking Data Set
Durability software for cyclic hygro-thermo-mechanical loading predicts number of flight cycles until microcracking and reduced mechanical properties at end of design life. It allows prediction of incidence and effects of microcracking, a key durability damage mode, thereby reducing long duration testing. It will help designer determine sensitivity of laminate to hygral, thermal, and cyclic mechanical loading to minimize testing.

**These Spreadsheets are not controlled databases. They will not be saved by this system software.**

**See also Structures Analysis Tools**

**Back to Durability Page**

**Back to Step 1**

**On to Step 3**

**Back to Durability Page**

**Figure 14-9. Library of Durability Models and Data**

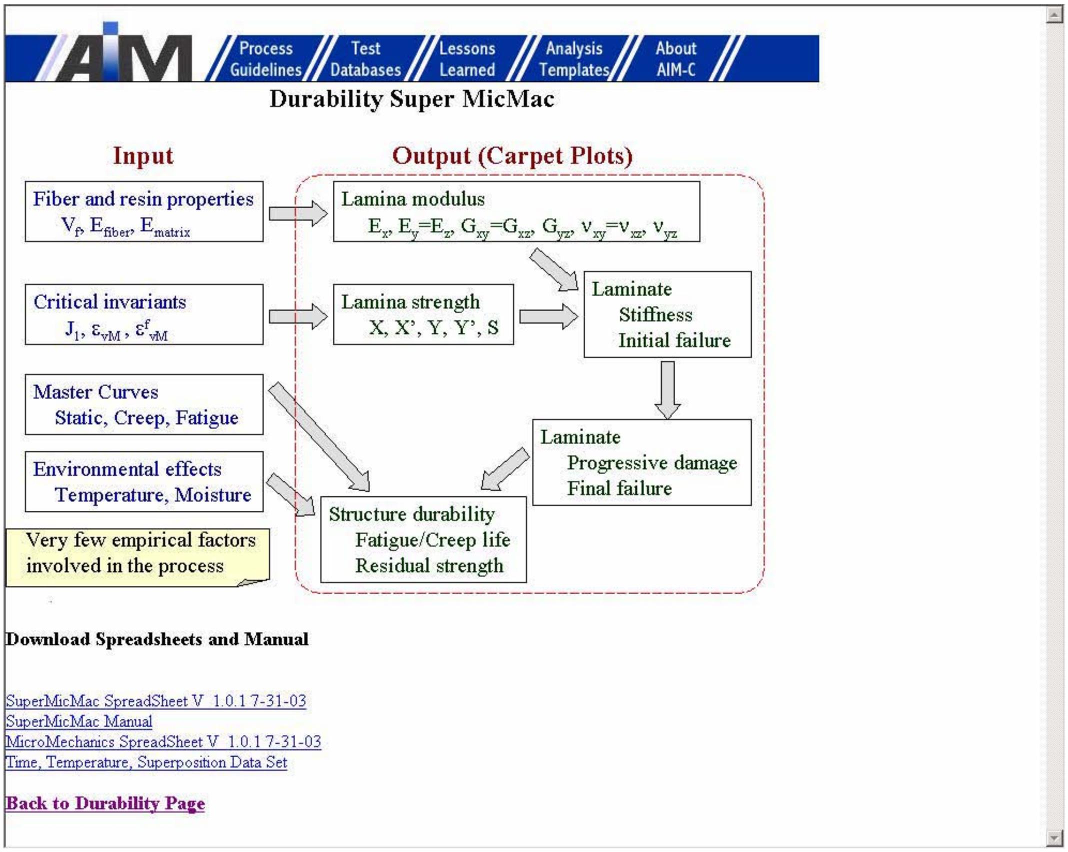



**Figure 14-10. Super Mic-Mac Durability Analysis Tool Home Page**

Figure 14-11 shows the SIFT Durability Spreadsheet developed by Stanford. The input sheet is where the material properties are entered, along with the laminate layup, the applied loads, the environmental conditions, and the type of analysis that will be conducted. Eventually, we would like for most of this information to be automatically entered from other regions of the system software or from answers to questions up to this point.

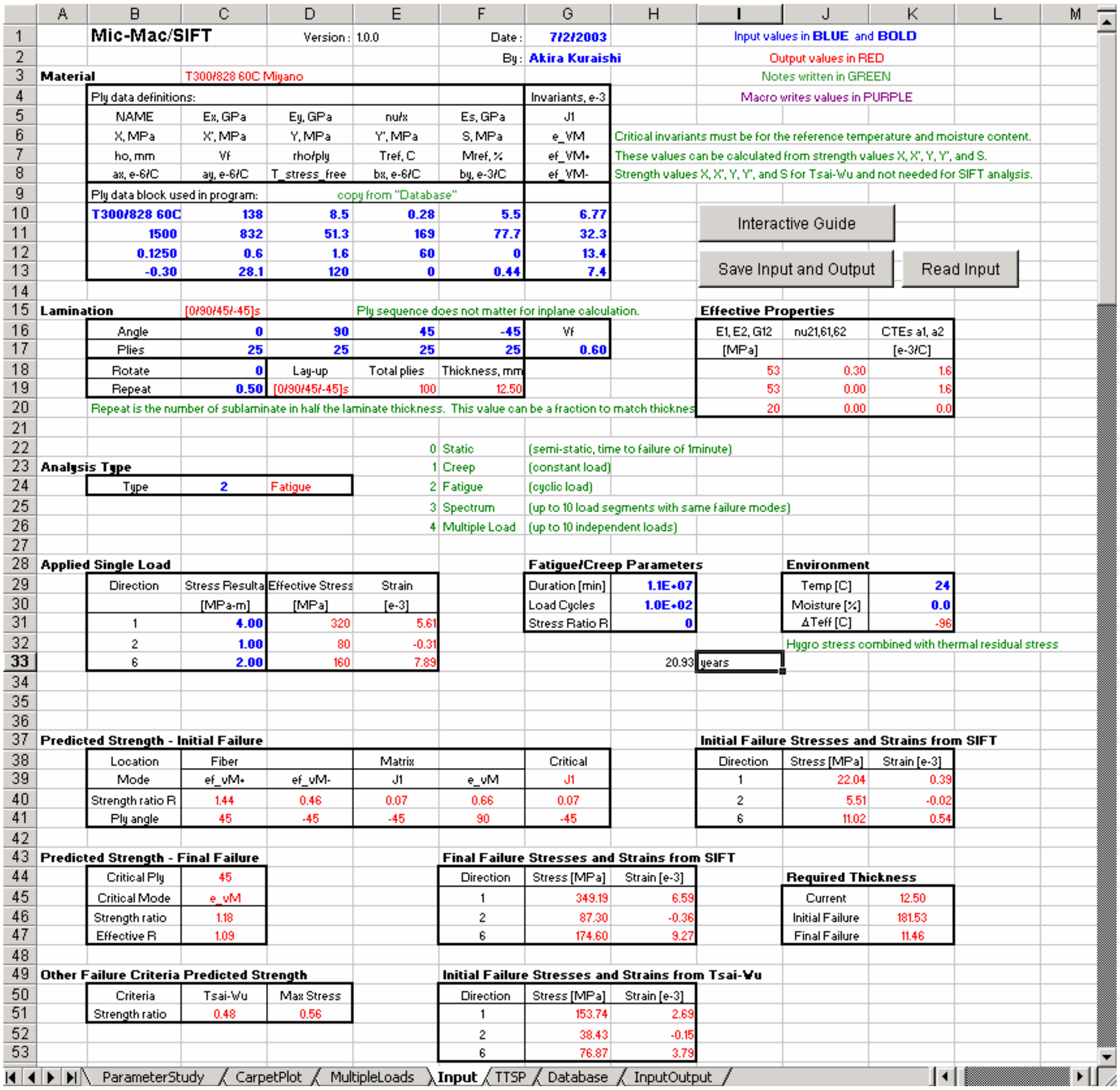



**Figure 14-11. SIFT Durability Spreadsheet (Super Mic Mac by Stanford University)**

FiFigure 14-12 shows that the carpet plot tab is one of two output tabs, the other being the parameter study. The carpet plot tab is where the user selects what results to plot in the carpet plot. As one can see, there are numerous choices.

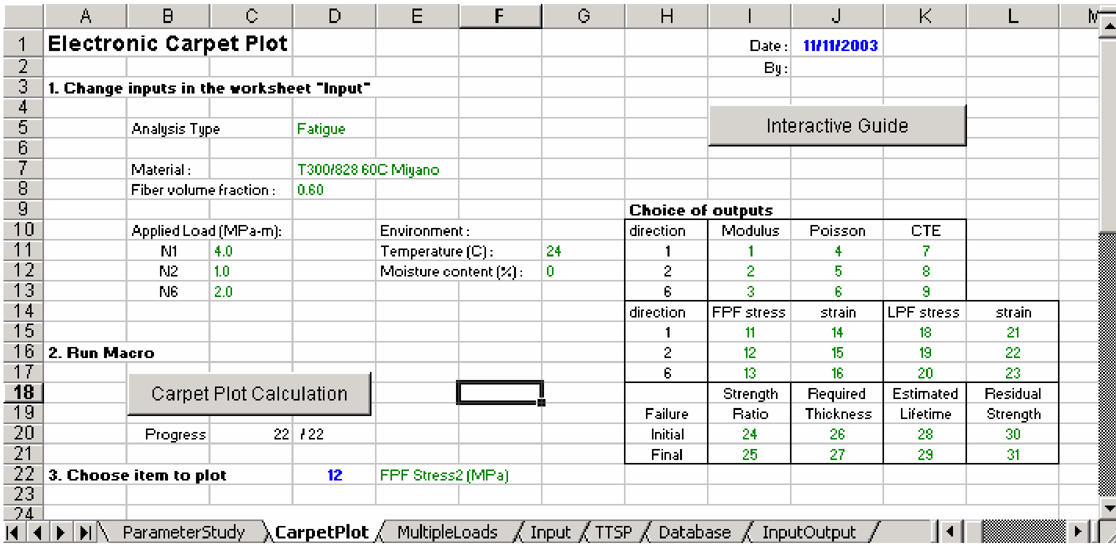



**Figure 14-12. Super Mic-Mac Carpet Plot Output Selection**

Figure 14-13 shows an example carpet plot for the first ply failure transverse stress (item #12 from the list). This type of plot could be generated for several "what if" scenarios where the user would go back to the input sheet and change loads, temperatures, material properties, etc. and see what effect that would have on the first ply failure stress.

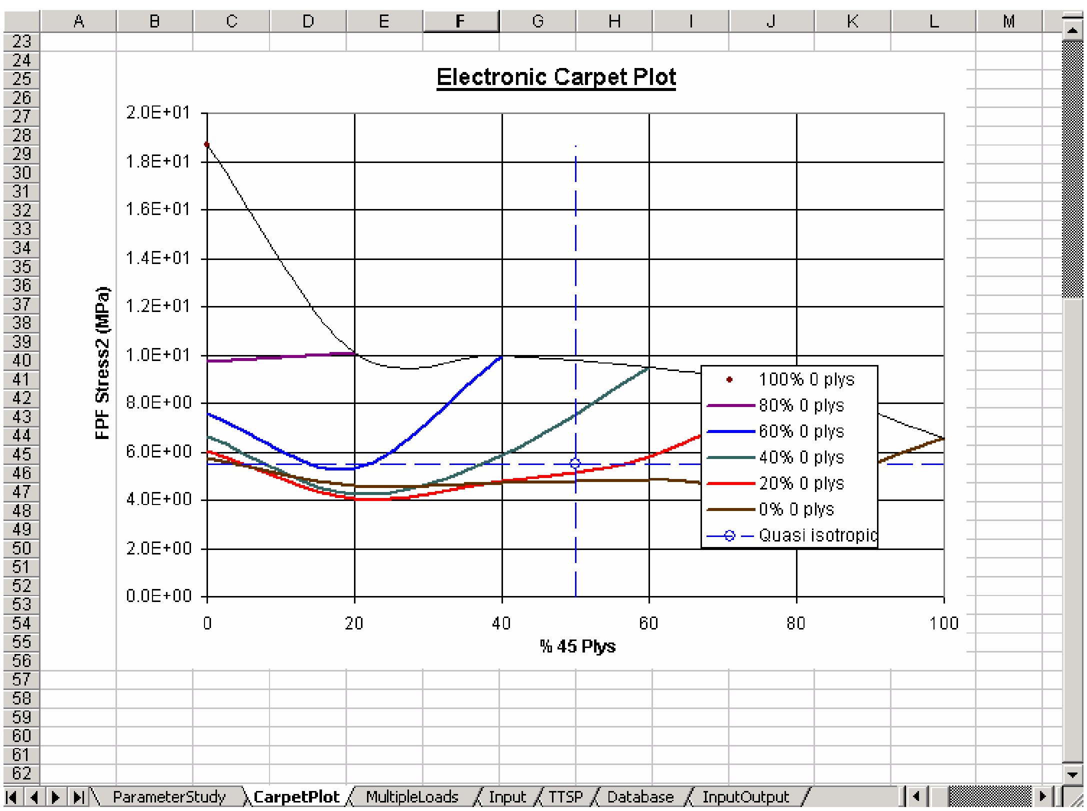



**Figure 14-13. Carpet Plot Output**

## Appendix

Working list of Categories/Questions/Prompts in each section of the durability methodology tool

A. Material:

Listing of material types

Either straight list of materials for which data/experience exists, perhaps subdivided into sub-categories:
graphite/epoxies, glass epoxies, graphite thermoplastics…)
or
listing by constituents: epoxy matrices, graphite fibers, fiber architectures

- Constituents
  - Graphite fibers
    - T300
    - IM7
    - AS4
  - Glass Fibers
  - Aramid Fibers
  - Thermoset Resins
    - 977-3
    - 934
    - 3501-6
  - Thermoplastic resins
    - PEEK
- Material Architecture
  - Unidirectional plies
  - Woven
  - Stitched
  - Braided
- Manufacturing Route
  - Prepreg/Autoclave
  - VARTM
  - Pultruded
  - Filament wound
- Coatings
  - Paints
  - Sealants
  - Sacrificial layers
- Hybrid Materials
  - Fiber metal laminates
    - TiGr
    - GLARE

ARALL
Glass/Carbon Hybrids

**B. Loads**

1. Phasing with environmental factors?

2. Monotonically increasing
    - Tension
    - Compression
    - Shear
    - Biaxial
    - Triaxial

3. Cyclic
    - Constant amplitude
    - Spectrum loading
    - Tension
    - Tension-Compression
    - Compression-Compression
    - Fretting loads?
    - Biaxial
    - Triaxial

4. Constant
    - Tension
    - Compression
    - Biaxial
    - Triaxial

5. Impact
    - Low velocity
        - Max force
        - Energy
    - High velocity
        - Velocity
        - Max force
        - Energy

6. Contact loads
    - Sliding contacts
    - Rolling contacts
    - Repeated normal contacts

**C. Environmental factors**

Phasing with load conditions?
Temperature
- Steady
- Cyclic

Moisture
- Constant exposure (e.g. immersion)
- Cyclic
- Freezing possible?

Solvents
Gaseous reagents
Plasmas
Atomic Oxygen

**D. Geometric Details**

Constant cross-section
Varying cross-section
Curved plates (shells)
Cut outs
Principally in-plane loading
3-Dimensional loading
T joints
Mechanical fasteners
- Bolts
  - Clamping force
- Rivets

Bimaterial Joints
- Composite-composite
- Composite-metal
- Etc.

**Durability Design Objectives**
- Nominal mission cycle (i.e. ground air ground)
- Number of intended missions
  - Single mission
  - Multiple mission cycles
- Total expected lifetime
- Target inspection frequency
- Target repair frequency

**Outputs**
- Degradation/Damage Mechanisms

- Fiber debonding
- Delamination
- Fiber failure
  - Tensile failure
  - Fiber Microbuckling (compression)
- Off-axis ply cracking
- Creep
- Physical aging
- Chemical Aging
- Erosion
- Wear
- Exceeds glass transition
- General tensile failure
- General fatigue failure
- General compressive failure
- Etc.

Modeling options
- See section 2

Test options
- See section 3

Literature
- Research papers in journals, conferences
- Reports from previous test programs

# 15 Assembly

Assembly is a primary area associated with material qualification and certification. The identification and evaluations of application assembly concepts and approaches is integrally tied to the element, subcomponent and component joints that have to be evaluated for application requirements and conformance. This section on assembly includes definitions, requirements and conformance but is lacks detail information below the top technology readiness level. This detail is on assembly processes along with their associated quality and tooling.

For purposes of the AIM-C program, assembly is composed of three primary items. First is the assembly processes of which there are several kinds. Second is quality associated with each assembly process. Third is assembly tooling associated with the assembly processes.

There are four primary types of assembly processes for connecting individual parts, subassemblies or assemblies together. First is secondary attachment by fasteners inserted into holes. Second is bonding by adhesives creating a “bonded structure” (this can be with either metallic or composite components/pieces). Third is composite cobonding where a cured detail/part/feature is attached to an uncured detail/part/feature during an autoclave cure to yield a completed structure. Fourth is composite cocure where individual details/parts/features are cured together at the same time to yield a completed structure.

## 15.1 REQUIREMENTS

The requirements for assembly are broken down into readiness level criteria going from the initial assembly concept through production and disassembly for disposal. This approach for assembly is the same as the other disciplines or areas associated with material qualification and certification and allows for coordinated maturity evaluations according to the maturity levels. The next section goes into the details of these top level requirements for assembly.

### 15.1.1 Technology Readiness Level (TRL) Chart

A technology readiness level chart was generated in order to identify specific exit criteria associated with assembly with maturity going from 1 to 10. This chart is shown in Figure 15-1.

| TRL | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Assembly/ Quality | Assembly Concept | Assembly Plan Definition | Key Assembly Detail Definitions | Key Assembly Details Tested | Subcomponents Assembled | Components Assembled | Airframe Assembled | Flight Vehicles Assembled | Production | Disassembly for Disposal |

**Figure 15-14 Assembly Technology Readiness Chart**

The exit criteria and what they mean are shown below.

1. **Assembly Concept –** Identification of assembly concept or concepts to be used on the application

2. **Assembly Plan Definition –** The overall assembly plan for the application is established and high risk areas identified.
3. **Key Assembly Detail Definitions –** Key details are defined and fabricated for assembly process evaluations of the joints
4. **Key Assembly Details Tested –** The key details assembled in TRL 3 are tested to verify joint capability for the application
5. **Subcomponents Tested –** Subcomponents are assembled and tested to validate the joint approaches
6. **Components Tested –** Components are assembled and tested to validate the joint approaches
7. **Airframe Assembled –** Assembly processes and methods are used to assemble the completed air frames for testing.
8. **Flight Vehicles Assembled –** Assembly processes and methods are used to assemble the flight vehicles.
9. **Production –** Assembly processes and methods are used in production
10. **Disassembly for Disposal –** Methods and processes have been identified for disassembly of production units for disposal.

The exit criteria shown in Figure 1 are relative to an application and associated items for application maturity. Details of what may be involved with the individual assembly processes and their maturity would be found in the XRL charts covering the specific process.

### 15.1.2 XRL Charts

Detailed XRL charts would be generated for each of the assembly processes covering the process itself, quality associated with the process, and tooling associated with the process. These XRL charts would utilize the generic materials/processing/producibility guide that covers both technical requirements definition and production readiness.

## 16. Supportability

The following describes the methodology and process definition for the Technology Readiness Levels (TRL) for the Supportability discipline related to the structural system of a vehicle. Included are the associated elements and their criteria for each readiness level, as well as a description of how the methodology is implemented.

**16.1 Supportability TRLs** – At the technology readiness level, it is difficult to distinguish the technology readiness level of supportability for just structural components as the supportability discipline is really focused at the system level. There are many elements of supportability; however, not all of the elements apply to the vehicle's structural system or components. Those elements that do apply have somewhat distinct attributes that make it difficult to describe in total at this high level. Therefore, in order to describe the Supportability TRLs in a succinct way (common for the other TRL definitions), reference to the specific elements of the discipline are not possible. Consequently, the TRLs are labeled, Figure 16-1, using descriptions appropriate for the "Support System" level, where the "support system" is comprised of the primary elements that contribute to a vehicle's supportability attribute.

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Supportability (TRL)** | Support System Concepts Formulated | Support System Methodologies Selected | Support System Requirements Specified | Support System Elements Applied | Support System Element Details Mature | Support System Defined | Initial Support System Ready | Support System Finalized | Support System Operational | Support System Deactivated |

*Figure 16-1 Supportability TRL Definitions*

The criterion that is used to determine compliance or maturity to each of these ten Supportability TRL levels is contained in the Supportability Readiness Level (the XRL for the supportability discipline if you will). It is not intended that one would be able to determine the status of a technology's maturity simply by evaluating it at the TRL level. The elements of the XRL must be evaluated and rated for compliance. Each element can also be given different importance to the overall system by assigning weights to it. However, the premise of the AIM-C program has been that all elements are equally important to the maturation of the system. Ignoring any one of the primary elements results in a system not fully qualified and an application not fully certified. The results from this analysis are then rolled-up to constitute a TRL rating for the structural supportability readiness level. The next section defines the Supportability XRL for the vehicle's structural system.

**16.2 Supportability XRL Elements** - The supportability discipline within Boeing has defined eight (8) primary elements for airframe structures. Each element contributes to the readiness level of structural supportability. The eight elements are listed below.

1. Damage Assessment and Characterization
2. Structural Repair Data
3. Repair Concepts
4. Support Materials and Maintenance Processes
5. Repair Design and Analysis
6. Maintenance Documentation
7. Supplier Management Procurement
8. Maintenance Training

Each element has a unique set of criteria defined for each of the maturity levels, where each criterion builds upon its lower level elements as the maturity level increases. A technology is evaluated to see if it meets or exceeds the criteria defined at each maturity level. If it does, it is then considered ready at least at that level for that element. For example, the "Repair Concepts" element is considered to be at the readiness level of 5 if it has met the criteria defined for levels one through five, but has not met the criteria for level six. Figures 16-2 through 16-9 contain the criterion that has been defined for each level for each element.

| | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| **Damage Assessment and Characterization** | Qualitative damage/failure assessment provided | Comparable historical maintenance data collected and assessed; types, location, and degradation rates determined | Damage types, impact energy levels, frequencies, and typical locations determined | Damage characterization data applied to preliminary design configurations; damage zones identified | Specific damage zones with modes, frequency, projected effects defined for each component |
| | **6** | **7** | **8** | **9** | **10** |
| | Damage zone and detailed definition and criteria refined for final designs | Damage zone and detailed definition and criteria updated based on ground tests | Damage zone and detailed definition and criteria finalized based on flight tests | Service damage data collection system in place; initial damage data and assessment documented | Damage characteristic data over vehicle life assessed, compiled, documented, and archived |

*Figure 16-2. Element Criteria: Damage Assessment and Characterization*

| | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| **Structural Repair Data** | Applicability of standard repair methods identified | Existing data collected from previous testing/ experienced; data shortfalls, inconsistencies, and incompatibilities identified | Structural repair element, subcomponent, and full-scale demonstration and test data requirements defined; repair test plan established | Repair joint configuration tests conducted and data documented | Subcomponent repair test data, as applicable and necessary, documented |
| | **6** | **7** | **8** | **9** | **10** |
| | Selected (critical) component tests completed and results documented | Structural repair test program fully documented, including lessons learned | Structural repair and maintenance experience from flight test documented | Repair and maintenance supporting data available to support maintenance and service life extension assessment | Repair and maintenance data collected over vehicle life documented/archived |

*Figure 16-3. Element Criteria: Structural Repair Data*

| Repair Concepts | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| | Draft operations and maintenance plan available and repair concept/methods explored and documented | Repair concepts/methods defined, including configuration, MTTR, limitations, risks involved, and any R&D needed | Existing repair method details quantified; new repair methods required undergoing R&D; repair/NDI criteria defined | Repair concept R&D complete and documented; repair concepts applied to structural components and repair level analysis performed | Repair method mature; repair and NDI methods demonstrated on subcomponents |
| | **6** | **7** | **8** | **9** | **10** |
| | Repair and NDI methods updated as required | Repair and NDI methods refined/updated as required | Repair and NDI methods updated as required, finalized, and documented | Repair and NDI methods/capability updated and documented as required | N/A |

*Figure 16-4. Element Criteria: Repair Concepts*

| Support Materials and Maintenance Processes | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| | Support infrastructure, repair, and NDI options, including material and fabrication methods, identified | Repair and NDI methods selected; repair materials and processes dowselected | Repair materials and processes sufficiently characterized; repair material, process, and field NDI requirements defined | Preliminary repair and NDI process procedures selected and outlined | Repair and NDI process procedures and associated limitations defined; repair material specifications finalized |
| | **6** | **7** | **8** | **9** | **10** |
| | Repair and NDI process procedures updated; repair materials qualified and associated specifications updated | Repair and NDI process procedures refined and validated | Repair and NDI process procedures certified for use | Repair and NDI process procedures updated as required based on operational use requirements | N/A |

*Figure 16-5. Element Criteria: Support Materials and Maintenance Processes*

| Repair Design and Analysis | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| | Repair design and analysis (RD&A) methodology identified | RD&A method determined for each component based on its configuration/classification (SSI, primary/secondary, nonstructural, FC, DC, SOF etc.) defined. | RD&A criteria defined and incorporated into overall structural design methodology | Preliminary structural assessment of "damaged" components performed; preliminary allowable damage limits (ADL) determined | Repair methods applied to "damaged" subcomponents and analyzed; repair design guidelines established |
| | **6** | **7** | **8** | **9** | **10** |
| | Repair damage limits (RDLs) defined and repair designs available | Repair damage limits (RDLs) refined and repair designs finalized | Structural repair analysis documentation updated from flight test data; sustaining engineering in place | Sustaining engineering/service life extension analysis support personnel, processes, and tools available | Sustaining engineering as-built drawings nad analysis packaged documented, archived, and personnel disbanded |

*Figure 16-6. Element Criteria: Repair Design and Analysis*

| Maintenance Documentation | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| | Draft strategic plan for maintenance documentation outlined | Comparable documentation gathered and assessed for applicability | Scope/purpose, statement of work, and plan for building structural repair manual (SRM) defined | Data requirements for SRM build established and in-place; SRM/IETM outlined; support process plans determined | Preliminary SRM materials and process procedures documented |
| | **6** | **7** | **8** | **9** | **10** |
| | Initial draft of SRM/IETM documentation available for review and trial use | SRM/IETM data updated and initial release ready to support flight test | SRM/IETM updated, certified for operational use, and released to operational units | SRM/IETM available for use; maintenance/updates as required | SRM/IETM data and associated documentation archived and de-activated |

*Figure 16-7. Element Criteria: Maintenance Documentation*

| Supplier Management Procurement | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| | Possible procurement concepts and methods identified | Procurement concept(s) and method(s) selected and approved | Contractual methods for procurement identified | Contractual processes for supplier procurement defined | Procurement contract methodology mature and initial contracts pursued |
| | **6** | **7** | **8** | **9** | **10** |
| | Procurement contract methodology for suppliers implemented | Capability to readily supply needed spares and materials for maintenance and repair established | Materiel suppliers all on board and initial deliveries in place | Supplier management process in place | Supplier management process deactivated |

*Figure 16-8. Element Criteria: Supplier Management Procurement*

| Maintenance Training | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| | Training methodology considered and documented | Training requirements defined and implementation plan established | Training methods determined and courses selected and outlined | Preliminary training courses built; beta tests underway | Training courses updated based on beta testing; training methods mature |
| | **6** | **7** | **8** | **9** | **10** |
| | Initial training on NDI and composite repairs provided to customers (supports full-scale repairs on test articles) | Flight test maintenance engineers and technicians possess ability to efficiently accomplish maintenance and repair procedures | Operational maintenance engineers and technicians fully trained to effectively support vehicle structures | Periodic maintenance team training in place; updates to processes provided; lessons learned documented | Maintenance training discontinued |

*Figure 16-9. Element Criteria: Maintenance Training*

The meaning and criteria definition for the TRL levels is illustrated in the following. The TRL level of 6, "Support System Defined", is defined by the following criteria that must be met (from each of the 8 elements) for that level.

- Damage zone and detailed definition and criteria refined for final designs
- Selected (critical) component tests completed and results documented
- Repair and NDI methods updated as required
- Repair and NDI process procedures updated; repair materials qualified and associated specifications updated
- Repair damage limits (RDLs) defined and repair designs available
- Initial draft of SRM/IETM documentation available for review and trial use
- Procurement contract methodology for suppliers implemented
- Initial training on NDI and composite repairs provided to customers (supports full-scale repairs on test articles)

Note that all of the criteria for the lower levels (1 – 5) must also have been met. Once all of the elements have been evaluated and a readiness level has been defined for each, they can be rolled up to determine the overall structural supportability readiness level. In addition, weighting factors can be assigned to each element, based on its overall importance to the supportability system, to obtain a more refined readiness level assessment. These weights could be program driven; however, consistency in sharing data across programs favors the establishment of a standardized system. The following example illustrates the use of these elements in assessing the readiness level for structural supportability.

## 16.3 Use of the Supportability XRL Definitions

Figure 16-10 shows the results of an artificial assessment of each element where the columns are filled in with the maturity level criteria that has been met to date. Totaling the results yields an overall Supportability Technology Readiness Level (TRL) of 3, which correlates to the definition of the TRL 3 of "Support System Elements Applied." Obviously some elements are being pursued beyond the TRL 3 level and those beyond TRL level of 5 are at risk should data not support the maturity levels of the current concepts at TRL = 4.

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Damage Assesment and Characterization** | Qualitative damage / failure assessment provided | Comparable historical maintenance data collected and assessed; types, location, and degradation rates determined | Damage types, impact energy levels, frequencies, and typical locations determined | Damage characterization data applied to preliminary design configurations; damage zones identified | Specific damage zones with modes, frequency, projected effects defined for each component | Damage zone and detailed definition and criteria refined for final designs | | | | |
| **Structural Repair Data** | Applicability of standard repair methods identified | Existing Data collected from previous testing / experience, data shortfalls, inconsistencies, and incompatibilities identified | Structural repair element, subcomponent, and full-scale demonstration and test data requirements defined, repair test plan established | Joint repair configuration tests conducted and data documented | | | | | | |
| **Repair Concepts** | Draft operations and maintenance plan available and repair concepts / methods explored and documented | Repair concepts / methods defined, including configuration, MTTR, limitations, risks involved, and any R&D needed | Existing repair method details quantified, new repair methods undergoing R&D, NDI requirements defined | | | | | | | |
| **Support Materials and Maintenance Processes** | Support infrastructure, repair, and NDI options, including material and fabrication methods, identified | Repair and NDI methods selected; repair mateirals and processes downselected | Repair materials and processes sufficeintly characterized; repair material, processes, and field NDI requirements defined | Preliminary repair and NDI process procedures selected and outlined | Repair and NDI process procedures and associated limitations defined; repair material specifications finalized | | | | | |
| **Repair Design and Analysis** | Repair design and analysis (RD&A); methodology identified | RD&A determined for each component based on its configuration / classification (SSI, primary / secondary, nonstructural FC, DC, SFO, etc) defined | RD&A criteria defined and incorpoarted into overall desing methodology | Preliminary structural assessment of "damaged" components performed, preliminary allowable damage limits (ADL) determined | | | | | | |
| **Maintenance Documentation** | Draft strategic plan for maintenance documentation outlined | Compoarable documentation gathered and assessed for applicability | Scope / purpose, statement of work, and plan for building structural repair manual (SRM) defined | Data requirements for SRM build established and in-place, SRM/IETM outlined; support process plans determined | | | | | | |
| **Supplier Management and Procurement** | Possible procurement concepts and methods identified | Procurement concept(s) and method(s) selected and approved | Contractual methods for procurement identified | Contractural processes for supplier procurement defined | | | | | | |
| **Maintenance Training** | Training methodology considered and documented | Training requirements identified and implementation plan established | Training methods determined / courses selected and outlined | | | | | | | |

*Figure 16-10. Example of Readiness Level Assessment*

# APPENDIX A - REQUIREMENTS DEVELOPMENT

## Introduction

The overall AIM-C methodology for accelerated materials and/or processes insertion is composed of four primary steps shown in Figure A-1. Requirements identification is incorporated as part of the problem statement according to objectives, applications and customers. Establishing these requirements has been an issue historically because they mean different things to different disciplines/people and they tend to shift or creep during qualification and certification.

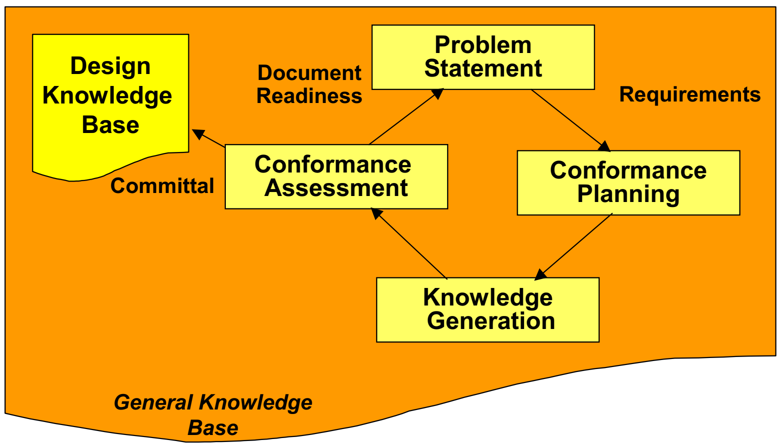



**Figure A-1 Overall Methodology**

The objective of the AIM-C process for requirements definition is to provide a disciplined framework for the insertion of a new material that captures the designers' application/problem statement. The methodology or process is intended to provide guidance at all levels and by all disciplines in the certification process. This methodology process is robust with flexibility so that change and customer perspective requirements can be easily addressed while maintaining full trace ability of information and data.

Requirements identification are a very important piece of the overall AIM-C methodology that has been overlooked in other approaches such as the Building Block, TRL, 2$^{nd}$ Source, and AGATE. The WHY of material qualification and certification is that requirements have to be met acceptably to the customers and certification agency.

One of the key problems encountered in accelerating the insertion of materials into products is that requirements are defined at the System or Vehicle levels, but the materials' decisions are made at the part level. Figure A-2 shows a schematic of how the system level requirements link to the part or component level decisions through a Systems Engineering approach known as the House of Quality. This can be considered as requirements flow down from the system level to airframe and component levels.

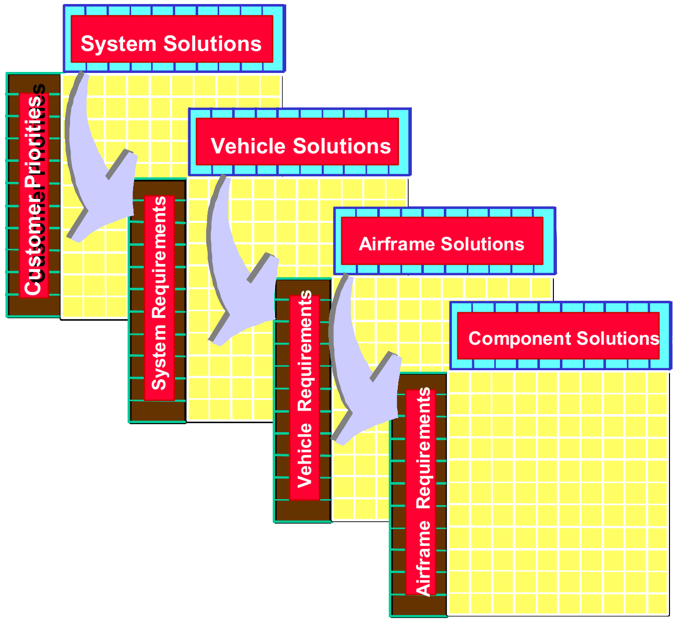



**Figure A-2. Requirements Flow Down to the Component Level for Qualification and Certification**

Satisfying the airframe and component requirements has been historically conducted through a building block process such as used for the F/A-18E/F qualification and certification. Figure A-1 illustrates the traditional steps in the building block insertion process.

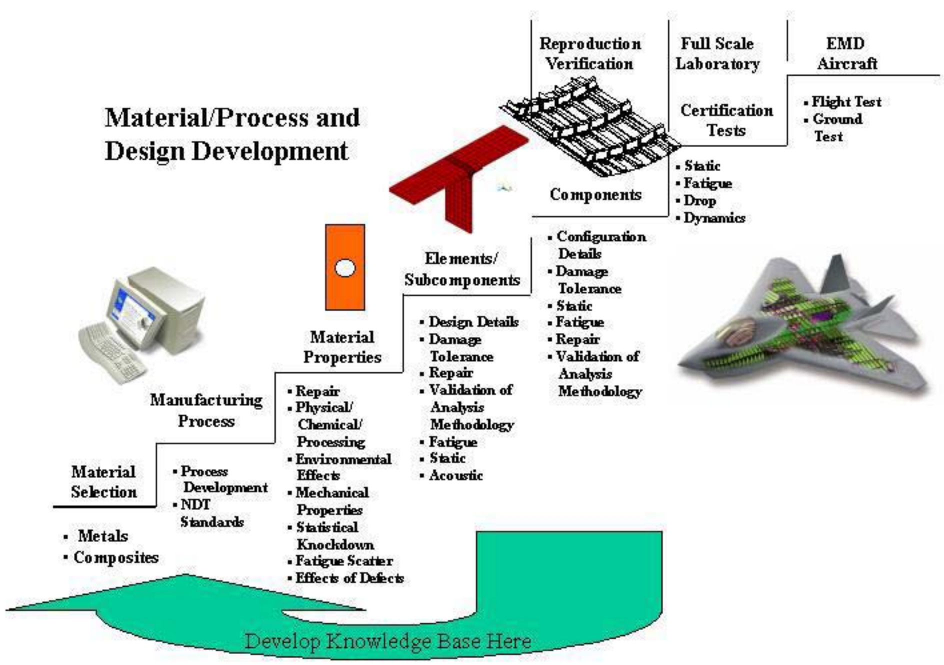



**Figure A-1 Methodology Approach With Early Knowledge Base Development.**

This AIM-C approach is presented in Figure A-2 in comparison to the conventional Building Block Approach and shows hen activity groups are conducted. The primary differences between the AIM-C approach and the Building Block Approach is the focus on addressing scale-up and design details (two recognized historical show-stoppers) before any allowables development begins. The AIM-C approach does this by focusing efforts on defining, producing, and testing a Key Features Article that represents the scale of the largest part to be fabricated, the most critical design detail features, and the most difficult tooling considerations included in it. This article could be a pre-production proof test article, or it might be an artificial article designed to include the most critical issues contained in a number of parts. The primary purpose of the article is to demonstrate that the material, processes, and fabrication capabilities are defined and stable enough to produce such parts consistently. This article also serves through destructive tests to guide the development of allowables toward those elements of the design that control certification. There are three stages to the AIM-C approach going from quick look assessments to mid depth assessments and then to detailed assessments. Each stage builds on previous stages with early risk reduction thereby minimizing the potential for showstopper issues.

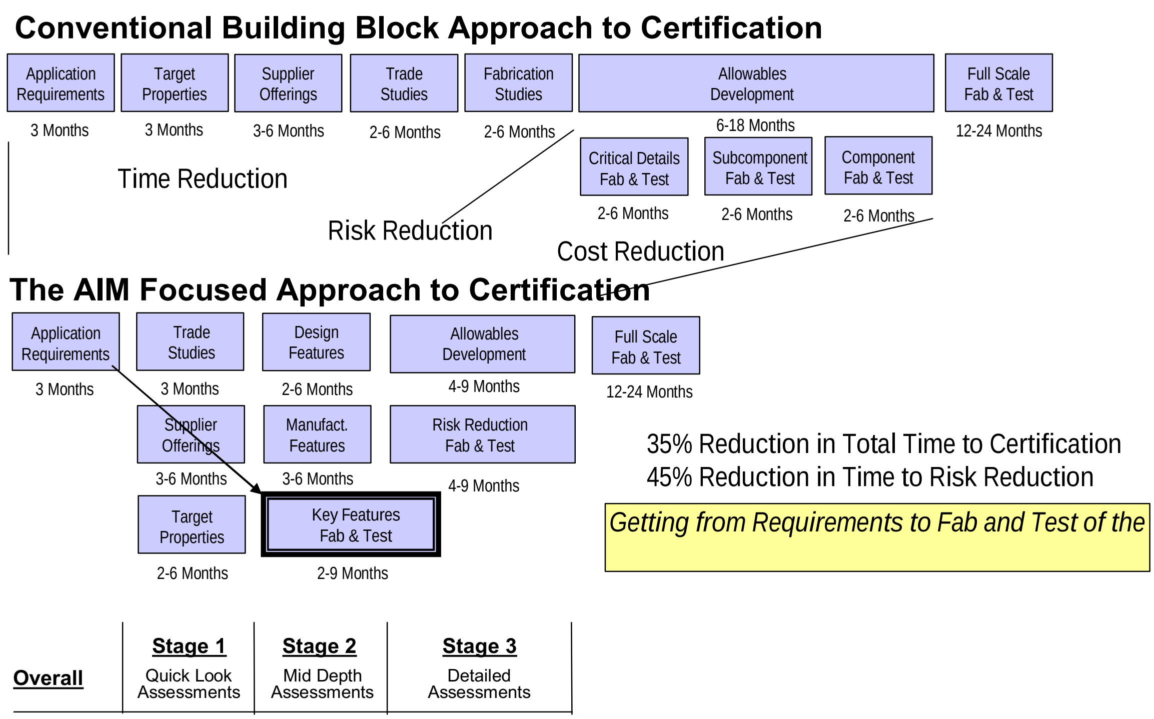
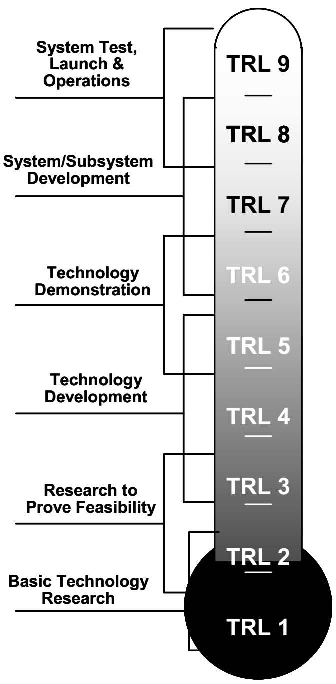



**Figure A-2. The AIM-C Process use IPT Lessons Learned to Drive Rapid Insertion**

The approach defined in Figure A-2 starts to establish a framework for an IPT effort toward accelerated insertion. This means that every test and every analysis performed and every bit of knowledge brought to the effort is available to speed the satisfaction of the requirements for certification of the material on a particular application being proposed. Moreover, the purpose is to ensure that every piece of data or knowledge obtained is used to the greatest extent possible and that no data or knowledge developed which has no relevance to the application being proposed.

Key to this accelerated insertion is understanding of what the requirements are and understanding what has been satisfied and what needs to be satisfied. The AIM-C program decided to utilize a technology readiness level concept similar to those defined by NASA and the Air Force. By linking the approach to an appropriate technology readiness level, the maturity of the product development cycle can be established from test tube materials development to qualification and certification in the application.

Technology readiness levels (TRL) were originally established to grade the maturity level of a system application and went from concept exploration of a 1 to production at a 9. This is shown in Figure A-3 for NASA's approach to TRL's. Usage of this numbered maturity level allows breaking requirements up into more understandable steps.




**TRL 9: Actual system "mission proven" through successful mission operations** *Thoroughly debugged software readily repeatable. Fully integrated with operational hardware/software systems. All documentation completed. Successful operational experience. Sustaining software engineering support in place. Actual system fully demonstrated.*

**TRL 8: Actual system completed and "mission qualified" through test and demonstration in an operational environment** *Thoroughly debugged software. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. V&V completed.*

**TRL 7: System prototype demonstration in high-fidelity environment (parallel or shadow mode operation)** *Most functionality available for demonstration and test. Well integrated with operational hardware/software systems. Most software bugs removed. Limited documentation available.*

**TRL 6: System/subsystem prototype demonstration in a relevant end-to-end environment** *Prototype implementations on full scale realistic problems. Partially integrated with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.*

**TRL 5: Module and/or subsystem validation in relevant environment** *Prototype implementations conform to target environment / interfaces. Experiments with realistic problems. Simulated interfaces to existing systems.*

**TRL 4: Module and/or subsystem validation in laboratory environment** *Standalone prototype implementations. Experiments with full scale problems or data sets.*

**TRL 3: Analytical and experimental critical function and/or characteristic proof-of-concept** *Limited functionality implementations. Experiments with small representative data sets. Scientific feasibility fully demonstrated.*

**TRL 2: Technology concept and/or application formulated** *Basic principles coded. Experiments with synthetic data. Mostly applied research.*

**TRL 1: Basic principles observed and reported** *Basic properties of algorithms, representations & concepts. Mathematical formulations. Mix of basic and applied research.*

**Figure A-3 NASA TRL Scale**

For the AIM-C methodology process, concept exploration starts at a 1 but it goes to 10 and covers recycle or disposal. This TRL application maturity ranking for the AIM-C program is shown in Figure A-4 for application maturity. Also shown are what could be primary activities or exit criteria for each of the application maturity levels.

| TRL | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Certification** | Qualification Plan Assessment | Certification Elements Documented | Certification Plan Documented | Certification Plan Approved | Elements | Subcomponent Testing | Full Scale Component Testing | Full Scale Airframe Tests | Flight Test | Production Approval | Disposal Plan Approval |

**Figure A-4. AIM-C Technology Readiness Levels 1 to 10 for Certification Maturity.**

The link between the AIM-C approach and the Technology Readiness Levels for each is shown schematically in Figure A-5. Stage 1 is early activities for concepts, approaches and material/process trade studies and/or down selection. The second stage covers TRLs 2 and 3 simultaneously as the material, process, fabrication, and structures elements are all addressed by concurrent or synergistic evaluations. Stage 3 is detailed assessment of design allowables and specific application certification at element and subcomponent levels.

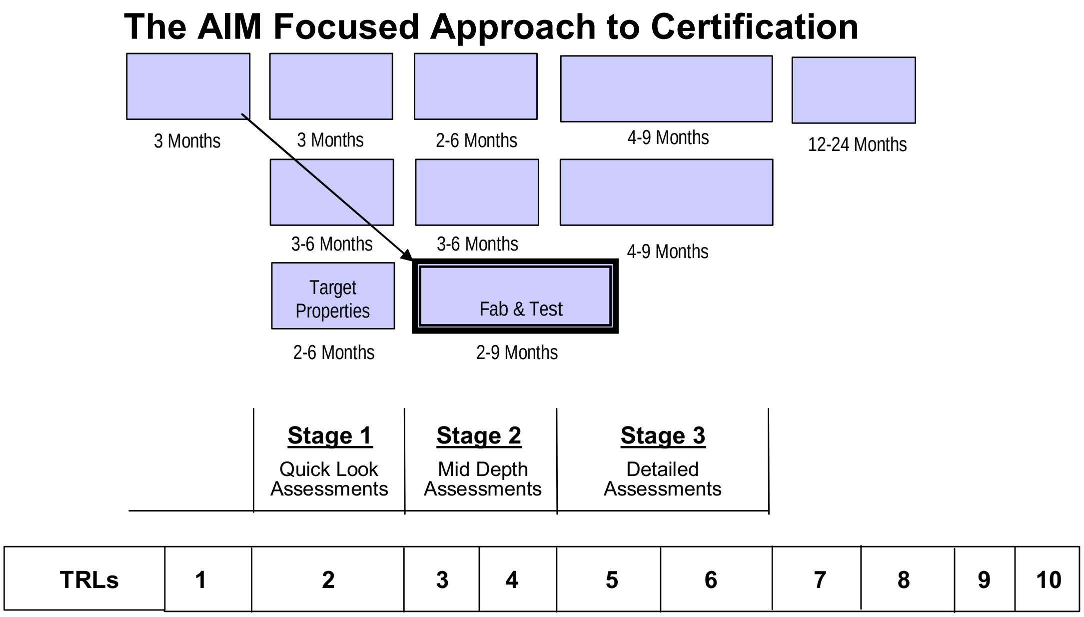



**Figure A-5 The AIM-C Methodology Links the AIM-C Process to Technology Readiness**

There are a number of engineering disciplines involved with qualification and certification requirements. For aircraft applications, the primary disciplines include design, structures/strength, materials, manufacturing/producibility, and supportability plus others as needed for specialty areas. The trend today is towards forming teams composed of the primary disciplines that work together on an application from initial material screening through final product qualification. These teams are called an integrated product team (IPT). Customers, suppliers, subcontractors, technical leads and management are also involved with qualification and certification as members of the IPT. The multiple disciplined IPT establishes objectives and requirements for qualification and certification data.

Requirements can be viewed as to what is needed for acceptance of a new material and/or process on an application from this multiple discipline perspective. A summary of the overall multiple discipline needs is shown in Figure A-6. These needs can be considered the overall designer knowledge base (DKB).


**Figure A-6 The Overall Design Knowledge Base**

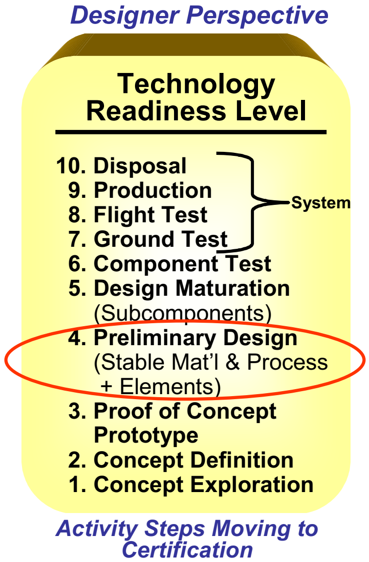
The overall DKB provides the broad, all inclusive definition of knowledge required for application design. It goes beyond what is absolutely necessary to obtain certification of the product to include those supportability and survivability. The AIM-C DKB definition is the information for the certification agent. This agent or person has a defined series of criteria to make sure that the material system meets the requirements of the application and will not prove ineffective during the use of the product.

The next section provides background information and definitions for the TRL numbers used in the AIM-C program.

## Maturity Level Scale Background and Definitions

Technology maturity measurement approaches have been established by several government agencies and incorporated into DoD acquisition regulations. The left side of FIGXX shows a designer perspective for technology maturity on applications going from 1 of concept exploration through 10 for disposal. This is very similar to the NASA numbering and activity definitions leading to certification on an application. There are positives and negatives associated with this Technology Readiness Level (TRL) approach that are also shown in Figure A-7.

## Technology Readiness Level (TRL) For Maturity




**PROS**

- Looks at maturity from a designer/system viewpoint
- Broken down into specific activity areas
- Is geared towards application products and systems for readiness

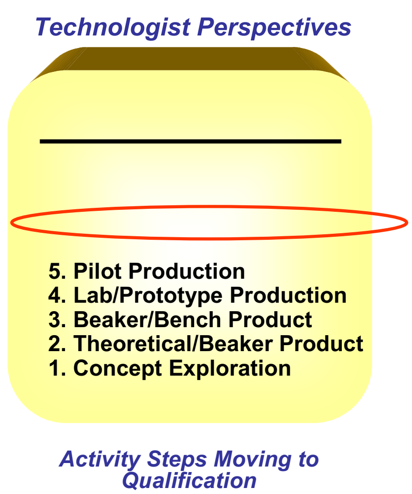
**CONS**

- Does not take into account different discipline perspectives
- Does not address detailed areas/items at each readiness level

**Figure A-7 Designer Perspective of Application TRL Maturity Leading to Certification**

Another issue with this designer/application perspective is the difficulty of interpretation for technologists who work with materials, processes or producibility/manufacturing. If a technologist view is used, there would be different definitions for the maturity levels that move from concept exploration at TRL of 1 to qualified material/process at 7 and industry standard at 9. This technologist view is shown in Figure A-8 along with positives and negatives of this perspective.

## Readiness Levels From a Technologist Viewpoint




**PROS**

- Looks at maturity from a technologist viewpoint
- Broken down into specific activity areas
- Is geared towards materials, processing and manufacturing for readiness

**CONS**

- Is not tied/connected to TRL's from the system or application viewpoint
- Does not take into account different discipline perspectives
- Does not address detailed areas/items at each readiness level

**Figure A-8 Technologist Perspective of TRL Maturity Leading to Qualification**

To take care of the connection of TRL's between the two viewpoints, the charts can be connected at two common denominators (Figure A-9). One is the designer/application TRL of 4 with a stable materials and process which correlates to the technologist readiness level of 7 with a qualified material and process. The second connection point is production at a designer/application TRL of 9 and a technologist readiness level of 8. Another distinction was made between the application and technologist views. Application readiness was described as Technology Readiness Levels or TRL. Technologist readiness was described as XRL or (x)RL where X was fill in the blank for the technology area. Example areas would be resin, fiber, prepreg, etc.

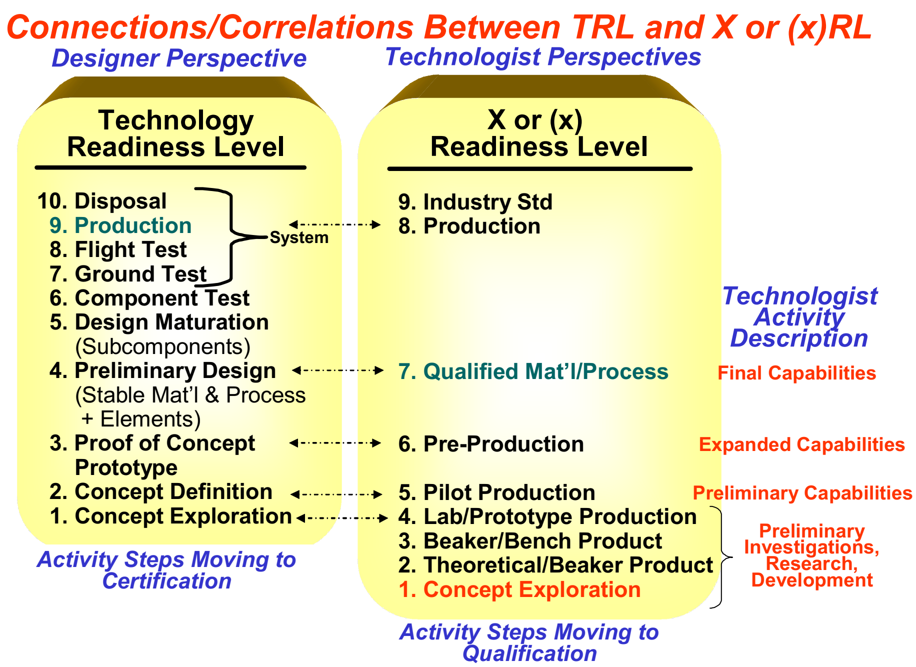



**Figure A-9 Connection of Common Application and Technologist Readiness Levels**

Another way of presenting this double scale is shown in Figure A-10. This was developed for use on technology transition onto the C-17 and was established independent of AIM-C activities. This indicates that this duality of measurements between application maturity and technology maturity is more typical in industry than originally thought.

*Technology Developers See TRLs Focused on That Development*

| Technology Readiness Levels | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Technology Development | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | | | | |
| Application Development | | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

*Application Developers See TRLs Focused on Insertion Into Their Products*

**Figure A-10 C-17 Technology Readiness Metric Approach**

These two measurement scales were used in the AIM-C program for a period of time but it tended to be confusing with the conversions that were happening between applications and technologies for their different numbers and what they meant. These measurement scales were modified based on inputs from the team and from customer groups. This modification consisted of putting both the application/designer perspective and the technologist perspective onto a single scale of 1 to 10. This updated numbering scheme is shown in Figure A-11 and will enable a common view of maturity regardless of individual perspectives to qualification and certification.

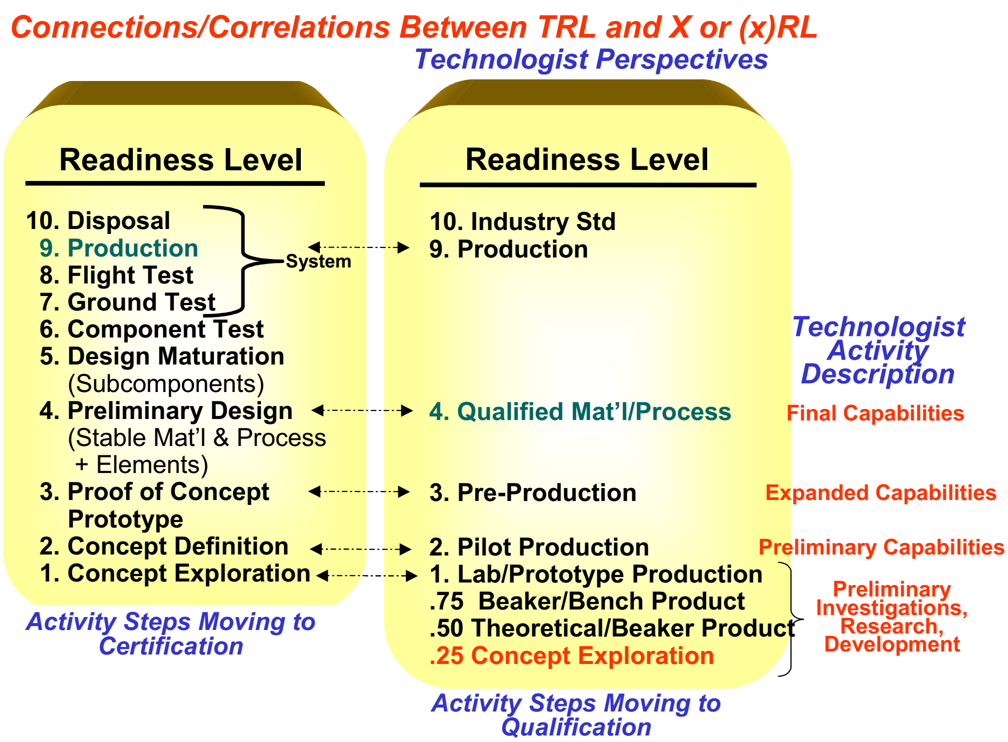



**Figure A-11 Connection of Common Application and Technologist Readiness Levels**

Another way of presenting this common number approach is shown in Figure A-12. It enables viewing the qualification and certification process as a whole with integrated product teams (IPT) working together for common goals and objectives.

*Technology Developers See TRLs Focused on That Development*

| Technology Readiness Levels | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Technology Development | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | | | | |
| Application Development | | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

*Application Developers See TRLs Focused on Insertion Into Their Products*

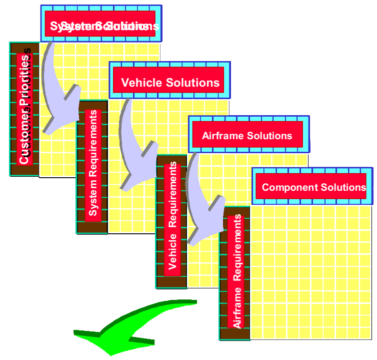
| Technology Readiness Levels | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Technology Development | 0.25 | 0.50 | 0.75 | 1 | 2 | 3 | 4 | 5 | 6 | | | | |
| | | | | One Team | | | | | | | | | |
| Application Development | | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

*AIM Developed TRLs Focused on Insertion but Linked Technology and Application Developers Into One Team*

**Figure A-12 Alternate Presentation of Common Number Metrics**

## Requirements Definition Process

The requirement definition process follows after the requirement flow down to the airframe and component levels. The AIM-C requirement definition process is comprised of two primary steps with associated tool sets to use with the steps. Figure A-13 depicts the requirement flow down through the two primary steps for specific requirement definition for areas/items/groups associated with meeting requirements.




**Step 1 – Establish TRL Sheet**

**Step 2 – Establish XRL Sheets**

**Figure A-13 Requirement Definition Primary Process Steps**

Step 1 activities focus on establishing graduated maturity level metrics for each of the primary areas identified with requirements in the problem statement. The metrics could be considered exit criteria to move from one maturity level to the next. These areas would make up the TRL sheet for maturity metric identification. Example areas would be Application/Design, Certification, Structures, Materials and Fabrication/Producibility plus others.

Step 2 activities focus on establishing detailed graduated maturity level metrics concentrating on items associated with each area on the TRL sheet. These detailed area requirement sheets are called XRL sheets where X stands for a specific area. For example, structures would have a detailed XRL sheet covering durability and properties. Material would have detailed XRL sheets covering resin, fibers and prepreg.

In the AIM-C program, two guides were developed to assist in establishing the XRL sheets. These guides are for structures and a generic guide that can be used for materials, processing and fabrication/producibility. The structures guide encompasses typical big picture requirements for component failure mode, property and durability requirements from which a tailored and specific XRL sheet for structures can be established. The material, process and fabrication/producibility guide looks at requirements for these areas from a production readiness perspective to ensure that all item requirements are established for successful transition to production through qualification and into certification. Figure A-14 shows an overview of this requirements definition process with the different tool sets and personnel conducting the activities. These activities could be considered assessments for requirements definition.

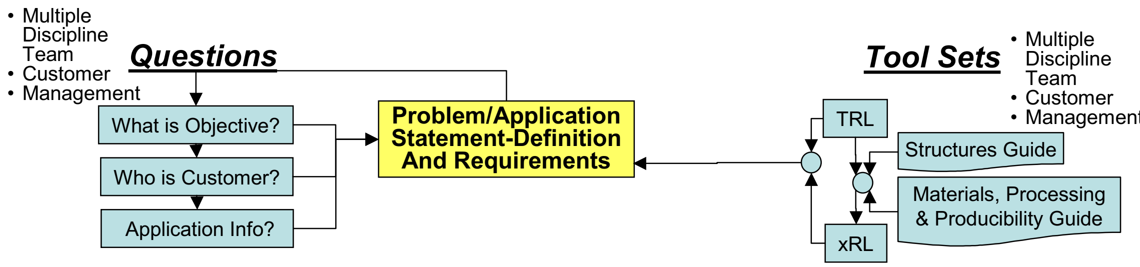



**Figure A-14 Requirement Definition Process Overview**

If the process steps and assessments are broken down further, a series of process flow steps could be shown. Figure A-15 and Figure A-16 show these process steps in a flow chart form.

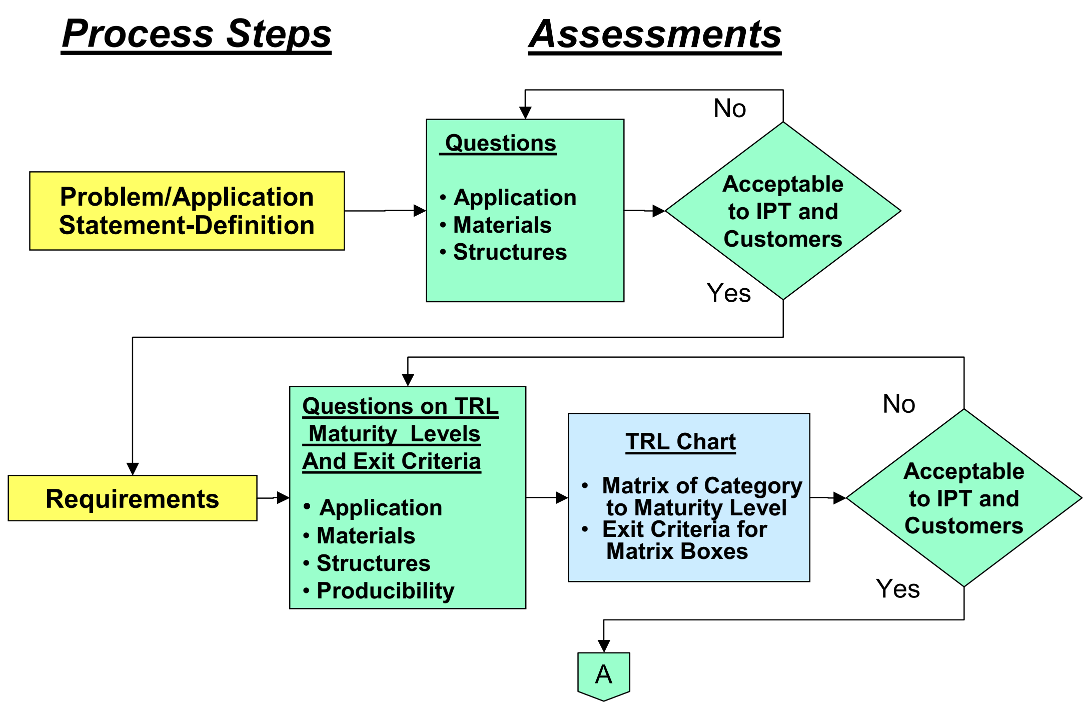



**Figure A-15 Process Flow for Requirements Definition**

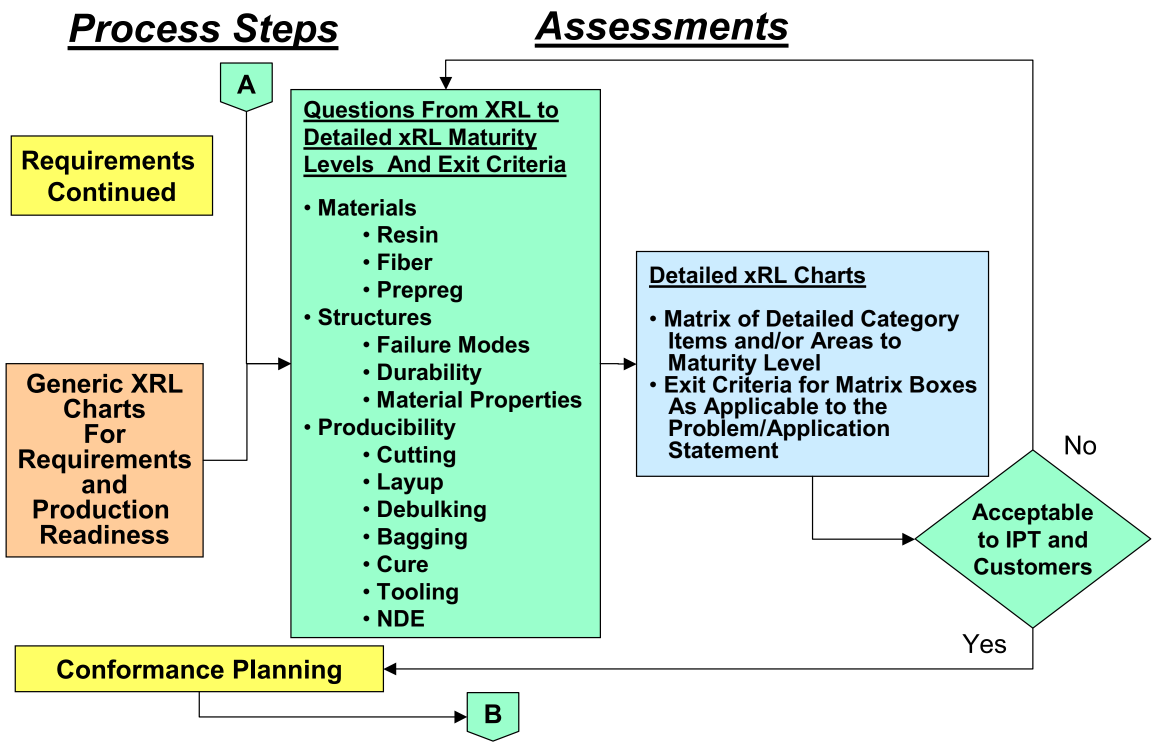



**Figure A-16 Process Flow for Requirements Definition, Continued**

An overview of the TRL sheet process flow is shown in Figure A-17. Also identified are inputs, outputs and metrics from this process.

## TRL Process Flow

1. **Identify Primary Areas Involved with Objective**
2. **Identify high level, sequential step-wise criteria going from conceptualization through disposal for each area**

INPUTS: Objective, Needs, and Customer
OUTPUTS: Technology Readiness Level Matrix Chart
METRICS: Increased Data and/or confidence and/or increased application complexity

**Figure A-17 TRL Sheet Process Flow**

An overview of the XRL sheet process flow is shown in Figure A-18. Also identified are inputs, outputs and metrics from this process along with references to be used as needed in establishing the XRL sheets.

## XRL Process Flow

1. **Identify Items Associated with Each Primary Area Involved in Objective**
   - **Include variability as an item for each primary area**
   - **Include quality characteristics relative to application or acceptance criteria as an item for each primary area**
   - **If applicable, address production readiness areas with the items**
2. **Identify sequential step-wise criteria going from conceptualization through disposal for each item**

INPUTS: Objective, Needs, and Customer plus TRL Matrix Chart
OUTPUTS: xRL Matrix Chart
METRICS: Increased Data and/or confidence and/or increased application complexity
REFERENCES: XRL Guides for Structures, Materials, Processing and Producibility/Fabrication

**Figure A-18 XRL Sheet Process Flow**

Obviously a key element in enabling AIM-C Process to be effective is to have a Methodology that links the process to the toolset that supports it and that allows accelerated technology insertion. We have chosen to do this by linking the requirements for certification of a material on an application to the technology readiness levels required for insertion of a technology into a product. Then, by tying the technology readiness levels to the readiness levels determined by each discipline required to support that level of readiness, we can roll down the requirements to the exit criteria required for a given application. This provides a roll up of the satisfaction of those requirements to the product technology readiness level so that the team can see the readiness, or the show stoppers for application of the technology to the product at any time. A design/development integrated product team (IPT) knows where to focus its resources or what expertise needs to be brought to bear in order to continue the accelerated insertion of that technology. In the worst case, the Methodology may allow the IPT to know when to curtail efforts to insert the technology because the show stoppers or schedule requirements simply cannot be met. But even in that case, the IPT has the information required to make that decision as early as it can be rationally made.

In summary, the requirements definition is conducted along with the problem statement and objective definition to identify the "Whys" of all qualification and certification activities that most programs focus on. These definitions take into account application aspects and certification agency aspects by bring them together in a systematic approach for requirements.

- **Application Aspects -** A definition has to be established for the application that the new material will be applied to. This forms the high level requirements in a complete problem statement with objectives that materials will have to meet for acceptance and insertion. Typical application information that has to be identified is working organization, program, component, manufacturing processes of interest, material systems of interest, operating environment, etc. Additional specific information is added such as associated part features and desired characteristics of prepreg ply thickness, fiber volume, resin content, dimensional accuracy, void content plus others.

- **Certification Agency Aspects -** Identification of the certification agency establishes a set of requirements that will have to be met in order to insert a new material. Items included are such things as the Joint Services Specification that establishes requirements for a full aircraft system. Areas that are included are detailed design, general parameters, specific design, structural loading, strength, durability, aeroelasticity, areoacoustic durability, survivability, plus a number of others. The intent is to develop a way of tying the certification agency requirements in to the overall methodology for new material insertion.
- **Systematic Requirements Definition Approach -** A key aspect of the AIM-C methodology is the systematic functional approach to identify requirements for what needs answering to insert a new material while simultaneously evaluating portions of risk and their consequences relative to what has to be answered. This approach is based on combining Technology Readiness Levels (TRL's) with building block segments, individual material insertion disciplines, and production readiness to establish what has been done from an exit criteria requirements standpoint. This is called a TRL sheet or tool set along with the XRL sheets or tool sets.

The requirement definition and problem/application statement activities are part of the overall AIM-C process for accelerated insertion of materials and/or processes. This total picture summary is shown in Figure A-19.

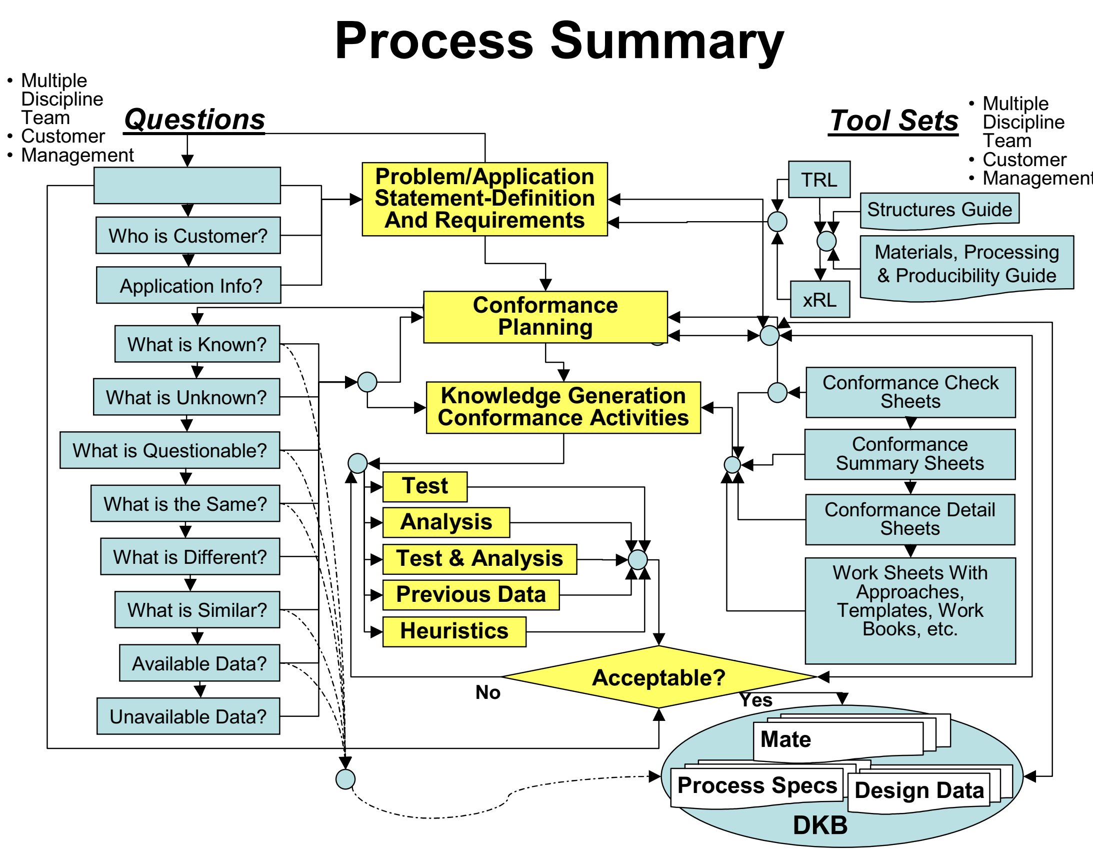



**Figure A-19 Overall AIM-C Process Summary**

In this big picture, activities are conducted simultaneously in multiple disciplines. The next series of figures shows example activities at TRL's of 2, 3, 4 and 5.

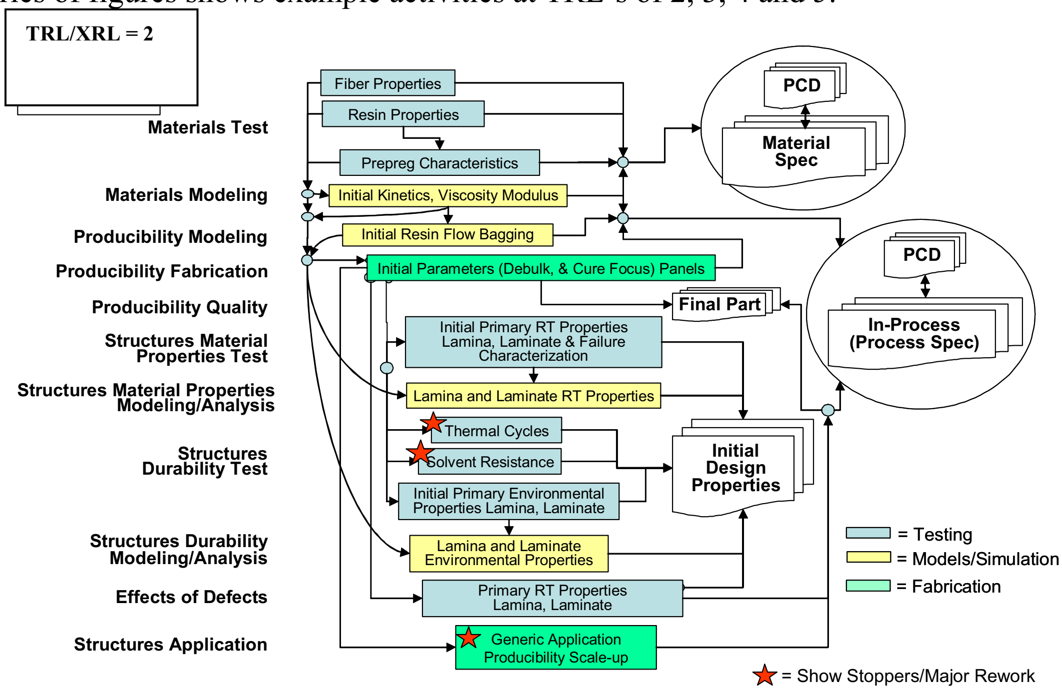



**Figure A-20 Example Common Activities at TRL 2**

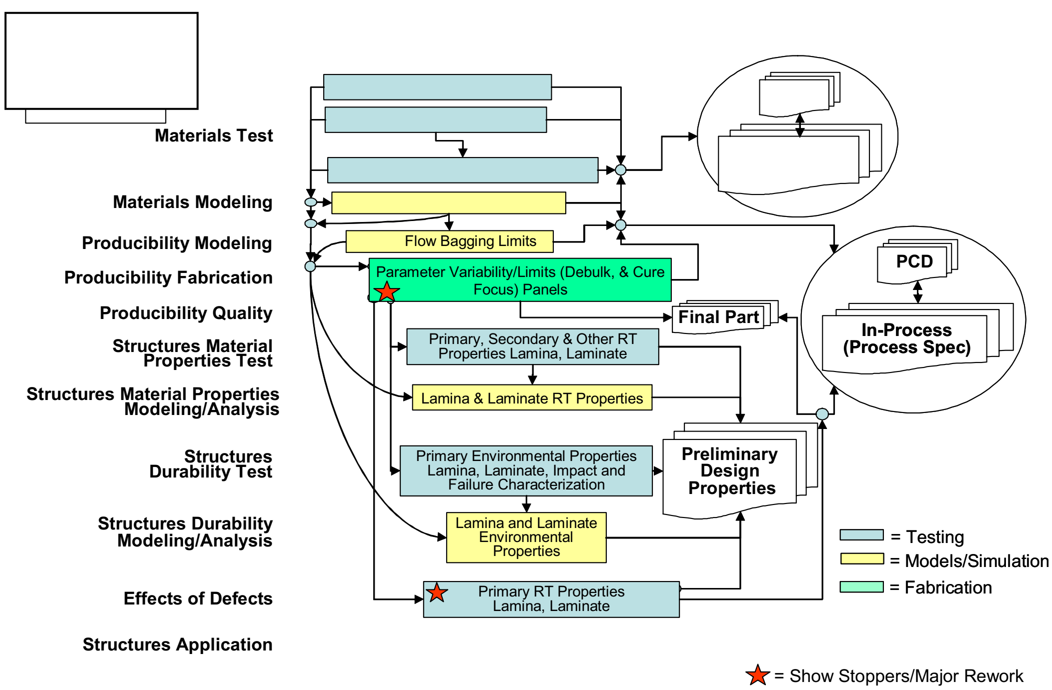



**Figure A-21 Common Activities at TRL 3**

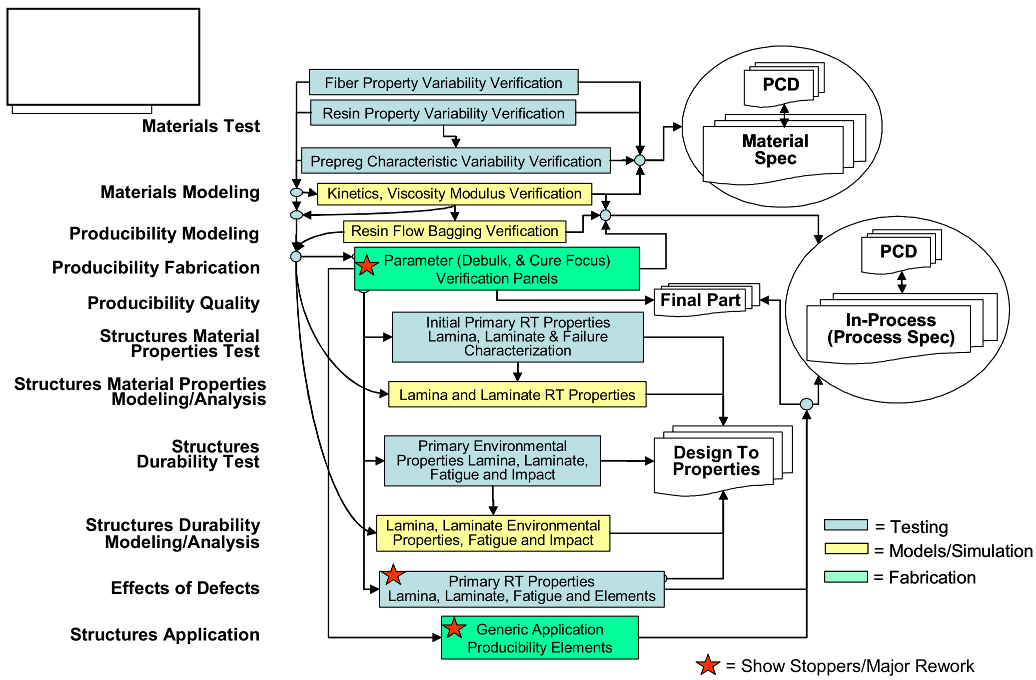



**Figure A-22 Common Activities at TRL 4**

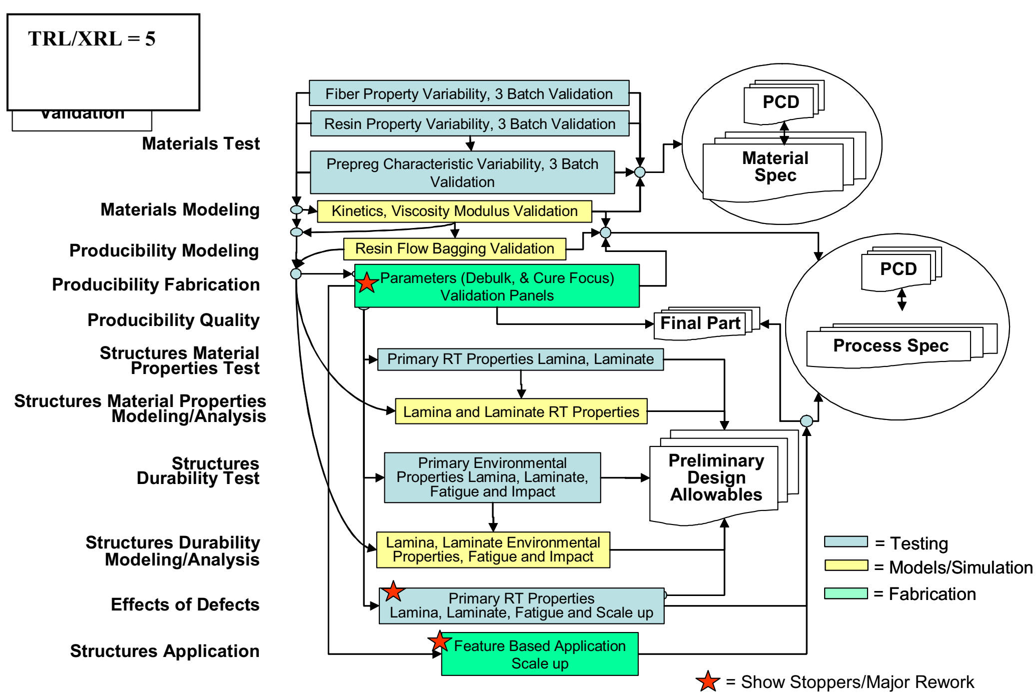



**Figure A-23 Common Activities at TRL 5**

# Technology Readiness Level (TRL) Sheets

The qualification, certification and insertion of a material is a multi-disciplined process and encompasses requirements from each of their viewpoints. This requirements methodology approach addresses each of the primary discipline and areas that have inputs to the process. These primary disciplines and areas material and/or process requirements identification are *Certification, Design, Assembly, Structures, Materials, Fabrication, Cost Benefits, Supportability, and Intellectual Property*.

To establish a TRL chart, these primary multiple discipline areas and/or items associated with the problem/application statement and requirements are listed on the left side of a sheet. An example of this is shown in Figure A-24 for a new material qualification and certification.


**Figure A-24 Primary Discipline/Areas Associated with Qualification and Certification**

The next step would be to add maturity numbers across the top of the sheet going from 1 to 10 relative to technology maturity numbering. This would form a matrix sheet as shown in Figure A-25.

| TRL | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Application/ Design | | | | | | | | | | |
| Certification | | | | | | | | | | |
| Assembly/ Quality | | | | | | | | | | |
| Structures & Durability | | | | | | | | | | |
| Materials | | | | | | | | | | |
| Fabrication/ Quality | | | | | | | | | | |
| Supportability | | | | | | | | | | |
| Survivability | | | | | | | | | | |
| Cost/Schedule/ Benefits | | | | | | | | | | |
| Intellectual Rights | | | | | | | | | | |

**Figure A-25 Example Blank Matrix TRL Sheet**

The TRL numbered blocks are filled in from a multi-disciplined perspective with specific exit criteria requirements. An example of this approach is shown for composites in Figure A-26. It was intended that each discipline would evaluate what requirements would have to be satisfied for a material insertion maturity assessment using this TRL chart with specific exit criteria.

| TRL | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Application/ Design** | Concept Exploration | Concept Definition | Proof of Concept | Preliminary Design (Elements) | Design Maturation (Revised by Subcomponent Testing) | Revised by Component Testing | Revised by Ground Testing | Revised by Flight Test | Production Support | Recycle or Dispose |
| **Certification** | Certification Elements Documented | Certification Plan Documented | Certification Plan Approved | Elements | Subcomponent Testing | Full Scale Component Testing | Full Scale Airframe Tests | Flight Test | Production Approval | Disposal Plan Approval |
| **Assembly/ Quality** | Assembly Concept | Assembly Plan Definition | Key Assembly Detail Definitions | Key Assembly Details Tested | Subcomponents Assembled | Components Assembled | Airframe Assembled | Flight Vehicles Assembled | Production | Disassembly for Disposal |
| **Structures & Durability** | Preliminary Properties-Characteristics | Initial Screening Properties (Lamina Data) | Design To Properties Developed (Laminate Data) | Preliminary Design Values | Final Design Allowables | Allowables for Critical Design Features | Production and Test Support | Certified Allowables | Flight Tracking/ Production Support/ Fleet Support | Retirement for Cause |
| **Materials** | Lab-Prototype Materials | Pilot Production Materials | Pre-Production Materials | Production Sacleability Validated | EMD Material Supplied | EMD Material Supplied | EMD Material Supplied | LRIP Material Supplied | Production Material Supplied | Support for Recycle or Disposal Decisions |
| **Fabrication/ Quality** | Unfeatured-Panel Fabrication | Feature Based Generic Small/Subscale Parts Fabricated | Property-Fab Relationships Tested/ Target Application Pilot Production of Generic Full Size Parts | Process Specs/ Effects of Fab Variations Tested/ Elements Fab'd/ Production Representative Parts Fab'd | Subcomponents Fab'd | Full Scale Components Fabricated | EMD Fabrication | Low Rate Initial Production (LRIP) | Production | Recycle or Disposal |
| **Supportability** | Repair Items/Areas Identified | Repair Materials & Processes Identified | Repair Materials & Processes Documented | Fab Repairs Identified | Fab Repair Trials/ Subcomponent Repairs | Component Repairs | Production Repairs Identified | Flight Qualified Repairs Documented | Repair-Replace Decisions | Support for Recycle or Disposal Decisions |
| **Survivability** | Requirements Definition | Concept Definition | Proof of Concept | Preliminary Design Data and Guidelines | Design Allowables and Guidelines Defined | Critical Details Testing | Ground Test | Flight Test | Production Support | Operations Support & Disposal |
| **Cost/Schedule/ Benefits** | Cost Benefit Elements ID'd & Projected | ROM Cost Benefit Analysis | Cost Benefit Analysis Reflect Size Lessons Learned | Cost Benefit Analysis Reflect Element and Production Representative Part Lessons Learned | Cost Benefit Analysis Reflect Subcomponent Fab & Assembly Lessons Learned | Cost Benefit Analysis Reflect Component Fab & Assembly Lessons Learned | Cost Benefit Analysis Reflect EMD Lessons Learned | Cost Benefit Analysis Reflect LRIP Lessons Learned | Cost Benefit Analysis Reflect Production Lessons Learned | Cost Benefit Analysis Reflect Disposal Lessons Learned |
| **Intellectual Rights** | Concept Documentation | Patent Disclosure Filed | Proprietary Rights Agreements | Data Sharing Rights | Vendor Agreements | Material and Fabrication Contracts | Production Rate Contracts | Vendor Requal Agreements | Post-Production Agreements | Liability Termination Agreements |

**Figure A-26 Example TRL Sheet with Exit Criteria**

In summary, the process steps to create a TRL matrix sheet are highlighted below. This information then leads into more detailed requirements definition sheets for each of the primary areas, items or disciplines shown in the left had column.

***<u>Create Technology Readiness Level (TRL) Matrix Sheet</u>***

**Purpose:** Identify the multiple disciplines and areas involved with the problem statement and identify top level graduated maturity exit criteria for each

- In column 1, list the areas and/or disciplines involved with problem statement
- For columns 2 through 11, use a maturity scale of 1 to 10 for matrix column headings
- For each line area/discipline box going from 1 to 10, identify specific top level exit criteria requirements

# X Readiness Level (XRL) Guides

When using this TRL table in a multi-disciplined team environment, it was found lacking as a tool to assess what had been completed for material insertion maturity for several disciplines. For example, materials could actually be divided into resin, fiber, prepreg, and adhesive which was not reflected in this chart. Another example was that fabrication could be broken down into the different methods and the methods relative to the materials. To get an accurate picture of the maturity level of materials and fabrication, other areas had to be taken into account such as equipment, tooling auxiliary processes, variability, etc. A number of these items were previously considered to be part of a production readiness assessment but really needed integration with the technical requirements and associated exit criteria. Additionally, the perspective of a system and technology readiness levels associated with the system created difficulties in communications with multiple disciplines because of semantics and multiple meanings to the same terminology. An alternative approach needed to be found to integrate disciplines into the top level TRL concepts to accommodate details from their perspectives.
The solution was establishing generic guides that could be used to generate specific XRL sheets for the different areas. These areas included structures, materials and fabrication/producibility. Details on these guides are in the next sections.

## Structures XRL Guide

The structures guide was difficult to generate because of the large areas covered. The final form generated for the AIM-C Phase I program focused on various failure mode examinations for applicability along with property generation for materials and for durability investigations. This guide is shown in the following Figure A-27.

**STRUCTURAL CHARATERISTIC** **Date: 10/6/2003**

| xRL | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| **In-plane Ultimate Strength -- Unnotched Compression** | Approximate design values based on at least 3 evaluation results at RT | Approximate design values based on at least 3 evaluation results at RT | Approximate design values based on initial tests of 3 laminates at RT. Environmental factors and statistical factors based on data from similar systems. Layup, environmental, and statistical corrections from similar systems. | Data for at least 3 laminates, 3 replicates at critical design environment. Statistical basis from similar data | Data for 3 laminates, 3 batches. Layup, environmental, and statistical corrections from actual system. | Test data sufficient to establish B-Basis values. Fully validated Analysis Method. Initial Effects of defects analyses performed. | Test data sufficient to establish A-Basis values where needed. Fully validated Analysis Method. | Effects of defects covering items such as oversized holes and short e/D. Fully validated Analysis Method. | Customer sign-off on open hole allowables and relevant analysis methods for off-design points. | Repair methods and approaches established and verified. |
| **In-plane Ultimate Strength -- Unnotched Tension** | Approximate design values based on at least 3 evaluation results at RT | Approximate design values based on at least 3 evaluation results at RT | | | | | | | | |
| **Ultimate Strength -- Combined Loads** | N/A | N/A | Approximate bending and shear interaction from experience/past data | | Bending and shear interaction from analysis using current data | Bending and shear interaction by validated analysis or data from similar concepts | | Bending and shear interaction validated by element tests | Customer sign-off on data and methods. Component and Full-scale static test validation. | |
| **In-plane Ultimate Strength -- Open Hole Compression** | Approximate design values based on at least 3 evaluation results at RT, ET, and ET Wet | Approximate design values based on at least 3 evaluation results at RT, ET, and ET Wet | Approximate design values based on initial tests of 3 laminates at RT. Environmental factors and statistical factors based on data from similar systems Layup, environmental, and statistical corrections from similar systems. | Data for at least 3 laminates, 3 replicates at critical design environment. Statistical basis from similar data | Data for 3 laminates, 3 batches. Layup, environmental, and statistical corrections from actual system. | Test data sufficient to establish B-Basis values. Fully validated Analysis Method. Initial effects of defects analyses performed | Test data sufficient to establish A-Basis values where needed. Fully validated Analysis Method. | Effects of defects covering items such as oversized holes and short e/D. Fully validated Analysis Method. | Customer sign-off on open hole allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **In-plane Ultimate Strength -- Open Hole Tension** | Approximate design values based on at least 3 evaluation results at RT and low temp | Approximate design values based on at least 3 evaluation results at RT and low temp | | | | | | | | |
| **Ultimate Strength -- Open Hole, Combined Loads** | N/A | N/A | Approximate bending and shear interaction from experience/past data | | Bending and shear interaction from analysis using current data | Bending and shear interaction by validated analysis or data from similar concepts Initial effects of defects analyses performed | | Bending and shear interaction validated by element tests | Customer sign-off on data and methods. Component and Full-scale static test validation. | |
| **Stability - Global/Panel** | Data (modulus) from similar system | Data (modulus) from similar system | Typical lamina vendor data. Laminate data by approx. analysis (e.g., CLPT). Layup, environmental, and statistical corrections from similar systems. | Typical lamina vendor data. Laminate data by approx. analysis (e.g., CLPT). Layup, environmental, and statistical corrections from similar systems. | Lamina modulus data sufficient to establish environmental and statistical corrections. Laminate data by approx. analysis (e.g., CLPT). | Laminate data sufficient to establish B-Basis values at all relevant environments. Analysis of typical areas (e.g., Eigenvalue buckling) Initial effects of defects analyses performed. | Laminate data sufficient to establish A-Basis values. Detailed Analysis of complex/ critical areas (e.g., NL FEA) | Critical areas validated by subcomponent test. Effects of manufacturing variations and defects analyzed. | Customer sign-off on data and methods. Component and Full-scale static test validation. | Repair methods and approaches established and verified. |
| **Stability - Skin Buckling** | Data (modulus) from similar system | Data (modulus) from similar system | Typical lamina vendor data. Laminate data by approx. analysis (e.g., CLPT). Layup, environmental, boundary conditions, and statistical corrections from similar systems. | Typical lamina vendor data tailored to available data. Laminate data by approx. analysis (e.g., CLPT). Layup, environmental, boundary conditions, and statistical corrections from similar systems. | Lamina modulus data sufficient to establish environmental and statistical corrections. Analysis uses more rigorous methods (FEM, Eigenvalue Extraction, etc) | Analysis of typical areas (e.g., Non-linear FEA, Eigenvalue buckling) verified by key features test. Initial effects of defects analyses performed. | Laminate data sufficient to establish A-Basis values if necessary. Detailed Analysis of complex/ critical areas (e.g., NL FEA) | Critical areas validated by subcomponent test. Effects of manufacturing variations and defects analyzed. | Customer sign-off on data and methods. Component and Full-scale static test validation. | Repair methods and approaches established and verified. |
| **Stability - Stringer Crippling** | Data (modulus) from similar system | Data (modulus) from similar system | Typical lamina vendor data. Laminate data by approx. analysis (e.g., CRIP). Layup, environmental, boundary conditions, and statistical corrections from similar systems. | Typical lamina vendor data tailored to available data. Crippling analysis by approx. methods (e.g., EBMCOL). Layup, environmental, boundary conditions, and statistical corrections from similar systems. | Lamina modulus data sufficient to establish environmental and statistical corrections. Analysis uses more rigorous methods (Eigenvalue Extraction, Non-Linear FEM, etc) | Analysis of typical areas (e.g., Non-linear FEA, Eigenvalue buckling) verified by key features test. Initial effects of defects analyses performed. | Laminate data sufficient to establish A-Basis values if necessary. Detailed Analysis of complex/ critical areas (e.g., NL FEA) | Critical areas validated by subcomponent test. Effects of manufacturing variations and defects analyzed. | Customer sign-off on data and methods. Component and Full-scale static test validation. | Repair methods and approaches established and verified. |
| **Stability - Stringer Column Buckling** | Data (modulus) from similar system | Data (modulus) from similar system | Typical lamina vendor data. Laminate data by approx. analysis (e.g., CRIP). Layup, environmental, boundary conditions, and statistical corrections from similar systems. | Typical lamina vendor data tailored to available data. Crippling analysis by approx. methods (e.g., EBMCOL). Layup, environmental, boundary conditions, and statistical corrections from similar systems. | Lamina modulus data sufficient to establish environmental and statistical corrections. Analysis uses more rigorous methods (Eigenvalue Extraction, Non-Linear FEM, etc) | Analysis of typical areas (e.g., Non-linear FEA, Eigenvalue buckling) verified by key features test. Initial effects of defects analyses performed. | Laminate data sufficient to establish A-Basis values if necessary. Detailed Analysis of complex/ critical areas (e.g., NL FEA) | Critical areas validated by subcomponent test. Effects of manufacturing variations and defects analyzed. | Customer sign-off on data and methods. Component and Full-scale static test validation. | Repair methods and approaches established and verified. |
| **Bond/Interlaminar Joint Strength - Damage Initiation** | Approximate design values based on experience. Data from similar system. | Approximate design values based on experience. Data from similar system. | Approximate design values based on initial tests of 3 laminates at RT. Environmental factors and statistical factors based on data from similar systems. Layup, environmental, and statistical corrections from similar systems. | Data for at least 3 laminates, 3 replicates at critical design environment. Statistical basis from similar data | Data for 3 laminates, 3 batches. Layup, environmental, and statistical corrections from actual system. | Test data sufficient to establish B-Basis values. Fully validated Analysis Method. Initial effects of defects analyses performed | Test data sufficient to establish A-Basis values where needed. Fully validated Analysis Method. | Effects of defects covering items such as oversized holes and short e/D. Fully validated Analysis Method. | Customer sign-off on open hole allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Bond/Interlaminar Joint Strength - Final Failure** | Approximate design values based on experience. Data from similar system. | Approximate design values based on experience. Data from similar system. | Approximate design values based on initial tests of 3 laminates at RT. Environmental factors and statistical factors based on data from similar systems. Layup, environmental, and statistical corrections from similar systems. | Data for at least 3 laminates, 3 replicates at critical design environment. Statistical basis from similar data | Data for 3 laminates, 3 batches. Layup, environmental, and statistical corrections from actual system. | Test data sufficient to establish B-Basis values. Fully validated Analysis Method. Initial effects of defects analyses performed | Test data sufficient to establish A-Basis values where needed. Fully validated Analysis Method. | Effects of defects covering items such as oversized holes and short e/D. Fully validated Analysis Method. | Customer sign-off on open hole allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Bolted Joint - Bearing/Bypass** | Approximate design values based on experience. Data from similar system. | Approximate design values based on experience. Data from similar system. | Approximate design values based on initial tests of 3 laminates at RT. Environmental factors and statistical factors based on data from similar systems. Layup, environmental, and statistical corrections from similar systems. | Data for at least 3 laminates, 3 replicates at critical design environment. Statistical basis from similar data | Data for 3 laminates, 3 batches. Layup, environmental, and statistical corrections from actual system. | Test data sufficient to establish B-Basis values. Fully validated Analysis Method. Initial effects of defects analyses performed | Test data sufficient to establish A-Basis values where needed. Fully validated Analysis Method. | Effects of defects covering items such as oversized holes and short e/D. Fully validated Analysis Method. | Customer sign-off on open hole allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Maximum Deflection** | Data (modulus) from similar system | Data (modulus) from similar system | Typical lamina vendor data. Laminate data by approx. analysis (e.g., CRIP). Layup, environmental, boundary conditions, and statistical corrections from similar systems. | Typical lamina vendor data tailored to available data. Crippling analysis by approx. methods (e.g., EBMCOL). Layup, environmental, boundary conditions, and statistical corrections from similar systems. | Lamina modulus data sufficient to establish environmental and statistical corrections. Analysis uses more rigorous methods (Eigenvalue Extraction, Non-Linear FEM, etc) | Analysis of typical areas (e.g., Non-linear FEA, Eigenvalue buckling) verified by key features test. Initial effects of defects analyses performed. | Laminate data sufficient to establish A-Basis values if necessary. Detailed Analysis of complex/ critical areas (e.g., NL FEA) | Critical areas validated by subcomponent test. Effects of manufacturing variations and defects analyzed. | Customer sign-off on data and methods. Component and Full-scale static test validation. | Repair methods and approaches established and verified. |
| **Residual Strength -- BVID, Compression** | Approximate design values based on experience. Data from similar system. | Approximate design values based on experience. Data from similar system. | Approximate design values based on initial tests of 3 laminates at RT. Environmental factors and statistical factors based on data from similar systems. Layup, environmental, and statistical corrections from similar systems. | Data for at least 3 laminates, 3 replicates at critical design environment. Statistical basis from similar data | Typical vendor data for 3 laminates, 3 batches. Layup, environmental, and statistical corrections from actual system. | Test data sufficient to establish B-Basis values. Fully validated Analysis Method. Initial effects of defects analyses performed | Test data sufficient to establish A-Basis values where needed. Fully validated Analysis Method. | Effects of defects covering items such as oversized holes and short e/D. Fully validated Analysis Method. | Customer sign-off on open hole allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Residual Strength -- Penetrations, Tension** | Approximate design values based on experience. Data from similar system. | Approximate design values based on experience. Data from similar system. | Approximate design values based on initial tests of 3 laminates at RT. Environmental factors and statistical factors based on data from similar systems. Layup, environmental, and statistical corrections from similar systems. | Data for at least 3 laminates, 3 replicates at critical design environment. Statistical basis from similar data | Typical vendor data for 3 laminates, 3 batches. Layup, environmental, and statistical corrections from actual system. | Test data sufficient to establish B-Basis values. Fully validated Analysis Method. Initial effects of defects analyses performed | Test data sufficient to establish A-Basis values where needed. Fully validated Analysis Method. | Effects of defects covering items such as oversized holes and short e/D. Fully validated Analysis Method. | Customer sign-off on open hole allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Residual Strength -- Penetrations, Compression** | | | | | | | | | | |
| **Residual Strength -- Penetrations, Combined Loads** | N/A | N/A | Approximate bending and shear interaction from experience/past data | | Bending and shear interaction from analysis using current data | Bending and shear interaction by validated analysis or data from similar concepts Initial effects of defects analyses performed | | Bending and shear interaction validated by element tests | Customer sign-off on data and methods. Component and Full-scale static test validation. | |
| **Local Stability - Face wrinkling (Sandwich Only)** | Approximate design values based on experience. Data from similar system. | Approximate design values based on experience. Data from similar system. | Approximate design values based on initial tests of 3 laminates at RT. Environmental factors and statistical factors based on data from similar systems. Layup, environmental, and statistical corrections from similar systems. | Data for at least 3 laminates, 3 replicates at critical design environment. Statistical basis from similar data | Typical vendor data for 3 laminates, 3 batches. Layup, environmental, and statistical corrections from actual system. | Test data sufficient to establish B-Basis values. Fully validated Analysis Method. Initial effects of defects analyses performed | Test data sufficient to establish A-Basis values where needed. Fully validated Analysis Method. | Effects of defects covering items such as oversized holes and short e/D. Fully validated Analysis Method. | Customer sign-off on open hole allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Local Stability - Intracell Buckling (Sandwich Only)** | Approximate design values based on experience. Data from similar system. | Approximate design values based on experience. Data from similar system. | Approximate design values based on initial tests of 3 laminates at RT. Environmental factors and statistical factors based on data from similar systems. Layup, environmental, and statistical corrections from similar systems. | Data for at least 3 laminates, 3 replicates at critical design environment. Statistical basis from similar data | Data for 3 laminates, 3 batches. Layup, environmental, and statistical corrections from actual system. | Test data sufficient to establish B-Basis values. Fully validated Analysis Method. Initial effects of defects analyses performed | Test data sufficient to establish A-Basis values where needed. Fully validated Analysis Method. | Effects of defects covering items such as oversized holes and short e/D. Fully validated Analysis Method. | Customer sign-off on open hole allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Local Stability - Shear Crimping (Sandwich Only)** | Approximate design values based on experience. Data from similar system. | Approximate design values based on experience. Data from similar system. | Approximate design values based on initial tests of 3 laminates at RT. Environmental factors and statistical factors based on data from similar systems. Layup, environmental, and statistical corrections from similar systems. | Data for at least 3 laminates, 3 replicates at critical design environment. Statistical basis from similar data | Data for 3 laminates, 3 batches. Layup, environmental, and statistical corrections from actual system. | Test data sufficient to establish B-Basis values. Fully validated Analysis Method. Initial effects of defects analyses performed | Test data sufficient to establish A-Basis values where needed. Fully validated Analysis Method. | Effects of defects covering items such as oversized holes and short e/D. Fully validated Analysis Method. | Customer sign-off on open hole allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |

**DURABILITY**

**STRUCTURAL CHARATERISTIC** **Date: 10/6/2003**

| xRL | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Durability/Life - Microcracking** | N/A | Approximate design values based on evaluations | Approximate design values based on initial tests of 3 laminates at RT. Environmental factors and statistical factors based on data from similar systems. Layup, environmental, and statistical corrections from similar systems. | Data for at least 3 laminates, 3 replicates at critical design environment. Statistical basis from similar data | Data for 3 laminates, 3 batches. Layup, environmental, and statistical corrections from actual system. | Test data sufficient to establish B-Basis values. Fully validated Analysis Method. Initial effects of defects analyses performed | Test data sufficient to establish A-Basis values where needed. Fully validated Analysis Method. | Effects of defects covering items such as oversized holes and short e/D. Fully validated Analysis Method. | Customer sign-off on open hole allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Durability/Life - Delamination Growth** | N/A | Approximate design values based on experience. Data from similar system. | Approximate design values based on initial tests of 3 laminates at RT. Environmental factors and statistical factors based on data from similar systems. Layup, environmental, and statistical corrections from similar systems. | Data for at least 3 laminates, 3 replicates at critical design environment. Statistical basis from similar data | Data for 3 laminates, 3 batches. Layup, environmental, and statistical corrections from actual system. | Test data sufficient to establish B-Basis values. Fully validated Analysis Method. Initial effects of defects analyses performed | Test data sufficient to establish A-Basis values where needed. Fully validated Analysis Method. | Effects of defects covering items such as oversized holes and short e/D. Fully validated Analysis Method. | Customer sign-off on open hole allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Durability/Life - Stiffness Degradation** | N/A | Approximate design values based on experience. Data from similar system. | Approximate design values based on initial tests of 3 laminates at RT. Environmental factors and statistical factors based on data from similar systems. Layup, environmental, and statistical corrections from similar systems. | Data for at least 3 laminates, 3 replicates at critical design environment. Statistical basis from similar data | Data for 3 laminates, 3 batches. Layup, environmental, and statistical corrections from actual system. | Test data sufficient to establish B-Basis values. Fully validated Analysis Method. Initial effects of defects analyses performed | Test data sufficient to establish A-Basis values where needed. Fully validated Analysis Method. | Effects of defects covering items such as oversized holes and short e/D. Fully validated Analysis Method. | Customer sign-off on open hole allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Durability/Life - Bearing Strength Degradation** | N/A | Approximate design values based on experience. Data from similar system. | Approximate design values based on initial tests of 3 laminates at RT. Environmental factors and statistical factors based on data from similar systems. Layup, environmental, and statistical corrections from similar systems. | Data for at least 3 laminates, 3 replicates at critical design environment. Statistical basis from similar data | Data for 3 laminates, 3 batches. Layup, environmental, and statistical corrections from actual system. | Test data sufficient to establish B-Basis values. Fully validated Analysis Method. Initial effects of defects analyses performed | Test data sufficient to establish A-Basis values where needed. Fully validated Analysis Method. | Effects of defects covering items such as oversized holes and short e/D. Fully validated Analysis Method. | Customer sign-off on open hole allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |

**MATERIAL FAMILY PROPERTIES AND MATERIAL DURABILITY (Material Allowables, Coupon Level Evaluations)**

**STRUCTURAL CHARATERISTIC** **Date: 10/6/2003**

| xRL | 0 | | | | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Material Mechanical Properties - Primary (Tension, Compression, Shear, Bearing By-pass)** | Approximate values based on experience/data from similar system. | Approximate values based on at least 3 evaluation results at RT plus data from similar systems | fo c values based on initia inate data at RT. Lay s initiated. Statistical similar systems. | | s, 3 ns f cts mer wabl Layup and al material ts analyses on lamina | Effects of defects covering items such as oversized holes and short e/D. Test data sufficient to establish B-Basis values. Fully validated Analysis Method. | Test data sufficient to establish A-Basis values where needed. | | Customer sign-off on all allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Material Mechanical Properties - Secondary (CTE, Poisson's, Fracture Toughness, )** | Approximate design values based on experience/data from similar system. | Approximate values based on at least 3 evaluation results at RT plus data from similar systems | App fo c values based on initia inate data at RT. Lay s initiated. Statistical similar systems. | | s, 3 ns f cts orm Layup and al material ts analyses | Effects of defects covering items such as oversized holes and short e/D. Test data sufficient to establish B-Basis values. Fully validated Analysis Method. | Test data sufficient to establish A-Basis values where needed. | | Customer sign-off on all allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Material Mechanical Properties - Other ()** | Approximate design values based on experience/data from similar system. | Approximate values based on at least 3 evaluation results at RT plus data from similar systems | A f values based on initia inate data at RT. Lay s initiated. Statistical similar systems. | | s, 3 ns f cts orm Layup and al material ts analyses | Effects of defects covering items such as oversized holes and short e/D. Test data sufficient to establish B-Basis values. Fully validated Analysis Method. | Test data sufficient to establish A-Basis values where needed. | | Customer sign-off on all allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Material Durability/Life Properties - Environmental Impact on Properties** | Approximate design values based on experience/data from similar system. | Approximate values based on at least 3 evaluation results at possibly low temp, ET and/or ET Wet plus data from similar systems. Other durability investigations initiated. | A f La values based on initia inate data at environm correlation activities in rom other similar syste | | s, 3 batches. Layup and ns from actual material cts of defects analyses mer sign off on lamina wables. | Effects of defects covering items such as oversized holes and short e/D. Test data sufficient to establish B-Basis values. Fully validated Analysis Method. | Test data sufficient to establish A-Basis values where needed. | | Customer sign-off on all allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Material Durability/Life Properties - Impact Resistance and Fatigue** | N/A | Approximate values based on experience/data from similar system. | sign values based on i Layup, environmental tions from similar syste | | s, 3 batches. Layup and ns from actual material cts of defects analyses ormed. | Effects of defects covering items such as oversized holes and short e/D. Test data sufficient to establish B-Basis values. Fully validated Analysis Method. | Test data sufficient to establish A-Basis values where needed. | | Customer sign-off on all allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Material Durability/Life Properties - Solvent Resistance** | N/A | Approximate values based on evaluation results of solvent investigations | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |

**Figure A-27 Generic Structures XRL Guide**

## Materials, Processing and Producibility XRL Guide

The guide for materials, processes and fabrication/producibility detailed requirements came about because of shortcomings in the requirements area for production readiness leading to qualification. The AIM-C program established a generic guide that could be used in defining specific exit criteria for different material, processing and fabrication/producibility areas.

Production readiness is normally associated with manufacturing/production equipment, tooling, and processes or methods. This definition has been expanded in the AIM-C program to cover all technology elements and would better be titled "Insertion" readiness because of this. A more detailed definition of production/insertion readiness is given in Figure A-28 and correlates with previous definitions of production readiness except with a larger perspective.

**Definition**

- The ability to adhere to appropriately documented processes/delineated procedures and to adequately record all pertinent information on what actually occurred for traceability.
- Paperwork includes procurement documents, specifications, process instructions (planning/work orders, travellers, quality techniques, etc.).
- Capital equipment needs and calibration/certification, tooling, personnel training, and process flow are typical elements.
- ISO 9000 methodologies should be used throughout the qualification process.
- It is important to establish a product dependability plan along the lines of ISO 9000-4.

**Figure A-28 Production/Insertion Readiness Definition**

By the previous definition, production/insertion readiness encompasses multiple areas besides production/manufacturing. Specific areas for the AIM-C program are shown in Figure A-29 and cover materials, analytical tools, design, manufacturing steps and repairs. These areas are expanded over the normal connotation of what production readiness covers. In practice, these areas are assessed for readiness but not usually under production readiness.

**Assessment Areas**

- **Primary Materials**
  - Resin
  - Fiber
  - Prepreg
- **Secondary Materials**
  - Adhesive
  - Core
  - Other
- **Analysis Tools**
- **Design**
  - Joints/Assembly
  - Features
  - Configuration
  - Application
- **Manufacturing Steps/ Operations**
  - Tooling
  - Cutting
  - Layup
  - Bagging
  - Cure
  - NDE
- **Repairs**

**Figure A-29 Production/Insertion Readiness Assessment Areas**

For each of the areas, there are a number of items that have to be addressed to give a complete picture of the readiness of a technology or area for insertion and usage. Figure A-30 shows representative items that are covered in an assessment of a technology area. These items cover most of the key aspects that have to be understood, evaluated or the metrics of for an assessment of where it is in a maturity or risk level.

**Assessment Items**

- **Production Processes**
- **Equipment**
- **Tooling**
- **Quality**
- **Variability**
- **Cost/Benefit Analysis**
- **Application Maturity**
- **Supportability**
- **Regulatory**
- **Intellectual Property**

**Figure A-30 Requirement Readiness Assessment Items**

These requirement assessment items were then incorporated into a generic maturity level matrix with example exit criteria to establish a guide. The guide can be used to develop specific XRL sheets for multiple areas in material, processing and fabrication/producibility. The generic sheet is shown in Figure A-31.

**Material and Producibility xRL Guide**

**Date: 10/6/2003**

| (x)RL Rating | 0 | | | 1 | 2 | | 3 | | 4 | 5 | 6 - 7 | 8 - 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 2.1 - 2.4 | 2.5 - 2.9 | 3.0 - 3.4 | 3.5 - 3.9 | | | | | |
| MATERIAL | Material ingredients/ combinations never used previously. No industrial base capability available. Constituent properties and compatibility issues unknown. | Material ingredients/combinations made in a laboratory environment. No industrial base capability available. Constituent properties and compatibility issues identified. | Key material ingredient characteristics identified for processing, quality, and application. Potential approaches identified to remedy incompatibilities. | Critical functions/ characteristics of material/ ingredients demonstrated. New material within state-of-the-art. Indirect material requirements identified. Facility requirements identified. | Proof-of-concept completed for production, properties, and scale-up of material under relevant conditions achieved (including resolving of material incompatibilities). | Material requirements/outputs OK based on models and/or prototypes and/or pilot plant in relavent environment. Marginal capacity (e.g., single source, offshore only, pilot plant, etc). | Material requirements tested in relevant environment. Scale-up and cost issues addressed. Adequate capacity for ingedients/material available in-house or in an industrial base (vendors). Certification requirements identified. | Material is repeatable, stable and storage requirements evaluated. Technical data packages and associated material proof tests completed. Materials and controls verified as sufficient to support scale-up, rate, cost, quality, and regulatory requirements. | Production readiness review accepts production material. All documentation is complete and training program for personnel complete for certification. | Successful prototype or low rate production of material achieved. Production readiness review accepts production material. Documentation/data package and training complete. | Successful production of less than 30 batches achieved. | Successful production of greater than 30 batches achieved. | Considered an industry standard. |
| PROCESSES | Requires technology never used previously. No industrial base capability available. Constituent properties and compatibility issues unknown. | Requires yields/tolerances/ throughput/scale not previously achieved. New process needed requiring state-of-the-art advance. Critical facility or vendor not available. Process compatibility issues identified. | Key characteristics identified for process, quality, and application. Potential approaches identified to remedy incompatibilities. | Critical functions/ characteristics of processing demonstrated. New process operates within state-of-the-art. Facility requirements identified. Indirect materials or process steps identified. | Proof-of-concept completed for production, properties, and scale-up of process achieved under relevant conditions (including resolving of material incompatibilities). One or more requirements only marginally achievable. | Process requirements/outputs OK based on models and/or prototypes and/or pilot plant. Marginal capacity (e.g., single source, offshore only, etc). | Processing requirements tested in relevant environment including scale-up issues. Yields/tolerances/process controls meet needs and blessed by all functions. Process limits defined and tested. Production capability verified (possibly for similar operational product). | Yields/tolerances/process controls meet needs and blessed by all functions. Process limits defined and tested. Production capability verified in operational environment (possibly for similar operational product). Qualification/certification requirements identified. | Adequate capacity available in-house or in an industrial base (vendors). Processes and controls verified as sufficient to support scale-up, rate, cost, quality, and regulatory requirements. | Production readiness review accepts production processes. Documentation/data package and training complete. | Associated process proof tests completed. Successful use of process for less than 30 times achieved. | Successful use of process for greater than 30 times achieved. | Considered an indusrty standard |
| EQUIPMENT | Appropriate equipment does not exist and/or requirements are not known. | Necessary equipment requirements identified including key technology areas. | Key characteristics identified for process, quality, and application. Characteristics applicable to technology areas and individual equipment pieces. | Critical functions/ characteristics of individual equipment pieces demonstrated. Indirect materials and facility requirements identified. Equipment accuracy requirements defined. | Initial proof-of-concept testing completed including critical scale-up issues. | Integration of equipment parts/systems demonstrated. | Capabilities of integrated equipment tested in relevant environment including scale-up issues. Certification requirements identified. | Equipment accuracy and consistency verified for operational environment (possibly on similar operational product). Demonstrated integration of equipment into the users systems/facility. | Verified as sufficient to support scale-up, rate, cost, quality, and regulatory requirements. Successful production of test articles. | Production readiness review accepts equipment. Documentation, training and certification complete. | Associated process proof tests completed. Successful use of equipment for less than 30 times and/or less than 30 pieces of equipment achieved. | Sucessful use of equipment for greater than 30 times and/or greater than 30 pieces of equipment achieved. | Considered an industry standard |
| TOOLING | Appropriate tooling does not exist or requirements are not known. | Necessary tooling requirements identified and includes key technology areas. | Key characteristics identified for process, quality, and application. Characteristics applicable to technology areas and individual equipment pieces. | Critical functions/ characteristics of individual tooling pieces demonstrated. Indirect materials and facility requirements identified. Tooling accuracy requirements defined. | Initial proof-of-concept testing completed including scale-up issues. | Integration of tooling parts/details/systems demonstrated. | Capabilities of integrated tooling tested in relevant environment including scale-up issues. Certification requirements identified. | Tooling accuracy and consistency verified for operational environment (possibly on similar operational product). Integration of tooling into the users systems/facility demonstrated. | Verified as sufficient to support scale-up, rate, cost, quality, and regulatory requirements. Successful production of test articles. | Production readiness review accepts tooling. Documentation, training and certification complete. | Associated process proof tests completed. Successful use of tooling for less than 30 times and/or less than 30 tools achieved. | Sucessful use of tooling for greater than 30 times and/or greater than 30 tools achieved. | Considered an industry standard |
| VARIABILITY | Drivers of variability unknown or not understood. | Some items of variability identified. | Key drivers of variability identified. Methods of measuring identified. | Variabilities roughly characterized. | Variabilities measured with tests on representative samples/items and used as base line capabilities. Proof-of-concept for scale-up variablity issues identified. | Variability requirements OK based on models and/or prototypes and/or pilot plant. | Variabilities measured in relevant environment and includes scale-up issues. | Variabilities measured in operational environment and consistent with projections. | Verified as sufficient to support scale-up, rate, cost, quality, and regulatory requirements. | Production readiness review accepts procedures and capabilities for variability management. Variability control plan accepted and documentation complete. | Variability measured on less than 30 parts/items. | Variability measured on greater than 30 parts/items. | Considered an industry standard |
| QUALITY - IN-PROCESS | Requires technology never used in manufacturing previously. No industrial base capability available | Requires Q/A capability levels not previously achieved. | Key quality characteristics identified. | Critical quality functions/characteristics demonstrated. Indirect material and/or process steps identified. Facility requirements identified. Defects identified | Proof-of-concept for quality practices/procedures/techniques successfully demonstrated including scale-up issues. | Quality requirements/outputs OK based on models and/or prototypes. Defects evaluated. | Inspection and Q/C techniques defined and tested in relevant environment including scale-up issues. Results are blessed by all functions. Capability for use in production verified (possibly for similar operational product). | Quality, accuracy and consistency verified for an operational environment. Demonstrated integration of the quality functions into user systems/facility. Defect limits establsihed | Quality procedures and techniques verified as sufficient to support scale-up, rate, cost, requirements, and regulatory requirements. Successful use on test articles. | Verified as sufficient to support scale-up, rate, cost, and regulatory requirements. Production readiness review accepts procedures and capabilities for final product quality assurance/control. Documentation, training, certification complete. Effects of defects known. | Quality techniques and procedures used for less than 30 final parts and quality acceptance. | Quality techniques and procedures used for greater than 30 final parts and quality acceptance. | Considered an industry standard. |
| QUALITY - FINAL PRODUCT | Requires technology never used in manufacturing previously. No industrial base capability available | Requires Q/A capability levels not previously achieved. | Key quality characteristics identified. | Critical quality functions/characteristics demonstrated. Indirect material and/or process steps identified. Facility requirements identified. Defects identified. | Proof-of-concept for quality practices/procedures/techniques successfully demonstrated including scale-up issues. | Quality requirements/outputs OK based on models and/or prototypes. Defects evaluated. | Inspection and Q/C techniques defined and tested in relevant environment including scale-up issues. Results are blessed by all functions. Capability for use in production verified (possibly for similar operational product). Generic sull-scale parts evaluated. | Quality, accuracy and consistency verified for an operational environment. Demonstrated integration of the quality functions into user systems/facility. Defect Llimits established. | Quality procedures and techniques verified as sufficient to support scale-up, rate, cost, and regulatory requirements. Successful use on test articles. Production representative parts evaluated | Verified as sufficient to support scale-up, rate, cost, and regulatory requirements. Production readiness review accepts procedures and capabilities for final product quality assurance/control. Documentation, training, certification complete. Effects of defects known. | Quality techniques and procedures used for less than 30 final parts and quality acceptance. | Quality techniques and procedures used for greater than 30 final parts and quality acceptance. | Considered an industry standard. |
| APPLICATION MATURITY | New technology required; state-of-the art advance. One or more requirements may be unachievable. | Relevant unit problems identified, technologies understood and tested at unit level. | Primary functions/characteristics understood and demonstrated. | Critical functions/characteristics demonstrated; physical phenomena understood. | Component/breadboard successfully tested in relevant environments,OR, existing item requiring major modification tested. One or more requirements only marginally achievable. | Generic small-subscale prototype parts or engineering models successfully tested in relevant environments, OR, existing item requiring significant modification tested. | Prototype or engineering model successfully tested in relevant environments, OR, existing item requiring minor modification. | Uses individually qualified items which require integration, OR, successfully tested in an operational environment, OR, uses existing item, but qualification needed. | Qualification testing initiated. | Qualification testing successfully completed. | Design uses only fully qualified existing items. No added development/integration. | Developmental/initial operational testing successfully completed. | Physical and functional audits successfully completed |
| COST/BENEFIT ANALYSIS | Cost/benfits not known. | High level costs/benefits identified. | Costs/benefits defined. | Key costs/benfits have had a preliminary assessment for quantification. | Key costs/benefits have been shown in a relavent environment with scale-up. | Key costs/benefits have been shown with models and/or prototypes. | All cost benefits elements have been shown in a relavent environment. | All cost benefits elements have been validated in a representative environment. | All cost benefits elements verified in actual usage environment. | Cost/benefit analysis accepted by users for production readiness reviews. | Costs/benefits validated on less than 30 items. | Costs/benefits validated on greater than 30 items. | Costs/benefits understood at an industry level. |
| SUPPORTABILITY | Requires repair technology never used before. No capability available. | New repair processes requiring state-of-the-art advanced. | Key characteristics identified for repair processes. | Critical repair functions and characteristics demonstrated. | Proof-of-concept completed for repair procedures under relevant conditions including scale-up issues, OR, major modification of proven repair procedure completed. | Repair requirements OK based on models and prototypes, OR, significant modification of proven repair procedures completed. | Repair requirements tested in relevant environment including cost and scale-up issues, OR, minor modification of proven repair procedures. | Repair processes meet need (possibly based on experience on similar product), and blessed by all functions. | | Repair procedures verified as sufficient to support operations. | Supportability readiness review accepts repair procedures. | | |
| REGULATORY | Potential problems unknown. | Potential regulatory issues identified. | Federal, state, and local applicable regulations identified (i.e. OSHA, NIOSH, EPA, air, water, building, shipping, etc.). | Regulatory issues understood. | Potential approaches identified to eliminate regulatory concerns. | Initial proof-of-concept tests of potential approaches successfully completed. | Approaches to remedy regulatory problems successfully tested in a relevant environment. | Approaches to remedy regulatory problems successfully tested in a representative environment. | Approaches to remedy regulatory problems successfully tested in operational environment. | Qual tests (or equivalent) demonstrate satisfaction of regulatory requirements. | Meets all company SOP's, and accepted by regulatory agencies. | | Considered an industry standard. |
| **Intellectual Property** | | Proprietary material and process concepts identified. | Patent disclosures based on data drafted. Trademark and potential trade secret issues identified. | Reduction to practice in progress. Strategy to issue patents or preserve technology as trade secret accepted. | Patent Applications drafted. Trade secret practices in place. | Reduction to practice verified. | Patent applications completed and submitted with project approval. | Applications under review by patent office. | Applications updated after receiving remarks by the patent office. | Applications accepted by the patent office. | | Patents issued. | Considered an industry standard. |

**Figure A-31 Generic Material, Processing and Fabrication/Producibility Guide**

Activities for using the guides to establish specific XRL exit requirements are shown in Figure A-32.

## 3.0 xRL Flow

1. **Identify Items Associated with Each Primary Areas Involved with Objective**
   - **Include variability as an item for each primary area**
   - **Include quality characteristics relative to application or acceptance criteria as an item for each primary area**
2. **Identify sequential step-wise criteria going from conceptualization through disposal for each item**

INPUTS: Objective, Needs, and Customer plus TRL Matrix Chart

OUTPUTS: xRL Matrix Chart

METRICS: Increased Data and/or confidence and/or increased application complexity

**Figure A-32 XRL Sheet Process Flow**

## Example Multiple Disciplined XRL Sheets

Example structures XRL sheets have been generated. Also, the following material, processing and fabrication/producibility technology items could each have an example XRL sheet generated for maturity tracking.

| | | |
|---|---|---|
| • Resin | • Cutting | • Cure |
| • Fiber | • Layup | |
| • Prepreg | • Bagging | |

The steps for creation of these sheets are as follows.

- Create X Readiness Level (XRL) Matrix Chart (Where X represents an area/discipline in the TRL chart)
- Purpose: Establish detailed, graduated maturity exit criteria for each discipline/area identified in the TRL chart
- In column 1, list areas/items involved with each requirement area/discipline
- For columns 2 through 11, use a maturity scale of 1 to 10 for matrix column headings
- Identify specific exit criteria conformance to requirements for each area/item line box going from 1 to 10 in the matrix
- Utilize generic guides for structures, materials, processing, and producibility to identify specific exit criteria tailored for the problem/application statement-definition
- The structures guide is based on failure modes, durability, and material characteristics/properties
- The materials, processing and producibility guide is based on technical requirements and production readiness
- Utilize an approach of asking questions of whether the guide items apply to the problem/application statement-definition and if so, how for the individual line boxes
- Could be viewed from standpoint of increased information/data or fidelity or increased size or scale as maturity increases.

Example sheets are listed in the next sections.

## TRL

| TRL | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Application/ Design** | Concept Exploration | Concept Definition | Proof of Concept | Preliminary Design (Elements) | Design Maturation (Revised by Subcomponent Testing) | Revised by Component Testing | Revised by Ground Testing | Revised by Flight Test | Production Support | Recycle or Dispose |
| **Certification** | Certification Elements Documented | Certification Plan Documented | Certification Plan Approved | Elements | Subcomponent Testing | Full Scale Component Testing | Full Scale Airframe Tests | Flight Test | Production Approval | Disposal Plan Approval |
| **Assembly/ Quality** | Assembly Concept | Assembly Plan Definition | Key Assembly Detail Definitions | Key Assembly Details Tested | Subcomponents Assembled | Components Assembled | Airframe Assembled | Flight Vehicles Assembled | Production | Disassembly for Disposal |
| **Structures & Durability** | Preliminary Properties-Characteristics | Initial Screening Properties (Lamina Data) | Design To Properties Developed (Laminate Data) | Preliminary Design Values | Final Design Allowables | Allowables for Critical Design Features | Production and Test Support | Certified Allowables | Flight Tracking/ Production Support/ Fleet Support | Retirement for Cause |
| **Materials** | Lab-Prototype Materials | Pilot Production Materials | Pre-Production Materials | Production Sacleability Validated | EMD Material Supplied | EMD Material Supplied | EMD Material Supplied | LRIP Material Supplied | Production Material Supplied | Support for Recycle or Disposal Decisions |
| **Fabrication/ Quality** | Unfeatured-Panel Fabrication | Feature Based Generic Small/Subscale Parts Fabricated | Property-Fab Relationships Tested/ Target Application Pilot Production of Generic Full Size Parts | Process Specs/ Effects of Fab Variations Tested/ Elements Fab'd/ Production Representative Parts Fab'd | Subcomponents Fab'd | Full Scale Components Fabricated | EMD Fabrication | Low Rate Initial Production (LRIP) | Production | Recycle or Disposal |
| **Supportability** | Repair Items/Areas Identified | Repair Materials & Processes Identified | Repair Materials & Processes Documented | Fab Repairs Identified | Fab Repair Trials/ Subcomponent Repairs | Component Repairs | Production Repairs Identified | Flight Qualified Repairs Documented | Repair-Replace Decisions | Support for Recycle or Disposal Decisions |
| **Survivability** | Requirements Definition | Concept Definition | Proof of Concept | Preliminary Design Data and Guidelines | Design Allowables and Guidelines Defined | Critical Details Testing | Ground Test | Flight Test | Production Support | Operations Support & Disposal |
| **Cost/Schedule/ Benefits** | Cost Benefit Elements ID'd & Projected | ROM Cost Benefit Analysis | Cost Benefit Analysis Reflect Size Lessons Learned | Cost Benefit Analysis Reflect Element and Production Representative Part Lessons Learned | Cost Benefit Analysis Reflect Subcomponent Fab & Assembly Lessons Learned | Cost Benefit Analysis Reflect Component Fab & Assembly Lessons Learned | Cost Benefit Analysis Reflect EMD Lessons Learned | Cost Benefit Analysis Reflect LRIP Lessons Learned | Cost Benefit Analysis Reflect Production Lessons Learned | Cost Benefit Analysis Reflect Disposal Lessons Learned |
| **Intellectual Rights** | Concept Documentation | Patent Disclosure Filed | Proprietary Rights Agreements | Data Sharing Rights | Vendor Agreements | Material and Fabrication Contracts | Production Rate Contracts | Vendor Requal Agreements | Post-Production Agreements | Liability Termination Agreements |

**Figure A-35 Example TRL Sheet**

# XRL

## Structures

MATERIAL FAMILY PROPERTIES AND MATERIAL DURABILITY (Material Allowables, Coupon Level Evaluations) **Date: 10/6/2003**

| xRL | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Primary Mechanical Property - Tension (strength, modulus, strain to failure)** | Approximate values based on experience/data from similar systems. | Approximate values based on at least 3 evaluation results at RT plus data from similar systems | Approximate design values based on initial tests of 3 panels for lamina and laminate data at RT. Layup and statistical correlation activities initiated. Statistical basis from other similar systems. | Data for at least 3 laminates, 3 replicates, and 3 layups at a RT design environment. Statistical basis from similar material data | st ates, 3 batches. Layup and s from actual material system. efects analyses performed. off on lamina allowables. | Effects of defects covering items such as oversized holes and short e/D. Test data sufficient to establish B-Basis values. Fully validated Analysis Method. | Test data sufficient to establish A-Basis values where needed. | | Customer sign-off on all allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Primary Mechanical Property - Compression (strength, modulus, strain to failure)** | Approximate values based on experience/data from similar systems. | Approximate values based on at least 3 evaluation results at RT plus data from similar systems | Approximate design values based on initial tests of 3 panels for lamina and laminate data at RT. Layup and statistical correlation activities initiated. Statistical basis from other similar systems. | Data for at least 3 laminates, 3 replicates, and 3 layups at a RT design environment. Statistical basis from similar material data | st ates, 3 batches. Layup and s from actual material system. efects analyses performed. off on lamina allowables. | Effects of defects covering items such as oversized holes and short e/D. Test data sufficient to establish B-Basis values. Fully validated Analysis Method. | Test data sufficient to establish A-Basis values where needed. | | Customer sign-off on all allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Primary Mechanical Property - Shear (strength, modulus, strain to failure)** | Approximate values based on experience/data from similar systems. | Approximate values based on at least 3 evaluation results at RT plus data from similar systems | Approximate design values based on initial tests of 3 panels for lamina and laminate data at RT. Layup and statistical correlation activities initiated. Statistical basis from other similar systems. | Data for at least 3 laminates, 3 replicates, and 3 layups at a RT design environment. Statistical basis from similar material data | st Initial Cu ates, 3 batches. Layup and s from actual material system. efects analyses performed. off on lamina allowables. | Effects of defects covering items such as oversized holes and short e/D. Test data sufficient to establish B-Basis values. Fully validated Analysis Method. | Test data sufficient to establish A-Basis values where needed. | | Customer sign-off on all allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Primary Mechanical Property - Bearing Bypass (strength, strain to failure)** | Approximate values based on experience/data from similar systems. | Approximate values based on at least 3 evaluation results at RT plus data from similar systems | Approximate design values based on initial tests of 3 panels for laminate data at RT. Layup and statistical correlation activities initiated. Statistical basis from other similar systems. | Data for at least 3 laminates, 3 replicates, and 3 layups at a RT design environment. Statistical basis from similar material data | Data statistic Initial Cu ates, 3 batches. Layup and s from actual material system. efects analyses performed. off on lamina allowables. | Effects of defects covering items such as oversized holes and short e/D. Test data sufficient to establish B-Basis values. Fully validated Analysis Method. | Test data sufficient to establish A-Basis values where needed. | | Customer sign-off on all allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Secondary Mechanical Property - CTE** | Approximate values based on experience/data from similar systems. | Approximate values based on at least 3 evaluation results at RT plus data from similar systems | Approximate design values based on initial tests of 3 panels for lamina and laminate data at RT. Layup and statistical correlation activities initiated. Statistical basis from other similar systems. | Data for at least 3 laminates, 3 replicates, and 3 layups at a RT design environment. Statistical basis from similar material data | Data statistic Initial Cu ates, 3 batches. Layup and s from actual material system. efects analyses performed. off on lamina allowables. | Effects of defects covering items such as oversized holes and short e/D. Test data sufficient to establish B-Basis values. Fully validated Analysis Method. | Test data sufficient to establish A-Basis values where needed. | | Customer sign-off on all allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Secondary Mechanical Property - Poissons 1** | Approximate values based on experience/data from similar systems. | Approximate values based on at least 3 evaluation results at RT plus data from similar systems | Approximate design values based on initial tests of 3 panels for lamina and laminate data at RT. Layup and statistical correlation activities initiated. Statistical basis from other similar systems. | Data for at least 3 laminates, 3 replicates, and 3 layups at a RT design environment. Statistical basis from similar material data | Data statistic Initial Cu ates, 3 batches. Layup and s from actual material system. efects analyses performed. off on lamina allowables. | Effects of defects covering items such as oversized holes and short e/D. Test data sufficient to establish B-Basis values. Fully validated Analysis Method. | Test data sufficient to establish A-Basis values where needed. | | Customer sign-off on all allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Secondary Mechanical Property - Fracture Toughness** | Approximate values based on experience/data from similar systems. | Approximate values based on at least 3 evaluation results at RT plus data from similar systems | Approximate design values based on initial tests of 3 panels for lamina and laminate data at RT. Layup and statistical correlation activities initiated. Statistical basis from other similar systems. | Data for at least 3 laminates, 3 replicates, and 3 layups at a RT design environment. Statistical basis from similar material data | Data statistic Initial Cu ates, 3 batches. Layup and s from actual material system. efects analyses performed. off on lamina allowables. | Effects of defects covering items such as oversized holes and short e/D. Test data sufficient to establish B-Basis values. Fully validated Analysis Method. | Test data sufficient to establish A-Basis values where needed. | | Customer sign-off on all allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Secondary Mechanical Property - CME** | Approximate values based on experience/data from similar systems. | Approximate values based on at least 3 evaluation results at RT plus data from similar systems | Approximate design values based on initial tests of 3 panels for lamina and laminate data at RT. Layup and statistical correlation activities initiated. Statistical basis from other similar systems. | Data for at least 3 laminates, 3 replicates, and 3 layups at a RT design environment. Statistical basis from similar material data | Data statistic Initial Cu ates, 3 batches. Layup and s from actual material system. efects analyses performed. off on lamina allowables. | Effects of defects covering items such as oversized holes and short e/D. Test data sufficient to establish B-Basis values. Fully validated Analysis Method. | Test data sufficient to establish A-Basis values where needed. | | Customer sign-off on all allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Material Mechanical Properties - Other ()** | Approximate values based on experience/data from similar systems. | Approximate values based on at least 3 evaluation results at RT plus data from similar systems | Approximate design values based on initial tests of 3 panels for lamina and laminate data at RT. Layup and statistical correlation activities initiated. Statistical basis from other similar systems. | Data for at least 3 laminates, 3 replicates at a RT design environment. Statistical basis from similar material data | Data statistic Initial Cu ates, 3 batches. Layup and s from actual material system. efects analyses performed. off on lamina allowables. | Effects of defects covering items such as oversized holes and short e/D. Test data sufficient to establish B-Basis values. Fully validated Analysis Method. | Test data sufficient to establish A-Basis values where needed. | | Customer sign-off on all allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |

**Figure A-36 Example Structures XRL Sheet**

MATERIAL FAMILY PROPERTIES AND MATERIAL DURABILITY (Material Allowables, Coupon Level Evaluations)

**Date: 10/6/2003**

| xRL | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Material Durability/Life Properties - Enviromental (Temperature and Humditiy) Impact - Tension (strength, modulus, strain to failure)** | Approximate values based on experience/data from similar systems. | Approximate values based on at least 3 evaluation results at possibly low temp, ET and/or ET Wet plus data from similar systems. | Approximate design values based on initial tests of 3 panels for lamina and laminate data at environmental conditions. Layup and statistical correlation activities initiated. Statistical basis from other similar systems. | Data for at least 3 laminates, 3 replicates, and 3 layups at environmental conditions. Statistical basis from similar material data | Data for 3 laminates, 3 batches. Layup and statistical corrections from actual material system. Initial effects of defects analyses performed. Customer sign off on lamina allowables. | Effects of defects covering items such as oversized holes and short e/D. Test data sufficient to establish B-Basis values. Fully validated Analysis Method. | Test data sufficient to establish A-Basis values where needed. | | Customer sign-off on all allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Material Durability/Life Properties - Enviromental (Temperature and Humditiy) Impact - Compression (strength, modulus, strain to failure)** | Approximate values based on experience/data from similar systems. | Approximate values based on at least 3 evaluation results at possibly low temp, ET and/or ET Wet plus data from similar systems. | Approximate design values based on initial tests of 3 panels for lamina and laminate data at environmental conditions. Layup and statistical correlation activities initiated. Statistical basis from other similar systems. | Data for at least 3 laminates, 3 replicates, and 3 layups at environmental conditions. Statistical basis from similar material data | Data for 3 laminates, 3 batches. Layup and statistical corrections from actual material system. Initial effects of defects analyses performed. Customer sign off on lamina allowables. | Effects of defects covering items such as oversized holes and short e/D. Test data sufficient to establish B-Basis values. Fully validated Analysis Method. | Test data sufficient to establish A-Basis values where needed. | | Customer sign-off on all allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Material Durability/Life Properties - Enviromental (Temperature and Humditiy) Impact - Shear (strength, modulus, strain to failure)** | Approximate values based on experience/data from similar systems. | Approximate values based on at least 3 evaluation results at possibly low temp, ET and/or ET Wet plus data from similar systems. | Approximate design values based on initial tests of 3 panels for lamina and laminate data at environmental conditions. Layup and statistical correlation activities initiated. Statistical basis from other similar systems. | Data for at least 3 laminates, 3 replicates, and 3 layups at environmental conditions. Statistical basis from similar material data | Data for 3 laminates, 3 batches. Layup and statistical corrections from actual material system. Initial effects of defects analyses performed. Customer sign off on lamina allowables. | Effects of defects covering items such as oversized holes and short e/D. Test data sufficient to establish B-Basis values. Fully validated Analysis Method. | Test data sufficient to establish A-Basis values where needed. | | Customer sign-off on all allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Material Durability/Life Properties - Enviromental (Temperature and Humditiy) Impact - Bearing By-pass (strength, strain to failure)** | Approximate values based on experience/data from similar systems. | Approximate values based on at least 3 evaluation results at possibly low temp, ET and/or ET Wet plus data from similar systems. | Approximate design values based on initial tests of 3 panels for lamina and laminate data at environmental conditions. Layup and statistical correlation activities initiated. Statistical basis from other similar systems. | Data for at least 3 laminates, 3 replicates, and 3 layups at environmental conditions. Statistical basis from similar material data | Data for 3 laminates, 3 batches. Layup and statistical corrections from actual material system. Initial effects of defects analyses performed. Customer sign off on lamina allowables. | Effects of defects covering items such as oversized holes and short e/D. Test data sufficient to establish B-Basis values. Fully validated Analysis Method. | Test data sufficient to establish A-Basis values where needed. | | Customer sign-off on all allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Material Durability/Life Properties - Thermal Cycle Evaluations** | Approximate design values based on experience/data from similar systems. | Approximate design values based on at least 3 evaluation results of thermal aging times, temperatures, and/or cycles | Approximate design values based on initial tests of 3 panels for lamina and laminate data at environmental conditions. Layup and statistical correlation activities initiated. Statistical basis form other similar systems. | Data for at least 3 laminates, 3 replicates at environmental conditions. Statistical basis from similar material data | Data for 3 laminates, 3 batches. Layup and statistical corrections from actual material system. Initial effects of defects analyses performed. | Effects of defects covering items such as oversized holes and short e/D. Test data sufficient to establish B-Basis values. Fully validated Analysis Method. | Test data sufficient to establish A-Basis values where needed. | | Customer sign-off on all allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Material Durability/Life Properties - Impact Resistance** | N/A | Approximate design values based on experience/data from similar system. | Approximate design values based on initial tests of 3 laminates at RT. Environemntal factors and statistical factors based on data from similar systems. Layup, environmental, and statistical corrections from similar systems. | Data for at least 3 laminates, 3 replicates at environmental conditions. Statistical basis from similar material data | Data for 3 laminates, 3 batches. Layup and statistical corrections from actual material system. Initial effects of defects analyses performed. | Effects of defects. Test data sufficient to establish B-Basis values. Fully validated Analysis Method. | Test data sufficient to establish A-Basis values where needed. | | Customer sign-off on all allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Material Durability/Life Properties Coupon Fatigue** | N/A | N/A | Approximate design values based on initial tests of 3 panels for lamina and laminate data at environmental conditions. Layup and statistical correlation activities initiated. Statistical basis form other similar systems. | Data for at least 3 laminates, 3 replicates at environmental conditions. Statistical basis from similar material data | Data for 3 laminates, 3 batches. Layup and statistical corrections from actual material system. | Effects of defects covering items such as oversized holes and short e/D. Initial effects of defects analyses performed. | Test data sufficient to establish B-Basis values. Fully validated Analysis Method. | Test data sufficient to establish A-Basis values where needed. | Customer sign-off on all allowables and relevant analysis methods and numerical models. | Repair methods and approaches established and verified. |
| **Material Durability/Life Properties - Solvent Resistance** | N/A | Approximate design values based on at least 3 evaluation results of solvent investigations | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |

**Figure A-37 Example Structures XRL Sheet, Continued**

## Materials – Resin

**RESIN READINESS LEVEL (xRL)** **Date: 10/6/2003**

| | LABORATORY PRODUCT | | | | PILOT PLANT PRODUCT | | PRE-PRODUCTION PRODUCT | | PRODUCTION PRODUCT | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 2 | | 3 | | | | |
| (x)RL Rating | 0 | | | 1 | 2.0 - 2.4 | 2.5 - 2.9 | 3.0 - 3.4 | 3.5 - 3.9 | 4 | 5 | 6 - 7 |
| | Material Concept Identified | Concept Attempted with Lab/Experimental Number | | | | | | | | | |
| EXAMPLE PROPERTIES/ CHARACTERISTICS/ ACTIVITIES | | | • Viscosity and chemical tests plus volatiles on resin components and mixed liquid resin, Reaction kinetics (time/temperature profile), • Cured neat resin Tg-modulus-CTE-density tests, Initial lab prepregging performed and evaluated for translation of resin properties into composite | • Continued viscosity and chemical tests plus volatiles on resin components and mixed liquid resin, Reaction kinetics (time/temperature profile), • Cured neat resin Tg-modulus-CTE-density tests, moisture absorption, toxicity, fluid resistance, thermal decomposition in air, K1C, Flex at RT and ET • Preliminary ingredient inbalence studies | • moisture absorption, toxicity, fluid resistance, thermal decomposition in air, K1C, Flex at RT and ET Ingredient variations and storage evaluations using viscosity and chemical tests plus volatiles on resin components and mixed liquid resin, •Test on lab scale with relavant fiber or fabric for interfacial affects | Ingredient variations and storage evaluations using reaction kinetics (time/temperature profile), • Ingredient variations and storage evaluations using cured neat resin Tg-modulus-CTE-density tests, specific specialized tests as identified and conducted, K1C, Flex at RT and ET | Multiple lots and batches but not systematic evaluations, Continued testing with mechanicals Majority of testing from this point on is done in next higher level of material | Refine impregnation conditions flow vs temp profile of uncured resin as well as final cure recommendations | Multiple lot and batch test plan, Continued testing with mechanicals | Multiple lots and batches in a systematic approach, Continued testing with mechanicals | |
| MATERIAL INFORMATION | | | Preliminary testing, liquid components and mixed resin, cured neat resin cured composite with model reinforcement | Additional testing, liquid components and mixed resin, cured neat resin and cured composite with model reinforcement system | Additional cured resin testing begin testing on specific relavant fiber or fabric for further translation testing | Mass sensitivities investigated, Ingredient storage studies, Alternative suppliers investigated, | Used in multiple lots of prepreg (next higher level of product) Majority of testing done on prepreg from this point on | Multiple lots and batches but not systematic evaluations, Continued testing with mechanicals | Multiple lot and batch test plan, Continued testing with mechanicals | Multiple lots and batches in a systematic approach, Continued testing with mechanicals | |
| PROCESSES | | | Key steps ID'd and evaluated (I.e. weighing, mixing, heating, etc.), Processes conducted in a laboratory environment | Mixing times, temperatures, pressures and sequencing established, Packaging and storage requirements ID'd, Processes conducted in a laboratory environment | first scale up beyond lab reactors Time, temperature, pressure impacts evaluated, Indirect materials ID'd-checked for compatibility, Preliminary PCD established | Processes conducted in production relevent environment | Time, temperature, pressure impacts checked, Indirect materials ID'd-checked, PDC documented | Processes conducted in operational environment, Final PCD approved for production, processes validated | | | |
| EQUIPMENT | | | Laboratory reactors/mixing, Special requirements ID'd, | Laboratory reactor/mixing of product with possible initial pilot reactor use Lab prepregging to test for translation of properties | Reactor/mixing requirements ID'd, Indirect materials ID'd-checked for compatibility, | Intermediate sized reactor/mixing for product, Scale-up issues ID'd, Elements evaluated, Qualification requirements established, | Full scale reactor/mixing for product | Maintenance requirements and schedules established, Approved for production | | | |
| TOOLING | | | Special tooling ID'd | | | | | Approved for production | | | |
| VARIABILITY | | | Variability items ID'd, Measurement methods ID'd | Preliminary ingredient imbalance studies, | Ingredient and product storage studies started, | Expanded imbalance studies, Qualification requirements established, | Control variables established, PDC documented | Control variables validated, Final PCD approved, Measurement processes in place, | | | |
| QUALITY - IN-PROCESS | | | Requirements ID'd, Control methods ID'd, | PCD control items ID'd, Preliminary metrics established, | Control limits investigated | Preliminary control limits validated | Control limits established, PDC documented, | Control limits validated, Final PCD approved, | | | |
| QUALITY - FINAL PRODUCT | | | Quality items ID'd, | Defect items ID'd, Preliminary quality metrics established, | Effects of defects investigated | Preliminary effects of defects defined, | Draft material specification buy-off | Final material specification | Material specification approved, | Material specification validated | |
| APPLICATION MATURITY | | | Neat resin evaluations, Key cure characteristics/ requirements ID'd | Product used to make next higher level product form in a laboratory environment, Flat and ramped panels, Some lamina panels/properties | Product used to make next higher level product form in a relevant environment, Flat-multiple thickness and ramped panels, | Generic featured parts fab'd, Flat multiple thickness panels, Some laminate properties, Preliminary wet information | Product used to make next higher level product form in an operational environment, Flat and ramped panels | Design to properties, Generic scale up parts fab'd | Product used to make next higher level product form in an operational environment, | Multi batch qualification complete, Production representative parts fab'd, | |
| COST/BENEFIT ANALYSIS | | | Cost elements ID'd | Costs projected | Costs tracked vs Projected | Costs tracked to projected | | | | Costs tracked to projected | |
| REGULATORY | | | Ingredient family known for MSDS | Specific MSDS Issued for material, Environmental check for solvents, | Shipping and handling ID'd | Monitored Health and Safety, Solvents controlled, | Shipping and handling ID'd | Monitored Health and Safety, Solvents controlled, | | Health and Safety and environmental documented, | |
| **Intellectual Property** | | | PIA drafted | PIA signed | | | | | | | |

**Figure A-38 Example Materials-Resin XRL Sheet**

## Materials – Fiber

**FIBER READINESS LEVEL (xRL)** **Date: 10/6/2003**

| | LABORATORY PRODUCT | | | | PILOT PLANT PRODUCT | | PRE-PRODUCTION PRODUCT | | PRODUCTION PRODUCT | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 2 | | 3 | | | | |
| (x)RL Rating | 0 | | | 1 | 2.0 - 2.4 | 2.5 - 2.9 | 3.0 - 3.4 | 3.5 - 3.9 | 4 | 5 | 6 - 7 |
| MATERIAL INFORMATION | | | | | tensile strength and modulus, yeild, of first pilot lots of fiber | tensile strength and modulus as well as yield on first exoperimental production lots | repeat of production lots data generated in next higher form of material ie in prepreg material | repaetability of properties including composite properties demonstrated by multiple production lots | initial qualifiaction testing underway. Expanded test matrix to demonstrate all relevant properties | Fiber qualification complete for coupon testing | |
| PROCESSES | | Concept Attempted with Lab/Expermental Number | determine material and processes such as precursor material sizing and shear treatments as well as temperatures and pressures for spinning and Carbonization | Time, temperature, pressure impacts evaluated, Indirect materials ID'd-checked for compatibility, | Processes conducted in a relavent environment, | Initial attempts on production equipment | repeat of production on production equipment Initial PCD in place | PCD refined | | | |
| EQUIPMENT | Material Concept Identified | | lab and pilot equipment | lab and pilot equipment | pilot and initial small production use | pilot and initial small production use | Maintenance requirements and schedules established, Approved for production | Production equipment utilized exclusively | | | |
| TOOLING | | | | | | | | | | | |
| VARIABILITY | | | Variability items ID'd, Measurement methods ID'd | Preliminary ingredient imbalance studies, | Ingredient and product storage studies started, | Expanded imbalance studies, Qualification requirements established, | Control variables established, PDC documented | Control variables validated, Final PCD approved, Measurement processes in place, | | | |
| QUALITY - IN-PROCESS | | | Requirements ID'd, Control methods ID'd, | PCD control items ID'd, Preliminary metrics established, | Control limits investigated | Preliminary control limits validated | Control limits established, PDC documented, | Control limits validated, Final PCD approved, | | | |
| QUALITY - FINAL PRODUCT | | | Quality items ID'd, | Defect items ID'd, Preliminary quality metrics established, | Effects of defects investigated | Preliminary effects of defects defined, | Draft material specification buy-off | Final material specification | Material specification approved, | Material specification validated | |
| APPLICATION MATURITY | | | | Product used to make next higher level product form in a laboratory environment, Flat and ramped panels, Some lamina panels/properties | Product used to make next higher level product form in a relavent environment, Flat-multiple thickness and ramped panels, | Generic featured parts fab'd, Flat multiple thickness panels, Some laminate properties, Preliminary wet information | Product used to make next higher level product form in an operational environment, Flat and ramped panels | Design to properties, Generic scale up parts fab'd | Product used to make next higher level product form in an operational environment, | Multi batch qualification complete, Production representative parts fab'd, | |
| COST/BENEFIT ANALYSIS | | | Cost elements ID'd | Costs tracked to projected | | Costs tracked to projected | | | | Costs tracked to projected | |
| REGULATORY | | | Ingredient family known for MSDS | Specific MSDS Issued for material, Environmental check for solvents, | Shipping and handling ID'd | Monitored H&S, Solvents controlled, | Shipping and handling ID'd | Monitored H&S, Solvents controlled, | | H&S and environmental documented, | |
| **Intellectual Property** | | | PIA drafted | PIA signed | | | | | | | |

**Figure A-38 Example Materials-Fiber XRL Sheet**

## Materials – Prepreg

**PREPREG READINESS LEVEL (xRL) Date: 10/6/2003**

Material Concept Identified

Concept Attempted with Lab/Expermental Number

| | LABORATORY PRODUCT | | PILOT PLANT PRODUCT | | PRE-PRODUCTION PRODUCT | | PRODUCTION PRODUCT | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | 2 | | 3 | | | | |
| (x)RL Rating | 0 | 1 | 2.0 - 2.4 | 2.5 - 2.9 | 3.0 - 3.4 | 3.5 - 3.9 | 4 | 5 | 6 - 7 |
| EXAMPLE PROPERTIES/ CARACTERISTICS/ ACTIVITIES | | • Viscosity and chemical tests and kinetic test plus volatiles on neat resin and prepreg resin,<br>• Prepreg resin content and fiber areal weight, tack and drapability and resin flow evaluations.<br>• Cured prepreg panel per ply thickness, Tg (dry, wet), density, 0° Tension (RT), 0° Compression (RT), ILS (RT, ET, ET wet), micrographs | • Viscosity and chemical tests and kinetic test plus volatiles on neat resin and prepreg resin,<br>• Prepreg resin content and fiber areal weight, tack and drapability and resin flow evaluations.<br>• Cured prepreg panel per ply thickness, Tg (dry, wet), density, 0° Tension (RT), 0° Compression (RT), ILS (RT, ET, ET wet), OHC-laminate (RT), Solvent resistance, Moisture absorption, G1C, Micrographs | • Test data reduction/accumulation for statistical for variability and statistical evaluations<br>• Resin content variaiton effect on mechanical properties<br>• Effect of defect cured prepreg panel per ply thickness, Tg (dry, wet), density, 0° Tension (RT), 0° Compression (RT), ILS (RT, ET, ET wet), OHC-laminate (RT), micrographs<br>• ILS (RT, ET, ET wet) for out time and freezer time evaluations<br>• Decomposition in air, Thermal cycle, Thermal spike, Heat damage, Microcracking, Micrographs | • Viscosity and chemical tests and kinetic test plus volatiles on neat resin and prepreg resin,<br>• Prepreg resin content and fiber areal weight, tack and drapability and resin flow evaluations.<br>• Cured prepreg panel per ply thickness, Tg (dry, wet), density, 0° Tension (RT), 0° Compression (RT), ILS (RT, ET, ET wet), OHC-laminate (RT), micrographs | • Multiple lots and batches but not systematic evaluations,<br>• Viscosity and chemical tests and kinetic test plus volatiles on neat resin and prepreg resin,<br>• Prepreg resin content and fiber areal weight, tack and drapability and resin flow evaluations.<br>• Cured prepreg panel per ply thickness, Tg (dry), density, 0° Tension (RT), 0° Compression (RT), ILS (RT, ET, ET wet), OHC-laminate (RT), micrographs | • Cured prepreg panel per ply thickness, Tg (dry), density, 0° Tension (RT), 0° Compression (RT), ILS (RT, ET, ET wet), OHC-laminate (RT), micrographs<br>Initial pilot parts made and tested in relavent environment in ground tests | • Multiple lots and batches in a systematic approach,<br>• Viscosity and chemical tests and kinetic test plus volatiles on neat resin and prepreg resin,<br>• Prepreg resin content and fiber areal weight, tack and drapability and resin flow evaluations.<br>• Cured prepreg panel per ply thickness, Tg (dry), density, 0° Tension (RT), 0° Compression (RT), ILS (RT, ET, ET wet), OHC-laminate (RT), micrographs | |
| MATERIAL INFORMATION | Very preliminary bench prepregging opertions of neat resin onto a fiber tow on a bench for initial investigations. | Preliminary testing of mixed resin, prepreg and cured panels from prepreg | More extensive testing on cured panels work from optimum formulation | Mass sensitivities investigated, Ingredient storage studies, Alternative suppliers investigated, Define prepreg PCD | Prepreg PCD in place allowables testing begun | Complete allowables testing on panels and coupons. | Initial pilot parts.<br>Parts processing optimized Parts tested in flight type environment | Multiple lots and batches in a systematic approach, Continued testing with mechanicals | |
| PROCESSES | Key steps ID'd and evaluated (I.e. filming/solvent impregnation, prepregging, etc.), Processes conducted in a laboratory environment | Times, temperatures, pressures and sequencing established, Packaging and storage requirements ID'd, Processes conducted in a laboratory environment | Processes conducted in a relavent environment, Time, temperature, pressure impacts evaluated, Indirect materials ID'd-checked for compatibility, | Processes conducted in a relavent environment, | Time, temperature, pressure impacts checked, Indirect materials ID'd-checked, PDC documented | Processes conducted in operational environment, Final PCD approved for production, processses validated | | | |
| EQUIPMENT | Laboratory/bench impregnation, Special requirements ID'd, | initial use of pilot prepregging equipment for product | Filming/prepregging requirements ID'd, Indirect materials ID'd-checked for compatibility, Spool requirments | Intermiediate sized filming/prepregging equipment for product, Scale-up issues ID'd, Elements evaluated, Qualification requirements established, | Full scale filming/prepregging for product, All equipment I'D for production qualification, Spool requirements ID'd | Maintenance requirements and schedules established, Approved for production | | | |
| TOOLING | Special tooling ID'd | | | | | Approved for production | | | |
| VARIABILITY | Variability items ID'd, Measurement methods ID'd | Preliminary imbalance studies, | Product storage studies started, | Expanded variability studies, Qualification requirements established, | Control variables established, PDC documented | Control variables validated, Final PCD approved, Measurement processes in place, | | | |
| QUALITY - IN-PROCESS | Requirements ID'd, Control methods ID'd, | PCD control items ID'd, Preliminary metrics established, | Control limits investigated | Preliminary control limits validated | Control limits established, PDC documented, | Control limits validated, Final PCD approved, | | | |
| QUALITY - FINAL PRODUCT | Quality items ID'd, | Defect items ID'd, Preliminary quality metrics established, | Effects of defects investigated | • Preliminary effects of defects defined,<br>• Out time and freezer time evaluations | Draft material specification buy-off | Final material specification | Material specification approved, | Material specification validated | |
| APPLICATION MATURITY | Neat resin evaluations, Key cure characteristics/ requirements ID'd | Flat and ramped panels, Some lamina panels/properties initial coupon testing | Flat-multiple thickness and ramped panels, further coupon testing | Continued coupon testing and initial generic featured parts fab'd, Flat multiple thickness panels, Some laminate properties, Preliminary wet information | Flat and ramped panels | Design allowables complete, Generic scale up parts fab'd | Product used to make components in an operational environment, Flat and ramped panels | Multi batch qualification complete, Production representative parts fab'd, | |
| COST/BENEFIT ANALYSIS | Cost elements ID'd | Costs tracked to projected | | Costs tracked to projected | | | | Costs tracked to projected | |
| REGULATORY | Ingredient family known for MSDS | Specific MSDS Issued for material, Environmental check for solvents, | Shipping and handling ID'd | Monitored H&S, Solvents controlled, | Shipping and handling ID'd | Monitored H&S, Solvents controlled, | | H&S and environmental documented, | |
| **Intellectual Property** | PIA drafted | PIA signed | | | | | | | |

**Figure A-40 Example Materials-Prepreg XRL Sheet**

## Fabrication/Producibility – Cutting

**HAND CUTTING (x)RL Criteria Conformance Summar Date: 10/6/2003**

| (x)RL Rating | 0 | 1 | 2 | | 3 | | 4 | 5 |
|---|---|---|---|---|---|---|---|---|
| | | | 2.0 - 2.4 | 2.5 - 2.9 | 3.0 - 3.4 | 3.5 - 3.9 | | |
| PART MATERIAL | Environmental conditions defined from neat resin evaluations. Fiber cutting requirements identified. | Prepreg spool size and weight information, Indirect material identification (backing paper information and separator information if used), | Prepreg spool and weight information, preliminary material out time evaluations | | Prepreg spool and weight information, formalized out time limits evaluations | | Prepreg spool and weight information | |
| CUTTING PROCESSES | | Backing/separator paper slivers with cutting, Tack evaluations for separator application | Preliminary out time evaluations for cutting and separator use, | Indirect material compatibility with resin, | Formalized out time limits evaluations for cutting started, Formalized freezer time evaluations for cutting started, Preliminary process specification, | Indirect material compatibility over time completed, Production spool requirements ID'd | Process specification, | Process specification validated |
| CUTTING FACILITIES | Cutting area environmental requirements ID'd | Cutting done in laboratory environment | Cutting done in relevant environment, | Cutting done in relevant environment, | Cutting done in operational environment, | Cutting done in operational environment, | Cutting done in operational environment, | Cutting done in operational environment, |
| CUTTING EQUIPMENT | | Spool handling equipment ID'd, if required | Spool handling equipment ID'd | | Spool handling equipment ID'd | Spool handling equipment ID'd | Spool handling equipment ID'd | |
| TOOLING for CUTTING | | Templates/straight edges, hand tools (knives) | Templates/straight edges | Templates/straight edges | Templates/straight edges | Templates/straight edges | Templates/straight edges | Templates/straight edges |
| CUTTING VARIABILITY | | x and y dimensions, angle, environment conditions, tack, tooling, indirect matrrials | Cutting validated with any material change, x and y dimensions, angle, environment conditions | x and y dimensions, angle, environment conditions | Cutting validated with any material change, Control variables established, | | | |
| CUTTING QUALITY - IN-PROCESS | | Measured length-width of cut plies to template length and width, Angle measured to fiber direction, Slivers with cutting, logged times and temperatures, | Measured length-width of cut plies to template length and width, Angle measured to fiber direction, Slivers with cutting, logged times and temperatures, | Measured length-width-angle greater than 30 times, | Control limits established, Ply identification-marking-storage methods ID'd, Preliminary process specification, | Control limits validated | Quality plan, Process specification | Process specification validated |
| QUALITY - FINAL PRODUCT | | Cutting size and angle tolerance, Slivers with cutting; x, y, and angle accuracy | Indirect material size NDE detectability, Sliver detectability if applicable; x, y, and angle accuracy | Indirect material size NDE detectability, Sliver detectability if applicable; x, y, and angle accuracy | Preliminary process specification, | | Quality plan, Process specification | Process specification validated |
| APPLICATION MATURITY | Neat resin, | Flat and ramped panels fab'd | Multiple thickness flat panels, ramped panels, | Generic featured parts fab'd | Multiple thickness flat panels, ramped panels, | Generic scale up parts fab'd | Multiple thickness flat panels, ramped panels, | Production representative parts |
| COST/BENEFIT ANALYSIS | | | | | | | | |
| REGULATORY | | Spool sizes, weights and handling, MSDS handling requirements, | Spool sizes and handling, | | Spool sizes and handling, | | Spool sizes and handling, | |
| **Intellectual Property** | | | | | | | | |

**Figure A-41 Example Fabrication/Producibility Cutting XRL Sheet**

## Fabrication/Producibility – Hand Layup

### HAND LAYUP (x)RL Criteria Conformance Summary Date: 10/6/2003

| (x)RL Rating | 0 | 1 | 2 | | 3 | | 4 | 5 |
|---|---|---|---|---|---|---|---|---|
| | | | 2.0 - 2.4 | 2.5 - 2.9 | 3.0 - 3.4 | 3.5 - 3.9 | | |
| PART MATERIAL | Environmental conditions defined from neat resin evaluations | Indirect material identification (Backing paper information, separator information if used), | Preliminary material out time evaluations | | Formalized out time limits evaluations | Prepreg | Prepreg | Prepreg |
| LAYUP PROCESSES | | Backing paper removal evaluations, Separator removal evaluations, Tack evaluations, Ply removal evaluations, Indirect material identification, | Backing paper removal evaluations, Separator removal evaluations, Tack evaluations, Ply removal evaluations, Preliminary out time evaluations, Investigations of indirect material compatability with resin/plies, | Indirect material compatibility with resin, Layup done in relevant environment, | Formalized out time limits evaluations for layup tack started, Formalized freezer time evaluations for layup tack started, Preliminary process specification, Layup done in operational environment, | Indirect material compatibility over time completed, Layup done in operational environment, | Process specification, Layup done in operational environment, | Layup done in operational environment, Process specification validated |
| LAYUP FACILITIES | Layup area environmental requirements ID'd | Layup done in laboratory environment | Layup done in relevant environment, | Layup done in relevant environment, | Layup done in operational environment, | Layup done in operational environment, | Layup done in operational environment, | Layup done in operational environment, |
| LAYUP EQUIPMENT | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| LAYUP TOOLING | | Templates/straight edges, hand tools (sqeegees/scrapers, etc) idnetified | Tooling compatability investigations with resin/prepreg | Templates/straight edges | Templates/straight edges, Acceptance plan established, | Templates/straight edges | Templates/straight edges | Templates/straight edges |
| LAYUP VARIABILITY | | x and y position, angle, tack, environmental conditions, tooling, indirect materials | Layup validated with any material change, x and y position, angle, tack, environmental conditions, tooling, indirect materials, | x and y position, angle, tack, environmental conditions, tooling, indirect materials | Layup validated with any material change, tack, environmental conditions, Control variable limits established, | x and y position, angle, tack, environmental conditions, | Layup validated with any material change, | |
| LAUP QUALITY - IN-PROCESS | | Measured length-width position of laid up plies to reference position, Angle measured to reference direction, logged times and temperatures | Measured length-width position of laid up plies to reference position, Angle measured to reference direction, logged times and temperatures, limits investigated for position and angles, | Measured length-width-angle positions greater than 30 times, limits validated | Positional control limits established, Preliminary process specification, | Control limits validated | Quality plan, Process specification | Process specification validated |
| QUALITY - FINAL PRODUCT | | Layup positional and angle accuracy | Layup positional and angle accuracy, Indirect material NDE detectability and compatability, | Layup positional and angle accuracy, Indirect material NDE detectability and compatability, | Preliminary process specification, | | Quality plan, Process specification | Process specification validated |
| APPLICATION MATURITY | Neat resin, | Flat and ramped panels fab'd | Multiple thickness flat panels, ramped panels, | Generic featured parts fab'd | Multiple thickness flat panels, ramped panels, | Generic scale up parts fab'd | Multiple thickness flat panels, ramped panels, | Production representative parts |
| COST/BENEFIT ANALYSIS | | | | | | | | |
| REGULATORY | | | | | | | | |
| **Intellectual Property** | | | | | | | | |

**Figure A-42 Example Fabrication/Producibility Layup XRL Sheet**

# Fabrication/Producibility – Debulking

**DEBULKING (x)RL Criteria Conformance Summary ( Date: 10/6/2003**

| (x)RL Rating | 0 | 1 | 2 | | 3 | | 4 | 5 |
|---|---|---|---|---|---|---|---|---|
| | | | 2.0 - 2.4 | 2.5 - 2.9 | 3.0 - 3.4 | 3.5 - 3.9 | | |
| PART MATERIAL | Neat resin, Key time and temperature requirements for cure ID'd for all reactive materials to be used together. | Prepreg kinetic and viscosity results for understanding time and temperature relationships for all reactive materials. | Prepreg | Prepreg | Prepreg | Prepreg | Prepreg | Prepreg |
| DEBULK PROCESSES | Key time and temperature requirements for debulking ID'd | Debulking methods investigated (times, temperatures, pressures), Indirect materials identified, facilities, equipment and tooling requirements identified | Limits identified for debulking methods - times - temperatures -- pressures relative to flow/voids and porosity and thickness, | Limits validated, Out time & cure evaluations complete, | Preliminary process specifications established, | Preliminary process specifications validated, | Process specification finalized, | Final process specification validated, |
| DEBULK FACILITIES | | Lab environment, facility requirements identified | Relevant environment | Relevant environment | Operational environment | Operational environment | Operational environment | Operational environment |
| DEBULK EQUIPMENT | | Debulk equipment ID'd, Capabilities investigated, | Debulk equipment ID'd, Capabilities known, Characterized, | Debulk equipment capability validated, | Debulk equipment ID'd with know capabilities and characterized, Certification requirements ID'd | Certification requirements validated, | Debulk equipment ID'd with known capabilities and characterized, Certification requirements finalized | Certification complete, |
| DEBULK TOOLING | | Quick look at multiple tool material/concept simulations | Limits identified for multiple tooling materials and concepts, | Some tooling material/concepts validated, Initiate residual stress compensation factors investigations, | Expanded tooling material/concept simulations, | Expanded tooling material/concept validations, | Finalized tooling IPT and BTP information | Validated information |
| DEBULK VARIABILITY | Key material time/temperature characteristics ID'd, Key variability items ID'd, | Key variability items investigated (time, temperature, pressure, number of plies), *Iterate debulk cycle variables to achieve acceptable final product quality* , | Debulk validated with material changes, Additional variability items ID'd (I.e. thickness and out-of-plane fiber distortion), *Iterate debulk cycle variables to achieve acceptable final product quality or institute special debulk* , | Control variables validated, | Debulk validated with any material change, Preliminary process specifications established | Preliminary process specifications validated | Process specification finalized, | Final process specification validated |
| DEBULK QUALITY - IN-PROCESS | Control Items ID'd and logged, | Control methods established (time, temperature, pressure, number of plies), Preliminary tolerances established for control items impacting thickness and out-of-plane fiber distortion and voids/porosity, | Additional controls and tolerances established if necessary, Control limits established (time temperature, pressure, number of plies) that impact thickness and out-of-plane fiber distortion and voids/porosity, | Debulk profiles and tolerances validated, Control limits validated relative to thicknesses, out-of-plane fiber waviness, and voids/porosity | Preliminary process specifications established | Preliminary process specifications validated | Process specification finalized, | Final process specification validated |
| QUALITY - FINAL PRODUCT | Multiple end of cure metrics evaluated, Void porosity assessment, | Multiple end of cure measurements, Voids and porosity results evaluated, Part thicknesses evaluated, Part resin content evaluated, | Multiple end of cure measurements, Voids and porosity results evaluated, Part thicknesses evaluated, Part resin content evaluated, Defects ID'd, | Multiple end of cure measurements, Voids and porosity results evaluated, Part thicknesses evaluated, Part resin content evaluated, Defects evaluated | Preliminary process specifications established, Effect of defect formalized studies, | Preliminary process specifications validated, Effects of defects known, | Process specification finalized, | Final process specification validated |
| APPLICATION MATURITY | Neat resin, | Flat and ramped panels fab'd | Multiple thickness flat panels, ramped panels, | Generic featured parts fab'd | Multiple thickness flat panels, ramped panels, | Generic scale up parts fab'd | Multiple thickness flat panels, ramped panels, | Production representative parts |
| COST/BENEFIT ANALYSIS | | | | | | | | |
| REGULATORY | | | | | | | | |
| **Intellectual Property** | | | | | | | | |

**Figure A-43 Example Fabrication/Producibility Debulking XRL Sheet**

# Fabrication/Producibility – Bagging

**BAGGING (x)RL Criteria Conformance Summary Ch Date: 10/6/2003**

| (x)RL Rating | 0 | 1 | 2 | | 3 | | 4 | 5 |
|---|---|---|---|---|---|---|---|---|
| | | | 2.0 - 2.4 | 2.5 - 2.9 | 3.0 - 3.4 | 3.5 - 3.9 | | |
| PART MATERIAL | Neat resin, Key time and temperature requirements for cure ID'd, Offgassing byproducts identified, | Prepreg, offgassing investigations | Prepreg | Prepreg | Prepreg | Prepreg | Prepreg | Prepreg |
| BAGGING PROCESSES | Key time and temperature requirements for debulking ID'd | Bagging methods investigated (for times, temperatures, pressures). Indirect materials for bleeder/breather and bagging identified along with properties, facilities, equipment and tooling requirements identified, inner and outer bagging requirements identified | Limits identified for bagging methods - times - temperatures -- pressures relative to flow/voids and porosity and thickness and cure, | Limits validated, Out time & cure evaluations complete, | Preliminary process specifications established, | Preliminary process specifications validated, | Process specification finalized, | Final process specification validated, |
| BAGGING FACILITIES | | Lab environment, facility requirements identified | Relevant environment | Relevant environment | Operational environment | Operational environment | Operational environment | Operational environment |
| BAGGING EQUIPMENT | | | | | | | | |
| BAGGING TOOLING | | Compatability of bagging and tooling/mold releases investigated | Limits identified for multiple tooling materials and concepts, | Some tooling material/concepts validated, Initiate residual stress compensation factors investigations, | Expanded tooling material/concept simulations, | Expanded tooling material/concept validations, | Finalized tooling IPT and BTP information | Validated information |
| BAGGING VARIABILITY | Key material time/temperature characteristics ID'd, Key variability items ID'd, | Key variability items investigated (time, temperature, pressure, number of plies), *Iterate bagging variables (inner/outer bag, breathing, bleeder, pleats, sealant)to achieve acceptable final product quality* , | Bagging validated with material changes, Additional variability items ID'd, *Iterate bagging variables to achieve acceptable final product quality or institute special bagging procedures* , | Control variables validated, | Bagging validated with any material change, Preliminary process specifications established | Preliminary process specifications validated | Process specification finalized, | Final process specification validated |
| BAGGING QUALITY - IN-PROCESS | Control Items ID'd and logged, | Control methods established (time, temperature, pressure, number of plies), Preliminary tolerances established for control items, | Additional controls and tolerances established if necessary, Control limits established (time temperature, pressure, number of plies), | Debulk profiles and tolerances validated, | Preliminary process specifications established | Preliminary process specifications validated | Process specification finalized, | Final process specification validated |
| QUALITY - FINAL PRODUCT | Multiple end of cure metrics evaluated, Void porosity assessment, | Multiple end of cure measurements, Voids and porosity results evaluated, Part thicknesses evaluated, Part resin content evaluated, | Multiple end of cure measurements, Voids and porosity results evaluated, Part thicknesses evaluated, Part resin content evaluated, Defects ID'd, | Multiple end of cure measurements, Voids and porosity results evaluated, Part thicknesses evaluated, Part resin content evaluated, Defects evaluated | Preliminary process specifications established, Effect of defect formalized studies, | Preliminary process specifications validated, Effects of defects known, | Process specification finalized, | Final process specification validated |
| APPLICATION MATURITY | Neat resin, | Flat and ramped panels fab'd | Multiple thickness flat panels, ramped panels, | Generic featured parts fab'd | Multiple thickness flat panels, ramped panels, | Generic scale up parts fab'd | Multiple thickness flat panels, ramped panels, | Production representative parts |
| COST/BENEFIT ANALYSIS | | | | | | | | |
| REGULATORY | | | | | | | | |
| **Intellectual Property** | | | | | | | | |

**Figure A-44 Example Fabrication/Producibility Bagging XRL Sheet**

# Fabrication/Producibility – Cure

**CURE (x)RL Criteria Conformance Summary Chart   Date: 10/6/2003**

| (x)RL Rating | 0 | 1 | 2 | | 3 | | 4 | 5 |
|---|---|---|---|---|---|---|---|---|
| | | | 2.0 - 2.4 | 2.5 - 2.9 | 3.0 - 3.4 | 3.5 - 3.9 | | |
| PART MATERIAL | Neat resin, Key time and temperature requirements for cure Identified for all reactive materials to be used together. Off gassing byproducts identified. | Kinetic and viscosity test results for behavior understanding of time and temperature relationships for all reactive materials. By products investigated. | Kinetic and viscosity test results for behavior modeling of all reactive materials | Prepreg | Prepreg | Prepreg | Prepreg | Prepreg |
| CURE PROCESSES | One or two cure cycle variations tried, | Initial investigations to establish a very preliminary time temperature pressure cure profile relative to degree of cure, viscosity, and voids. One or two cure cycle variations tried, Requirements for facilities and equipment identified icluding vacuum and static port/line requirments, | Limits identified for heat up and cure times - temperatures -- pressures relative to flow/voids and porosity/end of cure relative to part thickness, equipment capability and tooling options; Exotherm potential evaluated, Cure impact on properties and residual stresses. Limits established for vacuum and static prot/line items. | Limits validated, Out time & cure evaluations complete, | Preliminary process specifications established, | Preliminary process specifications validated, | Process specification finalized, | Final process specification validated, |
| CURE FACILITIES | Laboratory environment | Laboratory environment | Relevant environment | Relevant environment | Operational environment | Operational environment | Operational environment | Operational environment |
| CURE EQUIPMENT | Oven | Autoclave ID'd, Capabilities investigated and variabilities identified, | Autoclave ID'd, Capabilities known, variabilities characterized (heating/cooling and pressurization rates and convective coefficients), | Autoclave capability validated, | Autoclave ID'd with know capabilities and characterized, Certification requirements ID'd | Certification requirements validated, | Autoclave ID'd with know capabilities and characterized, Certification requirements finalized | Certification complete, |
| CURE TOOLING | Simple plates/pans, | Quick look at multiple tool materials/concepts | Limits investigated for multiple tooling materials and concepts, | Some tooling material/concepts validated, Initiate residual stress compensation factors investigations, | Expanded tooling material/concept simulations, | Expanded tooling material/concept validations, | Finalized tooling IPT and BTP information | Validated information |
| CURE VARIABILITY | key material cure characteristics ID'd, Key cure variability items ID'd relative to the material, | Key variability items investigated for materials (time, temperature, pressure for individule and combined materials), tooling and equipment, *Iterate cure cycle variables to achieve acceptable final product quality* , | Cure validated with any material changes, Additional variability items ID'd, *Iterate cure cycle variables to achieve acceptable final product quality or institute special cure* , | Control variables validated, | Cure validated with any material changes, Preliminary process specifications established | Preliminary process specifications validated | Process specification finalized, | Process specification validated |
| CURE QUALITY - IN-PROCESS | Control Items ID'd and logged (time, temperature, pressure), | Control methods established, Preliminary tolerances established for control items, | Additional controls and tolerances established if necessary, Control abort limits established, | Cure profiles and tolerances validated, | Preliminary process specifications established | Preliminary process specifications validated | Process specification finalized, | Final process specification validated |
| QUALITY - FINAL PRODUCT | Multiple end of cure metrics evaluated, Void porosity assessment, | Multiple end of cure measurements, Voids and porosity results evaluated, Part thicknesses evaluated, Part resin content evaluated, | Multiple end of cure measurements, Voids and porosity results evaluated, Part thicknesses evaluated, Part resin content evaluated, Defects ID'd, | Multiple end of cure measurements, Voids and porosity results evaluated, Part thicknesses evaluated, Part resin content evaluated, Defects evaluated | Preliminary process specifications established, Effect of defect formalized studies, | Preliminary process specifications validated, Effects of defects known, | Process specification finalized, | Final process specification validated |
| APPLICATION MATURITY | Neat resin, | Flat and ramped panels fab'd | Multiple thickness flat panels, ramped panels, | Generic featured parts fab'd | Multiple thickness flat panels, ramped panels, | Generic scale up parts fab'd | Multiple thickness flat panels, ramped panels, | Production representative parts |
| COST/BENEFIT ANALYSIS | | | | | | | | |
| REGULATORY | | | | | | | | |
| **Intellectual Property** | | | | | | | | |

**Figure A-45 Example Fabrication/Producibility Cure XRL Sheet**

# Appendix B – References with Brief Abstracts

The purpose of this appendix is to provide a brief abstract for each of the references which appear in this methodology document. References from each section of the document are listed below by section. Abstracts of each reference follow this list in the order of their first appearance.

## 1. Methodology Overview


1. Banisaukas, J., Office of Naval Research, Contract No. N00014-97-C-0417, "New Materials, New Processes and Alternate Second Source Materials Data Base Generation and Qualification Protocol Development," Enclosure 4 to the Final Report dated 31 August 2000.
2. Lincoln, J. W., "USAF Experience in the Qualification of Composite Structures," Composite Structures: Theory and Practice, ASTM STP 1383, P. Grant, Ed., American Society for Testing and Materials, West Conshohocken, PA, 2000, pp. 1-11.
3. The Composites Materials Handbook-MIL17, MIL-HDBK-17E, Technomic Publishing Company, Inc., Lancaster, Pennsylvania, 1997.
4. Tomblin, J.S., Ng, Y.C., and Raju, K.R., DOT/FAA/AR-00/47, "Material Qualification and Equivalency for Polymer Matrix Composite Material Systems," Final Report Dated April 2001.
5. Funke, R.W., Rubin, A., Bogucki, G., and Ashton, H., Christenson, S., Contract No. N00421-01-3-0098, "Composite Materials and Structures Certification Process – Experience and Recommendations," Report No. BOE-STL 2001X0010, 15 March 2002.
6. Wallace, D.R., Abrahamson, S., Nicola, S., and Sferro, P., "Integrated Design in a Service Marketplace, Computer-aided Design," Volume 32, No. 2, pp. 97-107, 2000.
7. Mankins, John C. Technology Readiness Levels, http://advtech.jsc.nasa.gov/downloads/TRLs.pdf, 6 April 1995.
8. Technology Transition for Affordability, A Guide for S&T Program Managers, http://www.dodmantech.com/PUBS/TechTransGuide-Apr01.pdf, April 2001.
9. Interim Defense Acquisition Guidebook, AP6. Appendix 6 – Technology Readiness Levels and Their Definitions, October 30, 2002

## 2. Risk Management

1. Banisaukas, J., Office of Naval Research, Contract No. N00014-97-C-0417, "New Materials, New Processes and Alternate Second Source Materials Data Base Generation and Qualification Protocol Development," Enclosure 4 to the Final Report dated 31 August 2000.
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3. Department of the Air Force, *Acquisition Risk Management Guide*, AFMC Pamphlet 63-101, 15 September 1993.
4. The Composites Materials Handbook-MIL17, MIL-HDBK-17E, Technomic Publishing Company, Inc., Lancaster, Pennsylvania, 1997.

## 3. Business Case

1. McCarty, Robert, and Saff, C.R., "Next Generation Transparency," *Affordability Transition Conference,* Williamsburg, Virginia, 2000.
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## Selected Abstracts

**Banisaukas, J., Office of Naval Research, Contract No. N00014-97-C-0417, "New Materials, New Processes and Alternate Second Source Materials Data Base Generation and Qualification Protocol Development," Enclosure 4 to the Final Report dated 31 August 2000.**

The effective qualification of new or alternative composite materials and processes has been a significant problem for numerous military aircraft programs in recent years. Often, an older generation material or process has continued in use, not because of low risk or cost, but because qualifying a next generation material or an innovative process was cost prohibitive to a small program. At other times, a material or process has been qualified numerous times, each time duplicating the efforts of other qualifications while adding details particular to an application, an environment, or a user. Data sharing among programs has been deficient, even among programs supporting the same branch of service. In still other instances, established programs must contend with "qualification" of material or process changes due to obsolescence, plant relocations, substitutions due to environmental regulations, changes due to new safety requirements, or suppliers or processors going out of business.

This protocol was written to deal with the above issues. This document provides a framework for enhancing affordability, cycle time, and technical excellence in the development of material and process qualifications. It provides a methodology or framework for developing qualification success criteria, divergence and risk analyses, and guidelines as to the technical attributes of the material or process which might not require testing confirmation. It is not a catalog of test matrices to be followed without fore thought and business justification. This protocol document does not compete with Mil-Hdbk-17, SACMA, ASTM, or the other fine documents in the industry that provide test guidance or variability analysis. However, it does provide a methodology or framework for questioning the most appropriate qualification approach based on a written and agreed-to problem statement, and, therefore, it complements these other documents.

The intent of this qualification protocol is to provide a methodology when (a) attempting a blank sheet qualification of a material or process; (b) evaluating material or process changes to an already qualified material or process; and (c) evaluating the equivalency of second sources or alternate processes. This document should be used as a guide for any or all elements of the qualification process.

**Lincoln, J. W., "USAF Experience in the Qualification of Composite Structures," Composite Structures: Theory and Practice, ASTM STP 1383, P. Grant, Ed., American Society for Testing and Materials, West Conshohocken, PA, 2000, pp. 1-11.**

The prospect of significant reduction in aircraft structural mass has motivated the United States Air Force (UASF) and the aerospace industry to incorporate composite structures in their aircraft designs. The USAF found threats to structural integrity such as moisture, temperature, delaminations, and impact damage that made them take a cautious approach for the acquisition of aircraft with composite materials. However, the USAF has successfully incorporated composites on several aircraft including the B-2, C-17, and F-22. The challenge is to find new approaches for the qualification of composite structures that will make them more economically viable for future procurements. It is the purpose of this paper to discuss the background for the current qualification program for composites and suggest some possibilities for improvement of the certification process.

**The Composites Materials Handbook, MIL-HDBK-17, Technomic Publishing Company, Inc., Lancaster, Pennsylvania, 1997.**

MIL-HDBK-17 is a standardization of engineering data development methodologies related to characterization testing, data reduction, and data reporting of properties for polymer matrix composite materials. MIL-HDBK-17 publishes properties on composite material systems for which data meeting specific requirements is available. In addition, MIL-HDBK-17 provides selected guidance on technical topics related to composites, including material selection, material specification, material processing, design, analysis, quality control and repair of typical polymer matrix composites. MIL-HDBK-17 is published in three volumes: Volume 1 – Guidelines for Characterization of Structural Materials; Volume 2 – Material Properties; and Volume 3 – Materials Usage, Design, and Analysis Guidelines.

**Tomblin, J.S., Ng, Y.C., and Raju, K.R., DOT/FAA/AR-00/47, "Material Qualification and Equivalency for Polymer Matrix Composite Material Systems," Final Report Dated April 2001.**

This document presents a qualification plan that will provide the detailed background information and engineering practices to help ensure the control of repeatable base material properties and processes, which are applied to both primary and secondary structures for aircraft products using composite materials. This qualification plan includes recommendations for the original qualification as well as procedures to statistically establish equivalence to the original data set. The plan describes in detail the procedures to generate statistically based design allowables for both A- and B-basis applications. This plan only covers the initial material qualification at the lamina level and does not include procedures for laminate or higher-level building block tests. The general methodology, however, is applicable to a broader usage.

**Funke, R.W., Rubin, A., Bogucki, G., and Ashton, H., Christenson, S., Contract No. N00421-01-3-0098, "Composite Materials and Structures Certification Process – Experience and Recommendations," Report No. BOE-STL 2001X0010, 15 March 2002.**

This report presents the F/A-18 E/F composite materials certification process in some detail. It begins with material and process development and proceeds structural testing. It presents how the problem was approached, what was done, and the outcome. Lessons learned are presented which could be utilized to facilitate future qualifications.

**Wallace, D.R., Abrahamson, S., Nicola, S., and Sferro, P., "Integrated Design in a Service Marketplace, Computer-aided Design," Volume 32, No. 2, pp. 97-107, 2000.**

This paper presents a service marketplace vision for enterprise-wide integrated design modeling. In this environment, expert participants and product development organizations are empowered to publish their geometric design, CAE, manufacturing, or marketing capabilities as live services that are operable over the Internet. Product developers, small or large, can subscribe to and flexibly inter-relate these services to embody a distributed product development organization, while simultaneously creating system models that allow the prediction and analysis of integrated product performance. It is hypothesized that product development services will become commodities, much like many component-level products are today. It will be possible to rapidly interchange equivalent design service providers so that the development of the product and definition of the product development organization become part of the same process. Computer-aided design tools will evolve to facilitate the publishing of live design services. A research prototype system called DOME is used to illustrate the concept and a pilot study with Ford Motor Company is used in a preliminary assessment of the vision.

**Department of the Air Force, *Acquisition Risk Management Guide*, AFMC Pamphlet 63-101, 15 September 1993; Revised 09 July 1997.**

This pamphlet does not apply to the Air National Guard or US Air Force Reserve units and members. This pamphlet is intended to provide program managers and their program management team a basic understanding of the terms, definitions and processes associated with effective risk management.

Current acquisition reform initiatives embrace closer government/industry relationships and greater reliance on commercial technologies -- both designed to provide reliable, lower cost weapon systems. Hand-in-hand with these initiatives is an accompanying focus on risk management.

The risk management concepts and ideas presented in this pamphlet are focused on encouraging the use of risk-based management practices and suggesting ways to address the program risk without prescribing the use of specific methods or tools. Rather, this pamphlet was prepared as a guide, with the expectation that program risk management processes will be developed to meet the intent of this document.

**McCarty, Robert, and Saff, C.R., "Next Generation Transparency," *Affordability Transition Conference,* Williamsburg, Virginia, 2000.**

The design features developed for both the single piece canopy and the one piece, Next Generation Transparency (NGT) windscreen/canopy for the F-15 were used to estimate the costs for each of these candidate applications and to support a cost estimate for drop in replacement transparencies for the F-15. These analyses were done to evaluate the costs associated with replacements ranging from drop-in to complete reconfiguration. These costs are compared to the current costs for replacement of the F-15 windscreen and canopy. Windscreen replacements were not considered for either the drop-in replacements and the one piece canopy replacement.

When we get to the bottom line, it is apparent that NGT is far more cost effective in new designs than in retrofit designs. In retrofit designs the technology is hampered by the constraints of the existing design developed for the older transparency systems. It negates the savings and actually makes the NGT technology more costly than the original transparency system. But in new configurations, where the frameless transparency can be fully utilized in both production costs and life cycle costs, cradle to grave costs are reduced by more than half using the NGT technology.

**Younossi, O., Kennedy, M., and Graser, J., <u>Military Airframe Costs – The Effects of Advanced Materials and Manufacturing Processes</u>, The RAND Corporation, 2001.**

This is one of a series of reports from the RAND Project AIR FORCE project entitled "The Cost of Future Military Aircraft: Historical Cost Estimating Relationships and Cost Reduction Initiatives." The purpose of the project is to improve cost-estimating tools available for projecting the cost of future weapon systems. It focuses on how recent technical, management, and government policy changes affect cost. This report discusses the effects of airframe material mix and manufacturing techniques on airframe costs, emphasizing the effect of new manufacturing techniques. It also presents statistical analyses of a new airframe historical cost data set, MACDAR, which is owned by the Air Force Cost Analysis Agency (AFCAA). The study took place in Project AIR FORCE's Resource Management Program.

**Mabson, G.E., Fredrikson, H.G., Graesser, , D.L., Metschan, S.L. , Proctor, M.R., Stogin, D.C. , Tervo, D.K. , Tuttle, M.E., Zabinsky, Z.B. , Gutowski, T.G. , "Cost Optimization Software For Transport Aircraft Design Evaluation," <u>6th NASA Advanced Composite Technology Conference</u>, 1995.**

Cost Optimization Software for Transport Aircraft Evaluation (COSTADE) is being developed as a tool to support design build teams in their efforts to develop cost effective and feasible commercial aircraft composite fuselage structures. COSTADE is a multidisciplinary evaluation and optimization tool that includes cost, weight, design, stress, and manufacturing modules. Fabrication costs are included early in the structural cevelopment process allowing the identification of cost-weight sensitivities. The use of this tool also reduces engineering development costs by shortening design cycles times and by providing improved starting points for more detailed evaluations.

This paper presents details of the major modules included in COSTADE, and applications illustrating its use on the Advanced Technology Composite Aircraft Structures (ATCAS) program. Emphasis is given to the development of cost model equations. Applications of the cost model to the ATCAS full barrel are included.

**F/A-18E/F Material Substantiating Data and Analysis Report, Report MDC 93B0068.**

This report presents the F/A-18 E/F Material Substantiating Data and Analysis requirements in compliance with Addendum 697 to SD-8706C, Paragraph 3.10.5, dated 09 January 1992. This report was submitted in partial fulfillment of the data requirements for Contract N00019-92-C-0059, Exhibit A, Data Item Number A012.

This report includes data and analyses to substantiate the use of material property values and design allowables from sources other than MIL-HDBK-5 and MIL-HDBK-17, specifically, composites and adhesives. This report … covers testing and design allowable development completed to date on the F/A-18 E/F carbon/epoxy material systems IM7/977-3 tape, and AS4/977-3 cloth. All IM7/977-3 tape, AS4/977-3 tape, AS4/977-3 cloth, and AS4/977-3 hybrid testing and allowable development performed to date is covered in this report. This report presents the composites design allowables development testing and how the test results are utilized in the F/A-18 E/F structural designs. Subjects covered include the design allowable philosophy, test methods used for design allowable tests, environmental effects on composite properties, test results and how they were used to develop the carbon/epoxy structure design allowables.

**Paul, P.C., and Mahler, M.A., "Out-of-Plane Analysis for Composite Structures – Volume I. Final Report," Report NAWCADWAR-94138-60 (Vol. I), 15 September 1994.**

Composite airframe structures have recently experienced several unexpected failures due to the effects of out-of-plane loads. These loads are inherent to laminated, cocured, and adhesively bonded composite structures. There is great difficulty accounting for these loads and predicting their failures since the strength in the out-of-plane direction is commonly weak and inadequate design tools have been available.

The objective of this program was to develop simple two dimensional analysis methods that can be used to predict the primary out-of-plane failure modes and strengths of composite airframe structures. The primary sources of out-of-plane failures addressed by these developed analytical techniques are:

- induced stresses in laminate corner radii
- induced stresses due to ply drop off
- induced stresses due to panel buckling
- direct stresses due to fuel pressure loads
- induced stresses due to stiffener runouts or other load path changes

**Military Handbook – MIL HDBK-5F**

This handbook is primarily intended to provide a source of design, mechanical, and physical properties, and joint allowables. Material property and joint data obtained from tests by material and fastener producers, government agencies, and members of the airframe industry are submitted to MIL-HDBK-5 for review and analysis. Results of these analyses are submitted to the membership during semi-annual coordination meetings for approval and, when approved, are published in this Handbook.

# Appendix C. Definitions

| | |
|---|---|
| **Algorithm** | A standard set of procedures to solve a mathematical problem. |
| **Analysis Method** | A procedure for implementing a theoretical result. In the context of AIM-C, a set of engineering calculations generally performed by a computer code. |
| **Bayesian Statistics** | Baye's rule states that probability that both of the two events will occur is the probability of the first multiplied by the probability that if the first has occurred the second will also occur. There are two kinds of probability. The classical type based on empirical information and subjective probability. Bayesian statistics is based on subjective probabilities. |
| **Causative Event** | The beginning in time of an activity that results in particular outcomes of the activity. |
| **Coefficient of Correlation** | A statistical measure that is used to describe how well one variable is explained by another. When dealing with samples, it is the sample coefficient of variation. |
| **Confidence Interval** | A range of values that has some designated probability of including the true population parameter value. |
| **Confidence Level** | A range of values that has some designated probability of including the true population parameter value. |
| **Confidence Limits** | The upper and lower boundaries of a confidence interval. |
| **Correlation** | A statistical tool that is used to describe the degree to which one variable is *linearly* related to another. |
| **Counterintuitive** | Occurrence of things that we knew about but wrote-off as most unlikely to occur. |
| **DDSHM** | Discrete Damage Space Homogenization Method |
| **DDSHM_disbond_ Aijkl Code** | Code that analyzes the Discrete Damage Space Homogenization Method (DDSHM) for the A-matrix ($\mathbf{A}_{ijkl}$ in lamination plate theory). |
| **DDSHM_disbond_ SERR model** | Model that analyzes the Discrete Damage Space Homogenization Method (DDSHM) for strain energy release rate (SEER) |
| **Deformation Free Temperature** | The temperature at which an composite angle takes on the same shape as the tool from which it was manufactured. |
| **Demo-Version Module** | The version of the modules that will be used in the demonstration. |
| **Dummy Module** | A module created by the integration team, having the I/O structure of the proposed module, but none of the algorithms or models. |
| **Empirical** | Originating in or based on experience. |

**Estimate** A specific observed value of an estimator.

**Estimator** A sample statistic used to estimate a population parameter.

**Extrapolation** An inference made about the systems behavior in a new range of variables from experience in an old familiar range.

**Fiber Module** Provides properties of fiber, given temperature and fiber type. Uses historical data to provide values and variability. Outputs physical and mechanical properties.

**Frequentist Probability** The probability of an event occurring in a particular trial as the *frequency* with which it occurs in a long sequence of similar trails. More precisely, the probability is the value to which the long-run frequency converges as the number of trials increases.

**Heuristic** Describing an operational maxim derived from experience and intuition.

**Independence** A property shared by two or more entities when the performance of any one or any group has no effect on the performance of any other one or group.

**Input** Information, data, parameter values, etc, that is read by a module or model during the course of its execution, other then those values which the module or model itself writes and reads for internal operation.

**Interval Estimate** A range of values used to estimate an unknown population parameter.

**Lamina Module** An assemblage of analysis methods that predicts the governing damage/deformation mechanisms and the resulting effective engineering properties, such as moduli and strength, of a fiber-reinforced material given the properties of a fiber, resin, inter-phase, and constituent volume fractions, fiber architectures, and processing conditions.

**Laminate Module** An assemblage of analysis methods that provide the macroscopic constitutive relation for a laminated composite material constructed by stacking lamina. In the context of AIM-C, the laminate module provides the engineering properties and stress or strain results at a discrete point within the material. An example of a calculation to be performed in the laminate module would be resolving results of an un-notched coupon test to lamina stresses.

**Mechanistic or Physically Based Failure Criteria** A failure criterion in which the mode, or failure mechanism (in addition to failure level) is included in the analysis method. A physically based failure criterion has the key attributes of (1) allowing for calibration independent of the data set that it is being used to predict, i.e., it possesses a predictive capability beyond simple interpolation within a known data set and (2) being capable of independent verification via more than one observation (i.e., not just a failure load, but the extent of damage, or the deformation state, are correctly predicted). Examples of physically based failure criteria include: maximum strain, maximum stress, Hashin interaction, and the unified physics-based approach developed by Boeing including Von-Mises and Tresca yield criteria for metals (based on the mechanisms of dislocations moving under the influence of the resolved shear stresses) and fracture mechanics for homogeneous materials (based on the mechanism of crack propagation). These methods have the capability of predicting structural-level response from coupon-level test data. An example of a phenomenological based method (i.e., that is not physically based) is the well-known Tsai-Wu polynomial criteria. At this point it is a matter of debate as to which composite failure criteria have a mechanistic basis and which do not.

**Methodology**

1. An open system of procedures.

2. An overlying assemblage of processes, and procedures that defines a method, allowing one to achieve a particular goal or objective. Relative to the AIM-C program, it is the disciplined process, developed in close coordination with certifying personnel representing Department of Defense and commercial agencies.

**Model**

1. An abstraction of reality that is always an approximation to reality.

2. An assemblage of one or more mathematical expressions describing relationships between the input and output values.

**Model Error** Approximations in the model and/or in the algorithms.

**Module** A logical grouping of models compiled into a single code. Provides a service when linked with tools and/or other modules. Examples: Resin Module, Fiber Module, etc.

**Most Likely Value** A structured set of concepts, definitions, classifications, axioms, and assumptions used in providing a conceptual framework for studying a given problem.

**Multiple Regression** A process by which several variables are used to predict another.

**Objective Function** A specified mathematical relationship between a dependent variable and a set of independent variables.

**Optimization** The process of finding a set of system parameters that maximizes the attainment of system goals and objectives

**Ordinal Scale** An ordering (ranking) of items by the degree to which they satisfy some criterion.

**Outcome** The final result of an activity initiated by a causative event.

| | |
|---|---|
| **Output** | Information, data, parameter values, etc, that is written by a module or model during the course of its execution, excluding those values which the module or model itself writes and reads only for temporary internal operation. |
| **Paradigm** | A structured set of concepts, definitions, classifications, axioms, and assumptions used in providing a conceptual framework for studying a given problem. |
| **Parametric Variation** | A technique for sensitivity analysis of any given model in which the values of parameters that are input to the model's calculation are systematically varied to permit observation how such variation's affect the model output. |
| **Pareto Optimality** | An ideal state in the sense that o further distribution of economic activity will improve one's individual welfare without decreasing the welfare of an another individual. |
| **Pareto Optimization** | Optimization using a criterion that each person's needs be met as much as possible with out diminishing the degree of achievement of any other person. |
| **Point Estimate** | A single number that is used to estimate an unknown population parameter. |
| **Population** | A collection of *all elements* we are studying about which we are trying to draw conclusions. |
| **Precision** | The exactness with which a quantity is stated. The number of significant digits is a measure of precision. |
| **Predictive Modeling** | Use of a mathematical model that estimates or predicts the value of dependent variable in terms of component factors specified as independent variables |
| **Prepreg Module** | Combines resin and fiber into prepreg. Does not currently model temperature effects of impregnation process. Uses historical data to provide values and variability. Outputs physical properties of prepreg and relevant information on impregnation process. |
| **Process Module** | Converts uncured, collated debulked structure into cured structure through science-based models including effects of boundary conditions, geometry and material properties. Outputs physical and mechanical properties of cured structure and relevant information on curing process. |
| **Producibility Module** | Acts as a controller to compare requirements to capabilities for producibility and inspection. Also acts as a conduit to external producibility/cost tools. Uses a heuristic rules-based architecture. |
| **Quantification** | The assignment of a number to an entity or a method for determining a number to be assigned to an entity. |
| **Regression** | A general process of predicting one variable from another. |
| **Regression Analysis** | A process of developing an estimating equation (mathematical formula) that relates the known variables to unknown variables. It is important to realize this analysis defines the relationship of association *not necessarily* cause and effect. |

| | |
|---|---|
| **Reliability** | The probability that the system will perform it's required functions under given conditions for a specified operating time. |
| **Resin Module** | Provides properties of resin, given degree of cure, temperature and resin type. Uses science-based models. Outputs physical, mechanical, and chemical properties. |
| **Response** | A specific answer or visualization (graph) of data resulting from to the execution of a model or module. |
| **Risk** | The potential for realization of unwanted negative consequences of an event. |
| **Risk Agent** | A person or a group of persons who evaluates directly the consequence of risk to which he is subjected. |
| **Risk Consequence** | The impact to a risk agent of exposure to a risky event. |
| **Sample** | A collection of some, *but not all*, of the elements of population. |
| **Sensitivity Analysis** | A method used to examine the operation of a system by measuring the deviation of its nominal behavior due to perturbations of its components from their nominal values. |
| **SERR** | Strain Energy Release Rate |
| **SFT** | Stress Free Temperature |
| **SIFT** | Acronym for Strain Invariant Failure Theory |
| **Stochastic System** | A system whose behavior cannot be exactly predicted. |
| **Structures Module** | An assemblage of analysis methods that provide information on the performance of a material given a information on a structural detail. Examples of structures module analyses would be prediction of notched laminate behavior, free edge effects, and interlaminar stresses developed in curved regions subjected to in-plane loads. |
| **Subjective Probabilities** | The assignment of subjective weights to possible outcomes of an uncertain event where weights assigned satisfy axioms of probability |
| **Subjective Probabilities** | The assignment of subjective weights to possible outcomes of an uncertain event where weights assigned satisfy axioms of probability. |
| **Surprise** | Occurrence of an event previously thought to be of low probability or previously not consciously identified at all. |
| **System** | • A complex entity formed of many, often diverse, parts subject to a common plan or serving a common purpose.<br>• A composite of equipment, skills, and techniques capable of performing and/or supporting an operation. |

| | |
|---|---|
| **Taxonomy** | The identification and definition of properties of elements of universe; a disaggregation. |
| **Template** | A set of input and output files and executable code saved as an RDCS project file, which solves a specific problem. The template can be taken, modified and applied to solve the broader, general class of problems. |
| **Test-Version Module** | The first series of working version of the modules. These versions will be used for testing the module, trouble-shooting, and fixing errors. |
| **Tool** | An integrated software package having a user interface. Example: The comprehensive analysis tool (CAT), RDCS, DOME, ISAAC, COMPRO, CAICAT, CACC. |
| **Unacknowledged Error** | Errors due to human mistakes, blunders, etc. |
| **Uncertainty** | • A capacious term used to encompass a multiplicity of concepts<br>• Uncertainty may arise from incomplete information<br>• Uncertainty may arise from linguistic imprecision<br>• Uncertainty may refer to variability<br>• Uncertainty may arise because of simplification or approximations introduced to analyze the information cognitively or computationally more tractable<br>• Uncertainty may refer to uncertainty in our decisions<br>• We may even be uncertain about our uncertainty<br>• It is important to distinguish between different types and sources of uncertainty, since they need to be treated differently<br>• Probability is considered as an appropriate way to express some of the above uncertainties<br>• Ultimately uncertainty analysis should be the result of mutually compatible sets of models, beliefs, values and decisions |
| **Uncertainty (Epistemic)** | Represents partial ignorance or lack of perfect knowledge on the part of the analyst. This may reduced by further measurement or by improving the knowledge. |
| **Unexpected** | The occurrence of events or things that were not anticipated or imagined. |
| **Universe** | The totality under consideration often separated into system and environment. |
| **Utility Function** | A scale of preference (ordinal) or value (cardinal) to one or many decision makers. |
| **Variability (Aleatory)** | Represents diversity or heterogeneity in a population. Aleatory variability cannot be reduced by additional measurements. |
| **Wrapper** | A specialized piece of code used to provide the interface between tools and/or modules. |

# APPENDIX D - Conformance Planning Check Sheets

## Introduction

Conformance planning activities cover a large number of areas and items. Different questions are asked when starting the conformance planning activities. These questions establish what is known and what is unknown for conformance to the problem statement objectives and requirements. It is the first step in establishing what has to be conducted by multiple disciplines for qualification and certification of a new material and/or process. The answers form the nucleus of what existing information/data/ knowledge can be used and what has to be generated.

The process for conformance planning (Figure 3.2) includes asking questions about the detailed xRL exit criteria on how conformance will be met for materials, structures and producibility. A key item is that an Integrated Product Team (IPT) conducts this process with concurrence of results by the whole IPT and by customers. The outputs from these planning activities are a series of check sheets for materials, structures and producibility conformance activities listing what, when and how activities will be conducted.

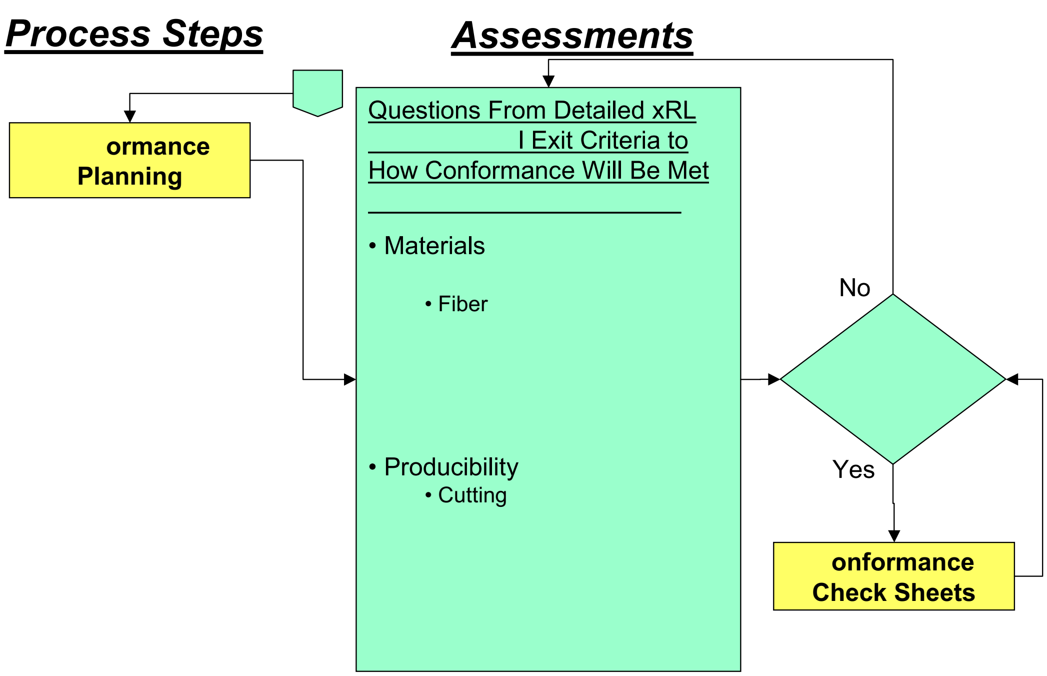



**Figure D-33 Conformance Planning Process**

There are a series of steps in this question answering process. The following items outline these steps.

- Gather existing knowledge: heuristics, lessons learned, information on similar problems or applications, public literature, analyses, and test results.

- Address every question/requirement. Address functional/disciplinary issues. Address interdisciplinary issues/assumptions/decisions as an IPT with all stakeholders involved.
- Determine divergence risk on existing information.
- Assess the conformance of existing knowledge with requirements.
- Handle Error and Uncertainty (See Methodology Section 18). Determine additional knowledge needed based on knowledge gaps, unacceptable risk, etc.
    - Understand and Classify Potential Uncertainty Sources
    - Determine What Is Important
    - Limit Uncertainty/Variation by Design and /or Process
    - Quantify Variation (Monte Carlo Simulation or Test)
- Address long lead items.
- Perform prudent studies to flesh out the conformance plan – could include trials, test, analyses, and combinations thereof.
- Prepare the conformance plan. Initiate efforts as applicable, while studies are underway to address details of the next maturity level of the plan.
- Address cost, schedule, and technical risk.
- Set up criterion for committal gates – analytical tools, test methods, guidelines, specifications, knowledge committal, maturity assessment, etc.
- Secure commitment to the plan from all stakeholders.
- Address the business case as appropriate.

A simplified tool for identification of areas and items for conformance planning was established. This tool is conformance check sheets for conformance areas and items.

## Conformance Check Sheet Areas and Items

Conformance check sheets are generated by individual disciplines addressing the details of what needs to be conducted to achieve conformance to problem statement objectives and requirements. Figure D-34 shows a listing of the different types of conformance check sheets for three disciplines.

- **Structures**
    - Application Failure Modes
    - Material Properties
    - Durability
- **Materials**
    - Fiber
    - Resin
    - Prepreg
- **Producibility**
    - Cutting
    - Layup
    - Debulking
    - Cure
    - In-Process Quality
    - Final Part Quality

**Figure D-34 Conformance Check Sheet Areas and Items**

## Process to Establish Conformance Planning Check Sheets

The purpose of the check sheets are to be simplified, quick look tools of what is planned to be done for conformance to requirements, how they are planned to be done and when they are planned to be done and possible how many to be done. The process to establish conformance check sheets is comprised of four steps. The first step is to identify the area and specific items in the area that are to be evaluated and listing them in a column as shown in Figure D-3.

| RESIN - THERMOSET |
|---|
| **Uncured Resin** |
| Viscosity |
| Reaction Rate |
| Heat of Reaction |
| Volatile Content/evolution temperature |
| Volatile Type |
| Volatile Vapor Pressure |
| Resin Cost |
| Density |
| Resin Cure Shrinkage |
| CTE |

**Figure D-35 Establish Check Sheet, Step 1**

Step two is to identify the primary variability items that have to be either controlled or have more data for than other areas. This Step 2 is shown in Figure D-4.

| RESIN - THERMOSET | |
|---|---|
| **Uncured Resin** | |
| Viscosity | ➢ |
| Reaction Rate | ➢ |
| Heat of Reaction | ➢ |
| Volatile Content/evolution temperature | ➢ |
| Volatile Type | ➢ |
| Volatile Vapor Pressure | |
| Resin Cost | |
| Density | |
| Resin Cure Shrinkage | |
| CTE | |

**Figure D-36 Establish Check Sheet, Step 2**

Step three is to add 14 columns to the matrix chart. Columns 1 through 11 are for a listing of the different maturity levels. Column 12 is to identify how the item result is to be obtained and specifics of the method to obtain the item result. The last column is to identify where the specific results would be kept. This Step 3 is shown in Figure D-5.

| | | TRL/XRL Maturity Level | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RESIN - THERMOSET | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | How Obtained, Test or Anlaysis | Test/Analysis Identification | Worksheet ID Reference |
| **Uncured Resin** | | | | | | | | | | | | | | | |
| Viscosity | ➢ | | | | | | | | | | | | Test | ASTM D 4473 | |
| Reaction Rate | ➢ | | | | | | | | | | | | Test | DSC via ASTM D 3418 and ISO 11357 | |
| Heat of Reaction | ➢ | | | | | | | | | | | | Test | DSC via ASTM D 3418 and ISO 11357 | |
| Volatile Content/evolution temperature | ➢ | | | | | | | | | | | | Test | TGA | |
| Volatile Type | ➢ | | | | | | | | | | | | Test/product knowledge | FTIR/Formula access | |
| Volatile Vapor Pressure | | | | | | | | | | | | | Test | | |
| Resin Cost | | | | | | | | | | | | | Specified Value | Based on vender input | |
| Density | | | | | | | | | | | | | Analysis | Based on cured/uncured test data | |
| Resin Cure Shrinkage | | | | | | | | | | | | | Analysis | Based on volumetric test data | |
| CTE | | | | | | | | | | | | | Analysis | based on TMA or linear dilatometer data | |

**Figure D-37 Establish Check Sheet, Step 3**

Step four is to identify at what maturity level results would be obtained. It could also be used to identify the number of evaluations that would be conducted at each of the maturity levels. This Step 4 is shown in Figure D-6.

| | | TRL/XRL Maturity Level | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **RESIN - THERMOSET** | | **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **How Obtained, Test or Anlaysis** | **Test/Analysis Identification** | **Worksheet ID Reference** |
| **Uncured Resin** | | | | | | | | | | | | | | | |
| Viscosity | ➢ | x | x | x | x | x | | | | | | | Test | ASTM D 4473 | |
| Reaction Rate | ➢ | x | x | x | x | x | | | | | | | Test | DSC via ASTM D 3418 and ISO 11357 | |
| Heat of Reaction | ➢ | x | x | x | x | x | | | | | | | Test | DSC via ASTM D 3418 and ISO 11357 | |
| Volatile Content/evolution temperature | ➢ | x | x | x | x | x | | | | | | | Test | TGA | |
| Volatile Type | ➢ | x | x | | | | | | | | | | Test/product knowledge | FTIR/Formula access | |
| Volatile Vapor Pressure | | | x | | | | | | | | | | Test | | |
| Resin Cost | | x | x | x | x | x | | | | | | | Specified Value | Based on vender input | |
| Density | | | x | x | x | x | | | | | | | Analysis | Based on cured/uncured test data | |
| Resin Cure Shrinkage | | | | x | | | | | | | | | Analysis | Based on volumetric test data | |
| CTE | | | | | | | | | | | | | Analysis | based on TMA or linear dilatometer data | |

**Figure D- 38 Establish Check Sheet, Step 4**

## Example Conformance Check Sheets

Figure D-7 through D-14 are example check sheets. They are representative of what could be established during a new activity.

| | | TRL/XRL Maturity Level | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RESIN - THERMOSET | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | How Obtained, Test or Anlaysis | Test/Analysis Identification | Worksheet ID Reference |
| **Uncured Resin** | | | | | | | | | | | | | | | |
| Viscosity | ➤ | x | x | x | x | x | | | | | | | Test | ASTM D 4473 | |
| Reaction Rate | ➤ | x | x | x | x | x | | | | | | | Test | DSC via ASTM D 3418 and ISO 11357 | |
| Heat of Reaction | ➤ | x | x | x | x | x | | | | | | | Test | DSC via ASTM D 3418 and ISO 11357 | |
| Volatile Content/evolution temperature | ➤ | x | x | x | x | x | | | | | | | Test | TGA | |
| Volatile Type | ➤ | x | x | | | | | | | | | | Test/product knowledg | FTIR/Formula access | |
| Volatile Vapor Pressure | | | x | | | | | | | | | | Test | | |
| Resin Cost | | x | x | x | x | x | | | | | | | Specified Value | Based on vender input | |
| Density | | | x | x | x | x | | | | | | | Analysis | Based on cured/uncured test data | |
| Resin Cure Shrinkage | | | | x | | | | | | | | | Analysis | Based on volumetric test data | |
| CTE | | | | | | | | | | | | | Analysis | based on TMA or linear dilatometer data | |
| Thermal Conductivity | | | x | | | | | | | | | | Analysis | Assumed to be that of cured resin | |
| Specific Heat | | | x | | | | | | | | | | Analysis | Assumed to be that of cured resin | |
| Kinetics Model | | | x | x | | | | | | | | | Analysis | Based on Reaction Rate | |
| Viscosity Model | | | x | x | | | | | | | | | Analysis | Based on Kinetics Model, Test Data | |
| Intellectual Property Issues | | x | x | x | x | x | | | | | | | | | |
| HPLC | ➤ | x | x | x | x | x | | | | | | | Test | | |
| FTIR | ➤ | x | x | x | x | x | | | | | | | Test | | |
| Health and Safety Information | | x | x | | | | | | | | | | MSDS | | |
| Morphology | | | x | | | | | | | | | | | | |
| Ingredient Suppliers | | | x | x | x | x | | | | | | | | | |
| **Cured Resin** | | | | | | | | | | | | | | | |
| Tensile Stress to Failure | | x | x | | | | | | | | | | Test | ASTM D638 | |
| Young's Modulus, Tensile | | x | x | | | | | | | | | | Test | ASTM D638 | |
| Tensile Strain to Failure | | x | x | | | | | | | | | | Test | ASTM D638 | |
| Glass Transition Temperature | | x | x | | | | | | | | | | Test | ASTM D3418 | |
| Volatile Content | ➤ | x | x | x | x | x | | | | | | | Test | ASTM D3530 | |
| Density | ➤ | x | x | x | x | x | | | | | | | Test | ASTM D-792 | |
| Modulus as a Function of Temp | | | | x | | | | | | | | | Test | Function of Temp and Degree of Cure | |
| CTE | | | | x | | | | | | | | | Test | ASTM E831 or linear diletometry | |
| Thermal Conductivity | | | | x | | | | | | | | | Test | ASTM C177 | |
| Solvent Resistance | | | x | | | | | | | | | | Test | ASTM D543 | |
| Specific Heat | | | | x | | | | | | | | | Test | ASTM E-1269 or Modulated DSC | |
| Bulk Modulus | | | | x | | | | | | | | | Analysis | | |
| Shear Modulus | | | | x | | | | | | | | | Test | ASTM E143 | |
| Poisson's Ratio | | | x | | | | | | | | | | Test | ASTM E143 (Room Temp) | |
| Coefficient of Moisture expansion | | | | x | | | | | | | | | Test | No Standard | |
| Compression Strength | | | | x | | | | | | | | | Test | ASTM D695 | |
| Compression Modulus | | | | x | | | | | | | | | Test | ASTM D695 | |
| Mass Transfer Properties | | | | x | | | | | | | | | Test | eight gain vs time, Ficks Law and modeling | |
| Viscoelastic Properties | | | | | x | | | | | | | | Analysis | | |
| Toughness Properties | | | | x | | | | | | | | | Test | | |
| Tg, Wet | | x | x | | | | | | | | | | Test | ASTM D3418 | |
| CME | | | | x | | | | | | | | | Test | | |
| Solvent (Moisture) Diffusitivity | | | | x | | | | | | | | | Test | | |
| Solvent Resistance | | | x | | | | | | | | | | Test | | |
| | ➤ | = Key Variability Limits Items | | | | | | | | | | | | | |

**Figure D-39 Example Resin Check Sheet**

| FIBER | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | How Obtained, Test or Anlaysis | Test/Analysis Identification | Worksheet ID Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **TEST TYPE/PROPERTIES - FIBER** | | | | | | | | | | | | | | | |
| Tensile Strength | ➤ | x | x | x | x | x | | | | | | | Analysis | SACMA SRM 16-94 | |
| Tensile Modulus E11 (longitudinal) | ➤ | x | x | x | x | x | | | | | | | Analysis | SACMA SRM 16-94 | |
| Tensile Strain to Failure | ➤ | x | x | x | x | x | | | | | | | Analysis | SACMA SRM 16-94 | |
| Yield (MUL) | ➤ | x | x | x | x | x | | | | | | | Analysis | SACMA SRM 13-94 | |
| Density | ➤ | x | x | x | x | x | | | | | | | Test | SACMA SRM 15-94 | |
| Heat Capacity (Cp) | | | | x | | | | | | | | | Test | ASTM E-1269 or Modulated DSC | |
| Thermal Conductivity Longitudinal | | | | x | | | | | | | | | Analysis | ASTM E-1225 | |
| Thermal Conductivity Transverse | | | | x | | | | | | | | | Analysis | ASTM E-1225 | |
| CTE - Axial | | x | x | | | | | | | | | | Analysis | Modeling with Lamina and resin CTE information | |
| CTE - Radial | | | | x | | | | | | | | | Analysis | Modeling with Lamina and resin CTE information | |
| Filament Diameter | ➤ | x | x | x | x | x | | | | | | | Test | Scanning Electron Microscopy | |
| Filament Count | ➤ | x | x | x | x | x | | | | | | | Test | Vendor | |
| Transverse Bulk Modulus | | | | x | | | | | | | | | Analysis | | |
| Youngs Modulus, E22 Transverse | | | | x | | | | | | | | | Test | Analysis combined with mechanical test data | |
| Shear Modulus, G12 | | | | x | | | | | | | | | Analysis | Analysis combined with mechanical test data | |
| Shear Modulus, G23 | | | | x | | | | | | | | | Analysis | Analysis combined with mechanical test data | |
| Poissons Ratio, 12 | | | | x | | | | | | | | | Analysis | Analysis combined with mechanical test data | |
| Poissons Ratio, 23 | | | | x | | | | | | | | | Analysis | Analysis combined with mechanical test data | |
| Compressive Strength | | | | | x | | | | | | | | Analysis | Analysis combined with mechanical test data | |
| Cost | | x | x | x | x | x | | | | | | | Specified Value | Vendor Provided | |
| T(g) | | | x | | | | | | | | | | Test | DMA | |
| wet T(g) | | | x | | | | | | | | | | Test | DMA | |
| Health and Safety | | x | x | | | | | | | | | | MSDS | | |
| **Fiber Surface** | | | | | | | | | | | | | | | |
| Sizing Type | ➤ | x | x | x | x | x | | | | | | | Specified Value | | |
| Fiber Surface Roughness | | | x | | | | | | | | | | Test | SEM or similar | |
| Surface Chemistry | | x | x | | | | | | | | | | Specified Value | | |
| **Fiber - Other** | | | | | | | | | | | | | | | |
| Fiber CME beta1 (Longitudinal) | | | | x | | | | | | | | | Test | | |
| Fiber CME beta2 (transverse) | | | | x | | | | | | | | | Test | | |
| Fiber Form and Type (Uni and Cloth, ie 5hs or plain or 8hs etc.) | | x | x | x | | | | | | | | | | | |
| Defect Identification | | | x | | | | | | | | | | | | |
| Defect Limits | | | | x | | | | | | | | | | | |
| | ➤ | = Key Variability Limits Items | | | | | | | | | | | | | |

**Figure D-40 Example Fiber Check Sheet**

| | | TRL/XRL | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **PREPREG** | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | How Obtained, Test or Anlaysis | Test/Analysis Identification | Worksheet ID Reference |
| **TEST TYPE/PROPERTIES - CHEMICAL** | | | | | | | | | | | | | | | |
| Viscosity | ➤ | x | x | x | x | x | | | | | | | Test | ASTM D 4473 | |
| Degree of Cure | ➤ | x | x | x | x | x | | | | | | | Test | DSC via ASTM D 3418 and ISO 11357 | |
| HPLC | ➤ | x | x | x | x | x | | | | | | | | | |
| FTIR | ➤ | x | x | x | x | x | | | | | | | | | |
| **TEST TYPE/PROPERTIES - PHYSICAL** | | | | | | | | | | | | | | | |
| Resin Areal Weight | ➤ | x | x | x | x | x | | | | | | | Test | ? digestion /burn-out ASTM D3171 or ASTM D3529 | |
| Fiber Areal Weight | ➤ | x | x | x | x | x | | | | | | | Test | ? digestion /burn-out ASTM D3171 or ASTM D3529 | |
| Mass Fraction Fiber | | | | | | | | | | | | | Test | digestion /burn-out ASTM D3171 or ASTM D3529 | |
| Prepreg Heat Capacity | | | | x | | | | | | | | | Analyisis | Rule of mixtures of cured resin / fiber | |
| Density | ➤ | | x | x | x | x | | | | | | | Analyisis | Rule of mixtures of cured resin / fiber | |
| Volume Fraction Fiber | ➤ | | x | x | x | x | | | | | | | Analyisis | From mass fraction and densities | |
| Prepreg Ply Thickness | ➤ | | x | x | x | x | | | | | | | Both | ? Measured for unconsolidated, calculated for consolidated | |
| Prepreg Areal Weight | ➤ | | x | x | x | x | | | | | | | Analyisis | From fiber areal weight | |
| Fiber Bed Permeability, x | | | | x | | | | | | | | | Test | Speciallized test | |
| Fiber Bed Permeability, y | | | | x | | | | | | | | | Test | Speciallized test | |
| Fiber Bed Permeability, z | | | | x | | | | | | | | | Test | Speciallized test | |
| Drape | | | x | x | | | | | | | | | Test | Generally qualitative | |
| Tack | | | x | x | | | | | | | | | Test | Generally qualitative | |
| Viscoelastic Properties | | | | | x | | | | | | | | Analyisis | | |
| Prepreg Defect Probability | | | | | x | x | | | | | | | Analyisis | | |
| Fiber Bed Elasticity | | | | x | | | | | | | | | Test | | |
| Cost | | | | | | | | | | | | | Specified Value | | |
| **Fiber - Other** | | | | | | | | | | | | | | | |
| Volume Fraction Fiber Range, One Sigma | | | | | x | x | | | | | | | Test | | |
| Backing Material ID | | | x | x | x | x | | | | | | | Specified Value? | | |
| Separator Material ID | | | x | x | x | x | | | | | | | Specified Value? | | |
| Available Widths | | | x | x | x | x | | | | | | | Specified Value? | | |
| Impregnation Level | ➤ | x | x | x | x | x | | | | | | | | | |
| Defect Limits | | | | x | | | | | | | | | | | |
| Defect Identification | | | x | | | | | | | | | | | | |
| Key Variability Limits Items = | ➤ | | | | | | | | | | | | | | |

**Figure D-41 Example Prepreg Check Sheet**

| | | | | MECHCANICAL PROPERTIES - LAMINA | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | How Obtained, Test or Anlaysis | Test/Analysis Identification | Worksheet ID Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PRIMARY LAMINA PROPERTIES And DURABILITY | | | | | | | | | | | | | | | | | | |
| | | | | Density of Composite | 3 | 3 | 3 | 3 | 3 | | | | | | | Analysis | Micromechanics | |
| Room Temperature | Tension | | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | 3 | x | x | x | x | | | | | | | Analysis | Volume average | |
| | | | Tranverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | 3 | x | x | | | | | | | | | Analysis | Volume average | |
| | | | Through Thickness | Strength | | | o | | | | | | | | | Analysis | Volume average | |
| | | | | Modulus | | | o | | | | | | | | | Analysis | Micromechanics | |
| | Compression | | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | 3 | x | x | x | x | | | | | | | Analysis | Volume average | |
| | | | Transverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | x | | | | | | | | | Analysis | Volume average | |
| | | | Through Thickness | Strength | | | o | | | | | | | | | Analysis | Volume average | |
| | Shear | | Longitudinal | Strength | | | o | | | | | | | | | Analysis | Volume average | |
| | | | | Modulus 1 | | | o | | | | | | | | | | | |
| | | | | Modulus 2 | | | o | | | | | | | | | Analysis | Micromechanics | |
| | | ±45° | | Stength, Modulus, Strain to Failure | 3 | x | x | x | x | | | | | | | | | |
| | | 0° | ILS | Strength | 3 | x | x | x | x | | | | | | | | | |
| | Other | | | Bulk Modulus | o | o | | | | | | | | | | Analysis | Micromechanics | |
| | | | | Transverse Poisson's ratio 3 | | | o | | | | | | | | | Analysis | Micromechanics | |
| | | | | Transverse Poisson's ratio 4 | | | o | | | | | | | | | Analysis | Micromechanics | |
| | | | | Through Thickness Thermal Conductivity | | | x | | | | | | | | | Analysis | Micromechanics | |
| | | | | Specific Heat | | | x | | | | | | | | | Analysis | Micromechanics | |
| | | | Longitudinal | Coeff. Of Thermal Expansion | x | x | | | | | | | | | | Analysis | Micromechanics | |
| | | | Transverse | | x | x | | | | | | | | | | Analysis | Micromechanics | |
| | | | Through Thickness | | | | x | | | | | | | | | Analysis | Micromechanics | |
| | | | Longitudinal | Coeff. Of Moisture Expansion | | | | x | | | | | | | | Analysis | Micromechanics | |
| | | | Transverse | | | | | x | | | | | | | | Analysis | Micromechanics | |
| | | | Through Thickness | | | | | x | | | | | | | | Analysis | Micromechanics | |
| | | | Longitudinal | Thermal Conductivity | | | x | | | | | | | | | Analysis | Micromechanics | |
| | | | Transverse | | | | x | | | | | | | | | Analysis | Micromechanics | |
| | SIFT | | | Lamina Effective Critical J1 | x | x | | | | | | | | | | Test | Boeing method | |
| | | | | Lamina Effective Critical Equivalent Strain | x | x | | | | | | | | | | Test | Boeing method | |
| | | | | Lamina Effective Pre -Critical Initiation J1 | x | x | | | | | | | | | | Test | Boeing method | |
| | | | | Lamina Effective Pre-Critical Initiation Equivalent Strain | x | x | | | | | | | | | | Test | Boeing method | |
| | | | | Fiber Effective Critical J1 | x | x | | | | | | | | | | Test | Boeing method | |
| | | | | Fiber Effective Critical Equivalent Strain | x | x | | | | | | | | | | Test | Boeing method | |

**Figure D-42 Example Lamina Property and Durability Check Sheet, 1 of 3**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Low Temperature | Tension | | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | x | x | x | Analysis | Volume average |
| | | | Tranverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | x | x | x | Analysis | Volume average |
| | | | Through Thickness | Strength | x | x | | Analysis | Volume average |
| | | | | Modulus | x | x | | Analysis | Micromechanics |
| | Compression | | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | x | Analysis | Volume average |
| | | | Transverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | x | Analysis | Volume average |
| | | | Through Thickness | Strength | | | | Analysis | Volume average |
| | Shear | | Longitudinal | Strength | | | x | Analysis | Volume average |
| | | | | Modulus 1 | | | x | | |
| | | | | Modulus 2 | | | x | Analysis | Micromechanics |
| | | ±45° | | Stength, Modulus, Strain to Failure | | | x | | |
| | | 0° | ILS | Strength | x | x | x | | |
| | SIFT | | | Lamina Effective Critical J1 | | | x | Test | Boeing method |
| | | | | Lamina Effective Critical Equivalent Strain | | | x | Test | Boeing method |
| | | | | Lamina Effective Pre -Critical Initiation J1 | | | x | Test | Boeing method |
| | | | | Lamina Effective Pre-Critical Initiation Equivalent Strain | | | x | Test | Boeing method |
| | | | | Fiber Effective Critical J1 | | | x | Test | Boeing method |
| | | | | Fiber Effective Critical Equivalent Strain | | | x | Test | Boeing method |
| Elevated Temperature 1 | Tension | | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | Analysis | Volume average |
| | | | Tranverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | Analysis | Volume average |
| | | | Through Thickness | Strength | | | o | Analysis | Volume average |
| | | | | Modulus | | | o | Analysis | Micromechanics |
| | Compression | | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | x | x | x | Analysis | Volume average |
| | | | Transverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | x | x | x | Analysis | Volume average |
| | | | Through Thickness | Strength | | | o | Analysis | Volume average |
| | Shear | | Longitudinal | Strength | | | | Analysis | Volume average |
| | | | | Modulus 1 | | | | | |
| | | | | Modulus 2 | | | | Analysis | Micromechanics |
| | | ±45° | | Stength, Modulus, Strain to Failure | x | x | | | |
| | | 0° | ILS | Strength | x | x | x | | |
| | SIFT | | | Lamina Effective Critical J1 | | | x | Test | Boeing method |
| | | | | Lamina Effective Critical Equivalent Strain | | | x | Test | Boeing method |
| | | | | Lamina Effective Pre -Critical Initiation J1 | | | x | Test | Boeing method |
| | | | | Lamina Effective Pre-Critical Initiation Equivalent Strain | | | x | Test | Boeing method |
| | | | | Fiber Effective Critical J1 | | | x | Test | Boeing method |
| | | | | Fiber Effective Critical Equivalent Strain | | | x | Test | Boeing method |

**Figure D-10 Example Lamina Property and Durability Check Sheet, 2 of 3**

| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Elevated Temperature 2 | Tension | | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | | Analysis | Volume average | |
| | | | Tranverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | x | | | | | | | | | Analysis | Volume average | |
| | | | Through Thickness | Strength | | | | | | | | | | | | | Analysis | Volume average | |
| | | | | Modulus | | | | | | | | | | | | | Analysis | Micromechanics | |
| | Compression | | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | x | x | | | | | | | | | Analysis | Volume average | |
| | | | Transverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | x | | | | | | | | | Analysis | Volume average | |
| | | | Through Thickness | Strength | | | | o | | | | | | | | | Analysis | Volume average | |
| | Shear | | Longitudinal | Strength | | | | o | | | | | | | | | Analysis | Volume average | |
| | | | | Modulus 1 | | | | o | | | | | | | | | | | |
| | | | | Modulus 2 | | | | o | | | | | | | | | Analysis | Micromechanics | |
| | | ±45° | | Stength, Modulus, Strain to Failure | | | x | x | | | | | | | | | | | |
| | | 0° | ILS | Strength | | | x | x | | | | | | | | | | | |
| | SIFT | | | Lamina Effective Critical J1 | | | | x | | | | | | | | | **Test** | **Boeing method** | |
| | | | | Lamina Effective Critical Equivalent Strain | | | | x | | | | | | | | | **Test** | **Boeing method** | |
| | | | | Lamina Effective Pre -Critical Initiation J1 | | | | x | | | | | | | | | **Test** | **Boeing method** | |
| | | | | Lamina Effective Pre-Critical Initiation Equivalent Strain | | | | x | | | | | | | | | **Test** | **Boeing method** | |
| | | | | Fiber Effective Critical J1 | | | | x | | | | | | | | | **Test** | **Boeing method** | |
| | | | | Fiber Effective Critical Equivalent Strain | | | | x | | | | | | | | | **Test** | **Boeing method** | |
| Elevated Temperature 1 or 2 and Wet | Tension | | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | x | x | | | | | | | | | Analysis | Volume average | |
| | | | Tranverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | x | | | | | | | | | Analysis | Volume average | |
| | | | Through Thickness | Strength | | | | o | | | | | | | | | Analysis | Volume average | |
| | | | | Modulus | | | | | | | | | | | | | Analysis | Micromechanics | |
| | Compression | | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | x | x | x | | | | | | | | Analysis | Volume average | |
| | | | Transverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | x | | | | | | | | | Analysis | Volume average | |
| | | | Through Thickness | Strength | | | | | | | | | | | | | Analysis | Volume average | |
| | Shear | | Longitudinal | Strength | | | | | | | | | | | | | Analysis | Volume average | |
| | | | | Modulus 1 | | | | | | | | | | | | | | | |
| | | | | Modulus 2 | | | | | | | | | | | | | Analysis | Micromechanics | |
| | | ±45° | | Stength, Modulus | | | | x | | | | | | | | | | | |
| | | 0° | ILS | Strength | | | x | x | | | | | | | | | | | |
| | SIFT | | | Lamina Effective Critical J1 | | | | x | | | | | | | | | **Test** | **Boeing method** | |
| | | | | Lamina Effective Critical Equivalent Strain | | | | x | | | | | | | | | **Test** | **Boeing method** | |
| | | | | Lamina Effective Pre -Critical Initiation J1 | | | | x | | | | | | | | | **Test** | **Boeing method** | |
| | | | | Lamina Effective Pre-Critical Initiation Equivalent Strain | | | | x | | | | | | | | | **Test** | **Boeing method** | |
| | | | | Fiber Effective Critical J1 | | | | x | | | | | | | | | **Test** | **Boeing method** | |
| | | | | Fiber Effective Critical Equivalent Strain | | | | x | | | | | | | | | **Test** | **Boeing method** | |
| | | | | Key Variability Limits Items = | ➤ | | | | | | | | | | | | | | |

**Figure D-10 Example Lamina Property and Durability Check Sheet, 3 of 3**

| 7. Detailed xRL for Structures, Material Properties and Material Durability | | | | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | How Obtained, Test or Anlaysis | Test/Analysis Identification | Worksheet ID Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | TRL/XRL | | | | | | | | | | | | | |
| PRIMARY LAMINATE MATERIAL PROPERTIES | | | | | | | | | | | | | | | | | | |
| | | | | Density of laminate | x | x | x | x | x | | | | | | | Test | | |
| Room Temperature | Tension | Layup 1 (Quasi) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | x | x | x | x | x | | | | | | | Test/Analysis | | |
| | | | | Open Hole Tensile Strength | | | x | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | x | | | | | | | | | | | |
| | | Layup 2 (Hard) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | x | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Tensile Strength | | | | x | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | x | | | | | | | | | | |
| | | | Transverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | x | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Tensile Strength | | | | x | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | x | | | | | | | | | | |
| | | Layup 3 (Soft) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | x | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Tensile Strength | | | | x | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | x | | | | | | | | | | |
| | | | Transverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | x | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Tensile Strength | | | | x | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | x | | | | | | | | | | |
| | Compression | Layup 1 (Quasi) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | x | x | x | x | x | | | | | | | Test/Analysis | | |
| | | | | Open Hole Compressive Strength | x | x | x | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | x | | | | | | | | | | | |
| | | Layup 2 (Hard) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | x | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Compressive Strength | | | | x | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | x | | | | | | | | | | |
| | | | Transverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | x | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Compressive Strength | | | | x | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | x | | | | | | | | | | |
| | | Layup 3 (Soft) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | x | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Compressive Strength | | | | x | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | x | | | | | | | | | | |
| | | | Transverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | x | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Compressive Strength | | | | x | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | x | | | | | | | | | | |
| | Shear | Layup 1 (Quasi) | Longitudinal | Shear Strength, Modulus, Strain to Failure | | | | | | | | | | | | Test/Analysis | | |
| | | | | Interlaminar Shear | | | | | | | | | | | | | | |
| | | | Transverse | Stength 1, Modulus 1, Strain to Failure 1 | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | | | Stength 2, Modulus 2, Strain to Failure 2 | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | Layup 2 (Hard) | Longitudinal | Shear Strength, Modulus, Strain to Failure | | | | | | | | | | | | Test/Analysis | | |
| | | | Transverse | Stength 1, Modulus 1, Strain to Failure 1 | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | | | Stength 2, Modulus 2, Strain to Failure 2 | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | Layup 3 (Soft) | Longitudinal | Shear Strength, Modulus, Strain to Failure | | | | | | | | | | | | Test/Analysis | | |
| | | | Transverse | Stength 1, Modulus 1, Strain to Failure 1 | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | | | Stength 2, Modulus 2, Strain to Failure 2 | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | Bearing By-Pass, Tension | Layup 1 (Quasi) | Longitudinal | Strength, Strain to Failure | | | | | | | | | | | | Test/Analysis | | |
| | | | Transverse | Strength, Strain to Failure | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | Layup 2 (Hard) | Longitudinal | Strength, Strain to Failure | | | | | | | | | | | | Test/Analysis | | |
| | | | Transverse | Strength, Strain to Failure | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | Layup 3 (Soft) | Longitudinal | Strength, Strain to Failure | | | | | | | | | | | | Test/Analysis | | |
| | | | Transverse | Strength, Strain to Failure | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | Bearing By-Pass, Compression | Layup 1 (Quasi) | Longitudinal | Strength, Strain to Failure | | | | | | | | | | | | Test/Analysis | | |
| | | | Transverse | Strength, Strain to Failure | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | Layup 2 (Hard) | Longitudinal | Strength, Strain to Failure | | | | | | | | | | | | Test/Analysis | | |
| | | | Transverse | Strength, Strain to Failure | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | Layup 3 (Soft) | Longitudinal | Strength, Strain to Failure | | | | | | | | | | | | Test/Analysis | | |
| | | | Transverse | Strength, Strain to Failure | | | | | | | | | | | | Analysis/Test | Laminate Module | |

**Figure D-11 Example Laminate Property and Durability Check Sheet, 1 of 7**

| 7. Detailed xRL for Structures, Material Properties and Material Durability | | | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | How Obtained, Test or Anlaysis | Test/Analysis Identification | Worksheet ID Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SECONDARY LAMINATE MATERIAL PROPERTIES | | | | | | | | | | | | | | | | | |
| Room Temperature | Secondary | Layup 1 (Quasi) | Laminate Interlaminar Mode I Fracture Toughness | | | | | | | | | | | | Test | | |
| | | | Laminate Interlaminar Mode II Fracture Toughness | | | | | | | | | | | | Test | | |
| | | | Stiffness Matrix | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | | Bending Matrix | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | | Laminate Poisson's ratio 1 | | | | | | | | | | | | Test/Analysis | | |
| | | | Laminate Longitudinal Coeff. Of Thermal Expansion | | | | | | | | | | | | Test | | |
| | | | Laminate Transverse Coeff. Of Thermal Expansion | | | | | | | | | | | | Analysis | Laminate Module | |
| | | | Laminate Intralaminar Mode I Fracture Toughness | | | | | | | | | | | | Test/Analysis | | |
| | | | Laminate Intralaminar Mode II Fracture Toughness | | | | | | | | | | | | Test/Analysis | | |
| | | | Flexural, torsional, and combined loading strength | | | | | | | | | | | | Analysis | Laminate Module | |
| | | | Fiber inputs: Weibull parameters, strain to failure | | | | | | | | | | | | Test | Lamina Module | |
| | | | Viscoelastic, nonlinear matrix behavior calculation methods | | | | | | | | | | | | Analysis | Lamina Module | |
| | | | First ply failure envelopes | | | | | | | | | | | | Analysis | Laminate Module | |
| | | | Laminate Shear Modulus | | | | | | | | | | | | Test/Analysis | | |
| | | | Laminate Longitudinal Coeff. Of Moisture Expansion | | | | | | | | | | | | Test | | |
| | | | Laminate Transverse Coeff. Of Moisture Expansion | | | | | | | | | | | | Test | | |

| 7. Detailed xRL for Structures, Material Properties and Material Durability | | | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | How Obtained, Test or Anlaysis | Test/Analysis Identification | Worksheet ID Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| OTHER LAMINATE MATERIAL PROPERTIES | | | | | | | | | | | | | | | | | |
| Room Temperature | Other | Layup 1 (Quasi) | Compressive Elastic Moduli | | | | | | | | | | | | Analysis | Lamina Module | |
| | | | Stochastic calculation methods | | | | | | | | | | | | Analysis | Laminate Module | |
| | | | Coupling Matrix | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | | Laminate Through Thickness Tensile Modulus | | | | | | | | | | | | Test/Analysis | | |
| | | | Laminate Shear Coeff. Of Thermal Expansion | | | | | | | | | | | | Analysis | Laminate Module | |
| | | | Laminate Longitudinal Thermal Conductivity | | | | | | | | | | | | Test | | |
| | | | Laminate Transverse Thermal Conductivity | | | | | | | | | | | | Test | | |
| | | | Laminate Through-Thickness Tensile Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | Laminate Through-Thickness Tensile Strain to Failure | | | | | | | | | | | | Test/Analysis | | |
| | | | Fiber/matrix interface properties | | | | | | | | | | | | Test | Lamina Module | |
| | | | Laminate Transverse Poisson's ratio 3 | | | | | | | | | | | | Analysis | Laminate Module | |
| | | | Laminate Transverse Poisson's ratio 4 | | | | | | | | | | | | Analysis | Laminate Module | |
| | | | Laminate Through-Thickness Compressive Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | Laminate Through-Thickness Compressive Strain to Failure | | | | | | | | | | | | Test/Analysis | | |
| | | | Isotropic Fiber Properties and/or option for associated calculation method | | | | | | | | | | | | Analysis | Lamina Module | |
| | | | Laminate Through Thickness Coeff. Of Thermal Expansion | | | | | | | | | | | | Analysis | Laminate Module | |
| | | | Laminate Shear Coeff. Of Moisture Expansion | | | | | | | | | | | | Analysis | Structures Module | |
| | | | Laminate Through Thickness Coeff. Of Moisture Expansion | | | | | | | | | | | | Analysis | Structures Module | |
| | | | Laminate Through Thickness Thermal Conductivity | | | | | | | | | | | | Analysis | Structures Module | |

**Figure D-11 Example Laminate Property and Durability Check Sheet, 2 of 7**

| 7. Detailed xRL for Structures, Material Properties and Material Durability | | | | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | How Obtained, Test or Anlaysis | Test/Analysis Identification | Worksheet ID Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DURABILITY - PRIMARY MATERIAL PROPERTIES | | | | | | | | | | | | | | | | | | |
| Low Temperature | Tension | Layup 1 (Quasi) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Tensile Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | | Layup 2 (Hard) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Tensile Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | | | Transverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Tensile Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | | Layup 3 (Soft) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Tensile Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | | | Transverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Tensile Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | Compression | Layup 1 (Quasi) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Compressive Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | | Layup 2 (Hard) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Compressive Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | | | Transverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Compressive Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | | Layup 3 (Soft) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Compressive Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | | | Transverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Compressive Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | Shear | Layup 1 (Quasi) | Longitudinal | Shear Strength, Modulus, Strain to Failure | | | | | | | | | | | | Test/Analysis | | |
| | | | | Interlaminar Shear | | | | | | | | | | | | | | |
| | | | Transverse | Stength 1, Modulus 1, Strain to Failure 1 | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | | | Stength 2, Modulus 2, Strain to Failure 2 | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | Layup 2 (Hard) | Longitudinal | Shear Strength, Modulus, Strain to Failure | | | | | | | | | | | | Test/Analysis | | |
| | | | Transverse | Stength 1, Modulus 1, Strain to Failure 1 | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | | | Stength 2, Modulus 2, Strain to Failure 2 | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | Layup 3 (Soft) | Longitudinal | Shear Strength, Modulus, Strain to Failure | | | | | | | | | | | | Test/Analysis | | |
| | | | Transverse | Stength 1, Modulus 1, Strain to Failure 1 | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | | | Stength 2, Modulus 2, Strain to Failure 2 | | | | | | | | | | | | Analysis/Test | Laminate Module | |

**Figure D-11 Example Laminate Property and Durability Check Sheet, 3 of 7**

| 7. Detailed xRL for Structures, Material Properties and Material Durability | | | | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | How Obtained, Test or Anlaysis | Test/Analysis Identification | Worksheet ID Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DURABILITY - PRIMARY MATERIAL PROPERTIES | | | | | | | | | | | | | | | | | | |
| Elevated Temperature 1 | Tension | Layup 1 (Quasi) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Tensile Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | | Layup 2 (Hard) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Tensile Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | | | Transverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Tensile Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | | Layup 3 (Soft) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Tensile Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | | | Transverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Tensile Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | Compression | Layup 1 (Quasi) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Compressive Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | | Layup 2 (Hard) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Compressive Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | | | Transverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Compressive Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | | Layup 3 (Soft) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Compressive Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | | | Transverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Compressive Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | Shear | Layup 1 (Quasi) | Longitudinal | Shear Strength, Modulus, Strain to Failure | | | | | | | | | | | | Test/Analysis | | |
| | | | | Interlaminar Shear | | | | | | | | | | | | | | |
| | | | Transverse | Stength 1, Modulus 1, Strain to Failure 1 | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | | | Stength 2, Modulus 2, Strain to Failure 2 | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | Layup 2 (Hard) | Longitudinal | Shear Strength, Modulus, Strain to Failure | | | | | | | | | | | | Test/Analysis | | |
| | | | Transverse | Stength 1, Modulus 1, Strain to Failure 1 | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | | | Stength 2, Modulus 2, Strain to Failure 2 | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | Layup 3 (Soft) | Longitudinal | Shear Strength, Modulus, Strain to Failure | | | | | | | | | | | | Test/Analysis | | |
| | | | Transverse | Stength 1, Modulus 1, Strain to Failure 1 | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | | | Stength 2, Modulus 2, Strain to Failure 2 | | | | | | | | | | | | Analysis/Test | Laminate Module | |

**Figure D-11 Example Laminate Property and Durability Check Sheet, 4 of 7**

| 7. Detailed xRL for Structures, Material Properties and Material Durability | | | | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | How Obtained, Test or Anlaysis | Test/Analysis Identification | Worksheet ID Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DURABILITY - PRIMARY MATERIAL PROPERTIES | | | | | | | | | | | | | | | | | | |
| Elevated Temperature 2 | Tension | Layup 1 (Quasi) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Tensile Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | | Layup 2 (Hard) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Tensile Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | | | Transverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Tensile Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | | Layup 3 (Soft) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Tensile Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | | | Transverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Tensile Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | Compression | Layup 1 (Quasi) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Compressive Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | | Layup 2 (Hard) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Compressive Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | | | Transverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Compressive Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | | Layup 3 (Soft) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Compressive Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | | | Transverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Compressive Strength | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | |
| | Shear | Layup 1 (Quasi) | Longitudinal | Shear Strength, Modulus, Strain to Failure | | | | | | | | | | | | Test/Analysis | | |
| | | | | Interlaminar Shear | | | | | | | | | | | | | | |
| | | | Transverse | Stength 1, Modulus 1, Strain to Failure 1 | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | | | Stength 2, Modulus 2, Strain to Failure 2 | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | Layup 2 (Hard) | Longitudinal | Shear Strength, Modulus, Strain to Failure | | | | | | | | | | | | Test/Analysis | | |
| | | | Transverse | Stength 1, Modulus 1, Strain to Failure 1 | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | | | Stength 2, Modulus 2, Strain to Failure 2 | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | Layup 3 (Soft) | Longitudinal | Shear Strength, Modulus, Strain to Failure | | | | | | | | | | | | Test/Analysis | | |
| | | | Transverse | Stength 1, Modulus 1, Strain to Failure 1 | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | | | Stength 2, Modulus 2, Strain to Failure 2 | | | | | | | | | | | | Analysis/Test | Laminate Module | |

**Figure D-11 Example Laminate Property and Durability Check Sheet, 5 of 7**

| 7. Detailed xRL for Structures, Material Properties and Material Durability | | | | | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | | How Obtained, Test or Anlaysis | Test/Analysis Identification | Worksheet ID Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DURABILITY - PRIMARY MATERIAL PROPERTIES | | | | | | | | | | | | | | | | | | | | |
| Elevated Temperature 1 and/or 2 Plus Wet | Tension | Layup 1 (Quasi) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Tensile Strength | | | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | | | |
| | | Layup 2 (Hard) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Tensile Strength | | | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | | | |
| | | | Transverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Tensile Strength | | | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | | | |
| | | Layup 3 (Soft) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Tensile Strength | | | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | | | |
| | | | Transverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Tensile Strength | | | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | | | |
| | Compression | Layup 1 (Quasi) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Compressive Strength | | | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | | | |
| | | Layup 2 (Hard) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Compressive Strength | | | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | | | |
| | | | Transverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Compressive Strength | | | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | | | |
| | | Layup 3 (Soft) | Longitudinal | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Compressive Strength | | | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | | | |
| | | | Transverse | Strength, Modulus, Strain to Failure, Poissons 1 & 2 | | | | | | | | | | | | | | Test/Analysis | | |
| | | | | Open Hole Compressive Strength | | | | | | | | | | | | | | Test/Analysis | | |
| | | | | Filled Hole | | | | | | | | | | | | | | | | |
| | Shear | Layup 1 (Quasi) | Longitudinal | Shear Strength, Modulus, Strain to Failure | | | | | | | | | | | | | | Test/Analysis | | |
| | | | | Interlaminar Shear | | | | | | | | | | | | | | | | |
| | | | Transverse | Stength 1, Modulus 1, Strain to Failure 1 | | | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | | | Stength 2, Modulus 2, Strain to Failure 2 | | | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | Layup 2 (Hard) | Longitudinal | Shear Strength, Modulus, Strain to Failure | | | | | | | | | | | | | | Test/Analysis | | |
| | | | Transverse | Stength 1, Modulus 1, Strain to Failure 1 | | | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | | | Stength 2, Modulus 2, Strain to Failure 2 | | | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | Layup 3 (Soft) | Longitudinal | Shear Strength, Modulus, Strain to Failure | | | | | | | | | | | | | | Test/Analysis | | |
| | | | Transverse | Stength 1, Modulus 1, Strain to Failure 1 | | | | | | | | | | | | | | Analysis/Test | Laminate Module | |
| | | | | Stength 2, Modulus 2, Strain to Failure 2 | | | | | | | | | | | | | | Analysis/Test | Laminate Module | |

**Figure D-11 Example Laminate Property and Durability Check Sheet, 6 of 7**

| DURABILITY OTHER MATERIAL PROPERTIES | | | | | | | |
|---|---|---|---|---|---|---|---|
| Thermal Cycling | | | | Microcracking | Test/Analysis | | |
| Impact | Compression | Layup 1 | Level 1 | Strength, Modulus, Strain to Failure | Test/Analysis | | |
| | | | Level 2 | Strength, Modulus, Strain to Failure | | | |
| | | | Level 3 | Strength, Modulus, Strain to Failure | Test/Analysis | | |
| (also delamination effect of defects) | | Layup 2 | Level 1 | Strength, Modulus, Strain to Failure | Test/Analysis | | |
| | | | Level 2 | Strength, Modulus, Strain to Failure | | | |
| | | | Level 3 | Strength, Modulus, Strain to Failure | Test/Analysis | | |
| | | Layup 3 | Level 1 | Strength, Modulus, Strain to Failure | Test/Analysis | | |
| | | | Level 2 | Strength, Modulus, Strain to Failure | | | |
| | | | Level 3 | Strength, Modulus, Strain to Failure | Test/Analysis | | |
| Solvent Reistance | | | | ILS | Test/Analysis | | |

➤ = Key Variability Limits Items

**Figure D-11 Example Laminate Property and Durability Check Sheet, 7 of 7**

| Operation | Activity | 0.25 | 0.50 | 0.75 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Hand Cutting | Requirements | | | | X | | | | | | |
| | Spool Information | | | | X | | | | | | |
| | Indirect Materials ID/Compatability | | | | x | X | | | | | |
| | Tack, Original | | | | X | | | | | | |
| | Tack, Out Time | | | | X | | X | | | | |
| | Tack, Freezer Time | | | | | | X | | | | |
| | Variability, Dimensions | | | | X | | | | | | |
| | Variability, Angle | | | | X | | | | | | |
| | Specification, Draft Items/Areas | | | | X | X | | | | | |
| | Specification, Preliminary | | | | | | X | | | | |
| | Specification, Final | | | | | | | X | | | |
| Hand Layup | Requirements | | | | X | | | | | | |
| | Indirect Materials ID/Compatability | | | | x | X | | | | | |
| | Tack, Original (lay down and removal) | | | | X | | | | | | |
| | Tack, Out Time (lay down and removal) | | | | x | | X | | | | |
| | Tack, Freezer Time | | | | | | X | | | | |
| | Variability, Dimensions | | | | X | | | | | | |
| | Variability, Angle | | | | X | | | | | | |
| | Specification, Draft Items/Areas | | | | X | X | | | | | |
| | Specification, Preliminary | | | | | | X | | | | |
| | Specification, Final | | | | | | | X | | | |
| Debulking | Requirements | | | | X | | | | | | |
| | Indirect Materials ID/Compatability | | | | x | X | | | | | |
| | Methods, Plies/Times/Temps/Pressures | | | | x | X | | | | | |
| | Limits, Plies/Times/Temps/Pressures | | | | | x | | | | | |
| | Specification, Draft Items/Areas | | | | X | X | | | | | |
| | Specification, Preliminary | | | | | | X | | | | |
| | Specification, Final | | | | | | | X | | | |
| Bagging | Requirements | | | | X | | | | | | |
| | Indirect Materials | | | | x | X | | | | | |
| | Edge Gaps, Initial | | | | X | | | | | | |
| | Edge Gaps, Limits | | | | | X | | | | | |
| | Specification, Draft Items/Areas | | | | X | X | | | | | |
| | Specification, Preliminary | | | | | | X | | | | |
| | Specification, Final | | | | | | | X | | | |
| Cure | Requirements | | | | X | | | | | | |
| | Initial Times/Temps/Pressures | | | | X | | | | | | |
| | Material Combinations | | | | X | | | | | | |
| | Limits, Times/Temps/Pressures | | | | | X | | | | | |
| | Limits, Heat up/Cool Down/Tooling/Equipment | | | | x | X | | | | | |
| | Specification, Draft Items/Areas | | | | X | X | | | | | |
| | Specification, Preliminary | | | | | | X | | | | |
| | Specification, Final | | | | | | | X | | | |
| Tooling | | | | | x | x | X | x | | | |
| NDE | | | | | x | X | X | x | | | |

= Primary Activity

**Figure D-12 Example Producibility Operations Check Sheet**

| Area | Item | Activity | 0.25 | 0.50 | 0.75 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| In-Process Qulaity | Cutting | Times | | | | x | | | | | | |
| | | Temperatures | | | | x | | | | | | |
| | | Dimensions | | | | x | | | | | | |
| | | Angles | | | | x | | | | | | |
| | | Indirect Manterial Compatability | | | | x | x | | | | | |
| | | Limitations | | | | | x | | | | | |
| | | Specification, Draft Items/Areas | | | | x | x | | | | | |
| | | Specification, Preliminary | | | | | | x | | | | |
| | | Specification, Final | | | | | | | x | | | |
| | Hand Layup | Times | | | | x | | | | | | |
| | | Temperatures | | | | x | | | | | | |
| | | Pressures | | | | x | | | | | | |
| | | Indirect Material Compatability | | | | x | x | | | | | |
| | | Dimensions | | | | x | | | | | | |
| | | Angles | | | | x | | | | | | |
| | | Limitations | | | | | x | | | | | |
| | | Specification, Draft Items/Areas | | | | x | x | | | | | |
| | | Specification, Preliminary | | | | | | x | | | | |
| | | Specification, Final | | | | | | | x | | | |
| | Debulking | Plies | | | | x | | | | | | |
| | | Times | | | | x | | | | | | |
| | | Temperatures | | | | x | | | | | | |
| | | Pressures | | | | x | | | | | | |
| | | Indirect Material Compatability | | | | x | x | | | | | |
| | | Limitations | | | | | x | | | | | |
| | | Specification, Draft Items/Areas | | | | x | x | | | | | |
| | | Specification, Preliminary | | | | | | x | | | | |
| | | Specification, Final | | | | | | | x | | | |
| | Bagging | Indirect Material Compatability | | | | x | x | | | | | |
| | | Edge Gaps | | | | x | | | | | | |
| | | Limitations | | | | | x | | | | | |
| | | Specification, Draft Items/Areas | | | | x | x | | | | | |
| | | Specification, Preliminary | | | | | | x | | | | |
| | | Specification, Final | | | | | | | x | | | |
| | Cure | Times | | | | x | | | | | | |
| | | Temperatures | | | | x | | | | | | |
| | | Pressures | | | | x | | | | | | |
| | | Aborts | | | | | x | | | | | |
| | | Limitations | | | | | x | | | | | |
| | | Specification, Draft Items/Areas | | | | x | x | | | | | |
| | | Specification, Preliminary | | | | | | x | | | | |
| | | Specification, Final | | | | | | | x | | | |
| | Other | Out Time | | | | x | | x | | | | |
| | | Freezer Time | | | | | | x | | | | |
| | | | | | | | = | Primary Activity | | | | |

**Figure D-13 Example Producibility In-Process Quality Check Sheet**

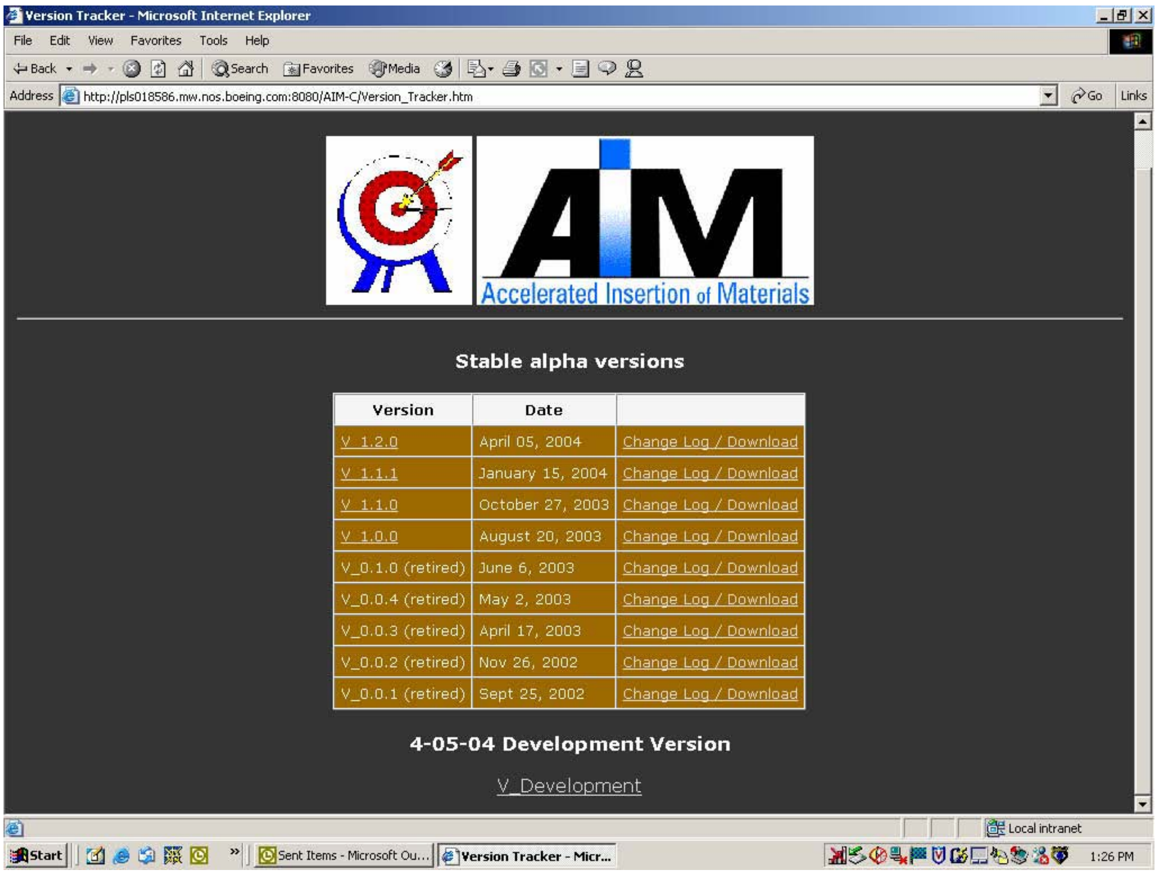
| Area | Item | Activity | 0.25 | 0.50 | 0.75 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Final Quality | Voids/ Porosity | Debulking | | | | x | | | | | | |
| | | Bagging | | | | x | | | | | | |
| | | Cure | | | | x | | | | | | |
| | | Flat Panels | | | | x | | | | | | |
| | | NDE Defect Detectability | | | | x | x | | | | | |
| | | NDE Defect Detectability Limits | | | | x | x | | | | | |
| | | Ramps | | | | x | | | | | | |
| | | Multiple Thickness Flat Panels | | | | | x | | | | | |
| | | NDE Thickness Standards | | | | | x | | | | | |
| | | Hats | | | | | x | | | | | |
| | | NDE Multiple Material Standards | | | | | x | | | | | |
| | | Size Scale up | | | | x | | x | | | | |
| | | Specification, Draft Items/Areas | | | | x | x | | | | | |
| | | Specification, Preliminary | | | | | | x | | | | |
| | | Specification, Final | | | | | | | x | | | |
| | Delaminations/ Inclusions | Indirect Material Detectability | | | | x | | | | | | |
| | | Indirect Material Detectability Limits | | | | | x | | | | | |
| | | Multiple Material Separation Detectability | | | | | x | | | | | |
| | | Specification, Draft Items/Areas | | | | x | x | | | | | |
| | | Specification, Preliminary | | | | | | x | | | | |
| | | Specification, Final | | | | | | | x | | | |
| | Thickness | Material Capability | | | | x | | | | | | |
| | | Producibility Capability | | | | x | x | | | | | |
| | | Specification, Draft Items/Areas | | | | x | x | | | | | |
| | | Specification, Preliminary | | | | | | x | | | | |
| | | Specification, Final | | | | | | | x | | | |
| | In-Plane Fiber Distortion | | | | | | | x | | | | |
| | | | | | | | | x | | | | |
| | | | | | | | | | | | | |
| | Out of Plane Fiber Distortion | | | | | | | x | | | | |
| | | | | | | | | x | | | | |
| | | | | | | | | | | | | |
| | Other | Effects of Defects | | | | | x | x | x | | | |

= Primary Activity

**Figure D-14 Example Producibility Final Quality Check Sheet**

# Appendix E - Accelerated Insertion of Materials – Composites (AIM-C): Users Manual

**By Alison Ruffing**




The original issue of this document was jointly accomplished by Boeing and the U.S. Government under the guidance of NAVAIR under N00421-01-3-0098, Accelerated Insertion of Materials – Composites.

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# 1. AIM-C Methodology and System

The AIM-C System provides a modeling environment capable of solving a broad range of complex problems by integrating together a host of modules, databases or other elements. Users are able to create a product's design, manufacture, and support knowledge base, starting with a problem statement, customer needs, and the certification agencies requirements.

The AIM-C methodology provides a disciplined process for materials insertion. The methodology does the following things: (1) captures the problem statement, (2) guides the Integrated Product Team (with technology and application development members) through requirements development, (3) facilitates conformance planning and provides tools for studies which can assess interactions, importance, and show-stoppers important to planning for qualification and certification conformance, (4) provides for documentation of knowledge generated by use of heuristics, lessons learned, and existing knowledge, by analysis, and by test with associated confidence levels, and (5) facilitates conformance assessment and committal of the knowledge base to the master.

The AIM-C methodology was built using ground rules: (1) the building block approach is integral to the insertion process (2) all relevant disciplines are involved, (3) testing is focused on needs that are identified through analysis and the current knowledge base, and (4) the insertion process targets long lead concerns, unknowns, and areas predicted to be sensitive to changes in materials, processing, or environmental parameters.

A feature of the AIM-C methodology is that the AIM-C system maintains three important characteristics: (1) any given piece of information resides in only one element (module, data set, etc), thus the system can quickly grow to adapt to a broad range of problems with minimal conflicts and programmer-intervention, (2) each element of the system has an owner or expert that updates, maintains and provides technical services to the user community, and (3) the database created by use of the system can be certified, meaning all elements and the system are validated, verified, uniquely identified and traceable.

## 1.1 Software Documentation

The AIM-C system was created with a variety of documentation depending on what aspect the user is looking at. This section will give a brief overview of the codes behind the scenes and how it works.

The interface currently uses a basic html (hypertext markup language) and Java Server Pages (JSP) style. The html is the page that actually displays in the browser. It contains the pictures and text that the user will see. The JSP is the code that provides capability to the developer to create the html pages. JSP facilitates a number of things behind the scenes to get the information to the user. For instance regular Java code can be called from the JSP that will retrieve and send data to a Microsoft Access database. It allows the developer to do calculations and execute complex logical statements to decide what the html page will display.

For the AIM-C GUI, java code is used in conjunction with SQL (Standard Query Language) to connect to the MS Access database using JDBC (Java Database Connectivity). There are a number of routines that are used to perform the tasks expected in the GUI. For instance, SQL commands retrieve all information from the database, update information in the database, grab any columns or rows, and create tables in the database. These are used to connect the GUI information with the database.

Other software involved is the Microsoft Access database. The current version is Windows 2000 compatible. Initially the administrator must connect the database using the Administrative Tools: Data Sources: ODBC connections. This is done only once by the administrator for each database used.

In order to make a computer act as a web server, the free software package called Apache Tomcat 4.0 is used to simulate a server situation. This allows the JSP pages to "compile" each time the page is hit. This means each page will update and perform the tasks in the code for every action the user performs. The Apache software must be started in order for the pages to display properly. This involves starting a command prompt window and starting up the Tomcat application, which creates the Catalina window application prior to the execution of the GUI. Generally the window is able to stay open for days without problems, thus it does not need to be restarted each time the GUI is executed, but can be left running in the background. If the Catalina window is closed, the computer will no longer act as a server and users will be unable to connect.

In order to run the Java code, the machine will need to have JAVA SDK 1.3 installed. After this is installed, system variables will need to be defined appropriately. These are JAVA_HOME, CATALINA_HOME, and CLASSPATH.

The java codes used in this application must be placed in packages and JAR (Java TM Archive) files for use. The JAR files must be placed inside a directory where Tomcat can use it. In the AIM-C case, this is in the Web-INF folder.

Often during the development process the JSP and html pages would not update when changed. One reason for this was that the Tomcat work directory did not compile new (or changed) pages on the fly like it was intended to do. Often the programmers needed to delete the work directory where the compiled files were stored to get a clean start on the GUI pages.

Tomcat also has a problem serving pages if the directory of the pages is different than its own. For instance, if Tomcat was installed on the C: drive, the html and jsp codes should reside there, too. It is recommended that all AIM-C GUI codes reside on the C: drive.

Another minor step is to make sure that Internet Explorer will check for new versions of pages. This is done by launching I.E., going to the Tools menu, opening the Internet

Options, and on the General tab, selecting the Settings button. This will bring up a screen where the default check should be set to every visit to every page. This will prevent old cached pages from being displayed if a new version exists.

Separate Java code is used to validate the user, password, and groups at the login screen. This is done to prevent groups from getting information they should not have. Once the username is validated against the password, the group is checked to see what projects are available to that group. Members of the team have provided a project manager, which is responsible for things like starting new projects, copying, deleting, and listing current projects.

To run the system, a laptop can be plugged into the Boeing dataline at any Boeing site. It will connect to a personal computer in St. Louis, which acts like a server. All of the pages are sent to the laptop through the I.E. browser. When the RDCS template run is initiated, the St. Louis server connects with the UNIX or Linux machines at Canoga Park, CA. The output is collected and sent to St. Louis to be displayed in the laptop or saved in the database. This provides a clear demonstration that the GUI will work no matter where the user is located. A simple sketch is shown in Figure E - 1 to clarify the connections, where the laptop is located in Seattle. A down side to this system is that currently; a user must be logged onto the Boeing network to avoid any firewall issues.

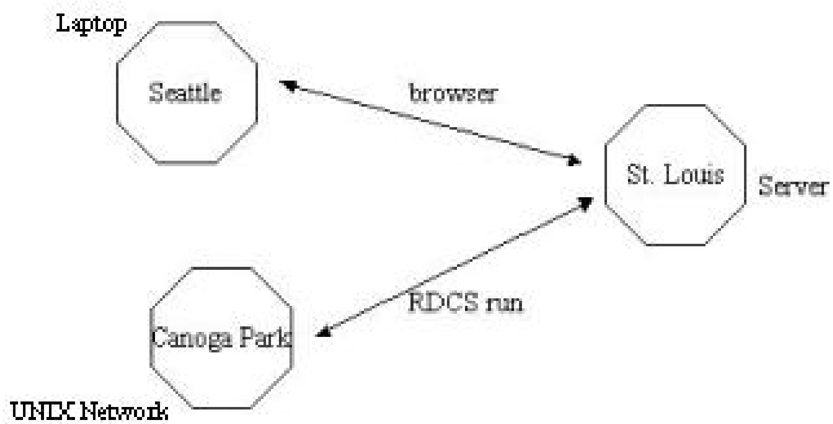



Figure E - 1. Map of Network Calls to Run Templates

If the GUI system is installed on a non-Boeing laptop, the functionality may not act the same, especially when running templates or accessing Boeing internal links. These will have to be set up on the non-Boeing system in the same fashion as the Boeing system. Therefore, the network map above would be altered for each separate system.

## 1.2 Pedigree

The pedigree of the software, the data, and all components relating to the AIM-C system is captured in a number of different ways.

The material data in the system has been marked with its own pedigree. Every test that takes place should have a pedigree that states what was done, how it was done, the date it was performed, and other significant data that the user should know. There is a place for this information for every material property that is placed in the readiness level charts. There are notes, pedigrees, and comments textboxes for every readiness level available. Between these three boxes, the test should be described or a Test Request Number should be mentioned. Many of the properties will have other associated data with them, such as which test was performed to get that specific information.

The pedigree of the executable codes is listed on the modules download page. All of the codes are downloadable from this page. After each hyperlink to the code, there is a date and a version number to keep track of the progression of each code. The user will have to install them on their own personal computer to get them to work. Some of these may need licenses to run. All of the codes are also in WINCVS on the correct system they were created on.

The codes and data have also been through a configuration control process where it has been placed in a file revision control area. Old versions of these codes can be recalled at any time.

The AIM-C interface software has been kept in a file revision storage area. The program that manages this is called WINCVS (Figure E - 2). It is located on the Boeing Canoga Park, CA machines. WINCVS keeps track of all the changes that occur on each of the files. If a file has been changed or modified, the file will show up as a red icon and will need to be committed into the repository. If a file has a question mark as an icon, the file is not captured in the system and changes will not be tracked. If a file icon shows up as a text box, the file is current. All of the folders that are tracked in WINCVS are designated by a check mark on the box. There are features about this program, where it will display the changes made from version to version and list the revision number and modified date for each file. The common user does not use this program.

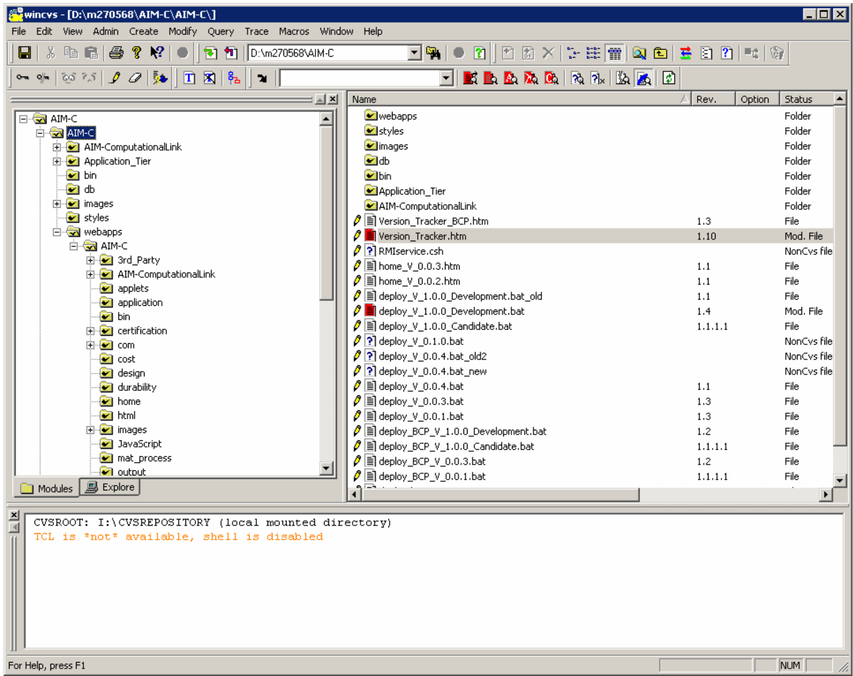


**Figure E - 2. WINCVS Version Control Software**

All of the executable codes that are run in the templates are also revision controlled. Each time the codes were updated, they were given a new revision number and controlled by the Seattle WINCVS server. So, the pedigree of the templates is controlled as well.

## 2.0 User Walk-Through and How-To Pages

### 2.1 Version Tracker

The AIM-C Version Tracker is used as a release bed for each new version of the software. The initial version of the software was called alpha minus and was updated daily. Unfortunately, the user had to be aware that at any time the system could be down. The Version Tracker was implemented in September 2002 to create a stable version of the software to use at any given time. The first version was V_0.0.1, which has progressed all the way to the Alpha system. Along with the current version, there has always been a development version of the software. This is to give access to the all the developers so they can update and enhance the software while testing it in the environment it was intended to be used.

After a version of the software has become obsolete, the link on the Version Tracker page is removed. This forces the users to use the latest and greatest information and GUI. This can be seen in Figure E - 3.

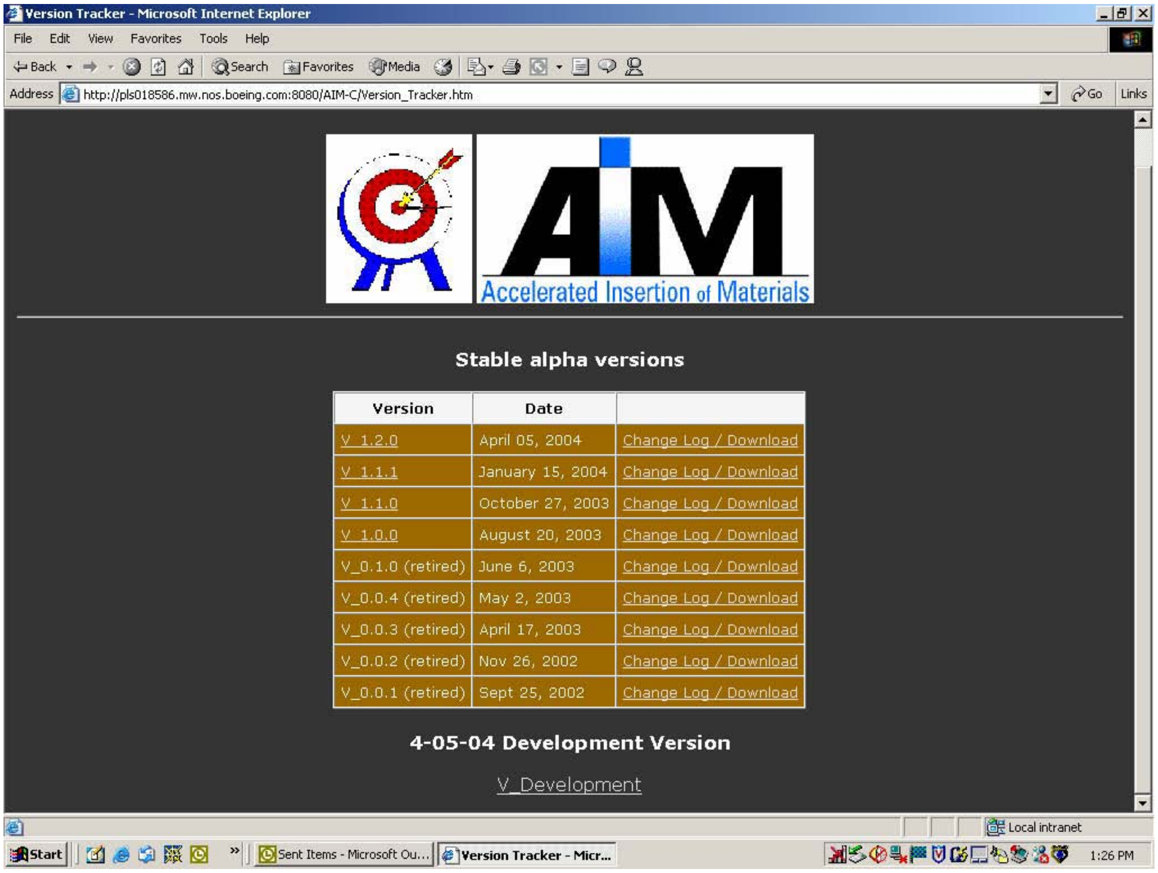



**Figure E - 3.  Version Tracker Page**

On the Version Tracker Page, there is also a downloadable page called "Change Log/ Download", which contains descriptions of the modifications for that version, dates of past releases, and a list of downloadable resources that the user may need in order to run the AIM-C system.  Some of these resources include Java Development Kit, Tomcat Engine, Java 3-D, COS (Server Utilities), Java Expression Parsing, Python, and a Boeing Web Based Engineering Environment.  This can be seen in Figure E - 4.

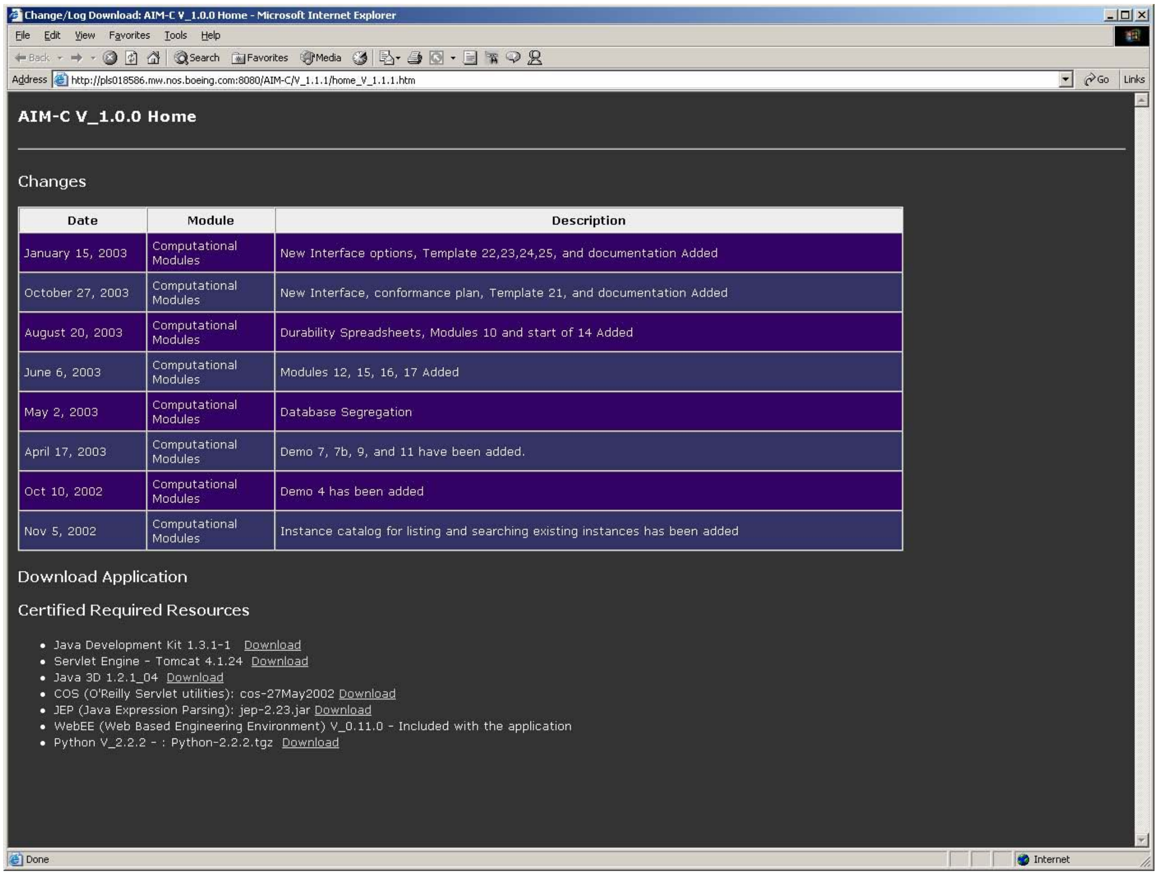



**Figure E - 4. Download and Changes Page**

To start using the AIM-C GUI, click on the Version Tracker page the version number. Generally the most recent version number is suggested, which is the one on the top of the list. After the button is clicked the Legal Rights page will show up.

## 2.2 Rights/licensing

AIM-C Software and System was developed under contract. The following information pertains to the rights and licensing of the AIM-C system.

1) Use, duplication, or disclosure is subject to the restrictions as stated in Agreement No. N00421-00-3-0098 between the U.S. Government and BOEING. RESTRICTION OF DISCLOSURE OF USE OF DATA.
Distribution authorized to U.S. Government agencies only to protect information not owned by the U.S. Government and protected by a contractor's "limited rights" statement, or received with the understanding that it not be routinely transmitted outside the U.S. Government. Other requests for this document shall be referred to NAVAIR Technical Information Officer.

2) Certain of the included/enclosed technical data is provided in support of use of the software/system developed under Agreement No. N00421-00-3-0098. It is to be used only in support of the authorized Government programs. As such, this data may not be

shared with any non-U.S. party who has not previously been approved in writing by the U.S. Department of State. This definition includes other entities of the foreign parties to this TAA not located in their respective countries.

3) a. Warning: This software/system/data contains or may contain technical data whose export is restricted by the Arms Export Control Act (Title 22, U.S.C. Section 2751 et. seq.) or the Export Administration Act (50 U.S.C. App. 2401). Violation of these export laws is subject to severe criminal penalties.

b. 22 CFR 125.4(b)(2)- data does not exceed the scope of the agreement or limitations/provisos imposed thereto by the Department of State. (Reference 22 CFR125.6(a) and 124.3(a)).

4) Certain portions of the software used in this system are provided by contractors to the U.S. Government and such software is or may be copyrighted by such contractor(s) and other restricted/limited rights apply or may apply thereto and duplication and other usage is not permitted.

5) Boeing provides this software and data "as is" and makes no warranty, express or implied, as to the accuracy, capability, efficiency, or functioning of the product.
In no event will Boeing be liable for any general, consequential, indirect, incidental, exemplary or special damages, even if Boeing has been advised of the possibility of such damages.

After the user has read this page, in order for the user to proceed, they must pick the “Accept Terms” button. If they accept, this will lead them to the login screen. If they do not accept, it will push them back to the Version Tracker page. A sample of what this page looks like is shown in Figure E - 5.

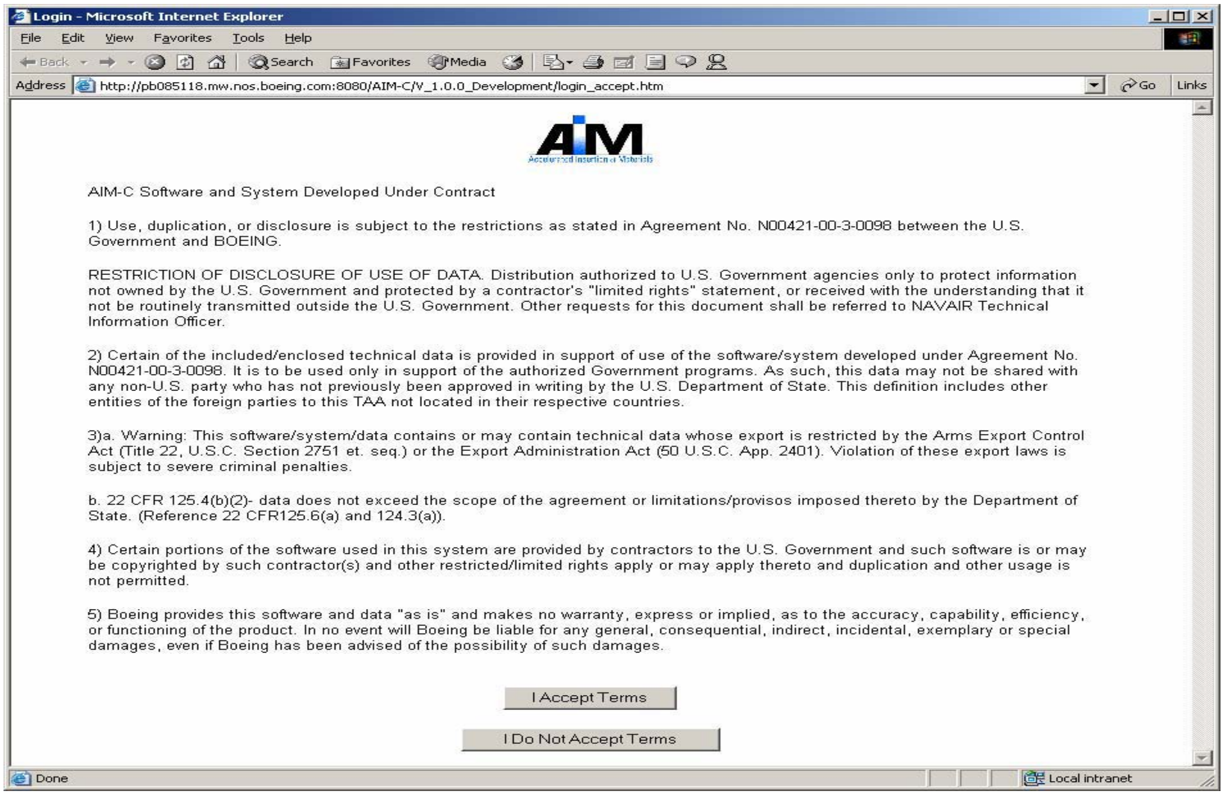



**Figure E - 5. Rights and Legal Page**

## 2.3 Login

Figure E - 6 shows the initial login screen that the user sees when he or she accesses the website. The username and password should be given along with the group to which the user belongs. All three of these are validated using Java code supported by a database. The group is the key element that allows users to view and edit projects only within their group. This will prevent different people from getting data that they should not have. A system administrator will assign a new user the username, password, and group upon request. At that time a new entry is placed in the user database for validation.

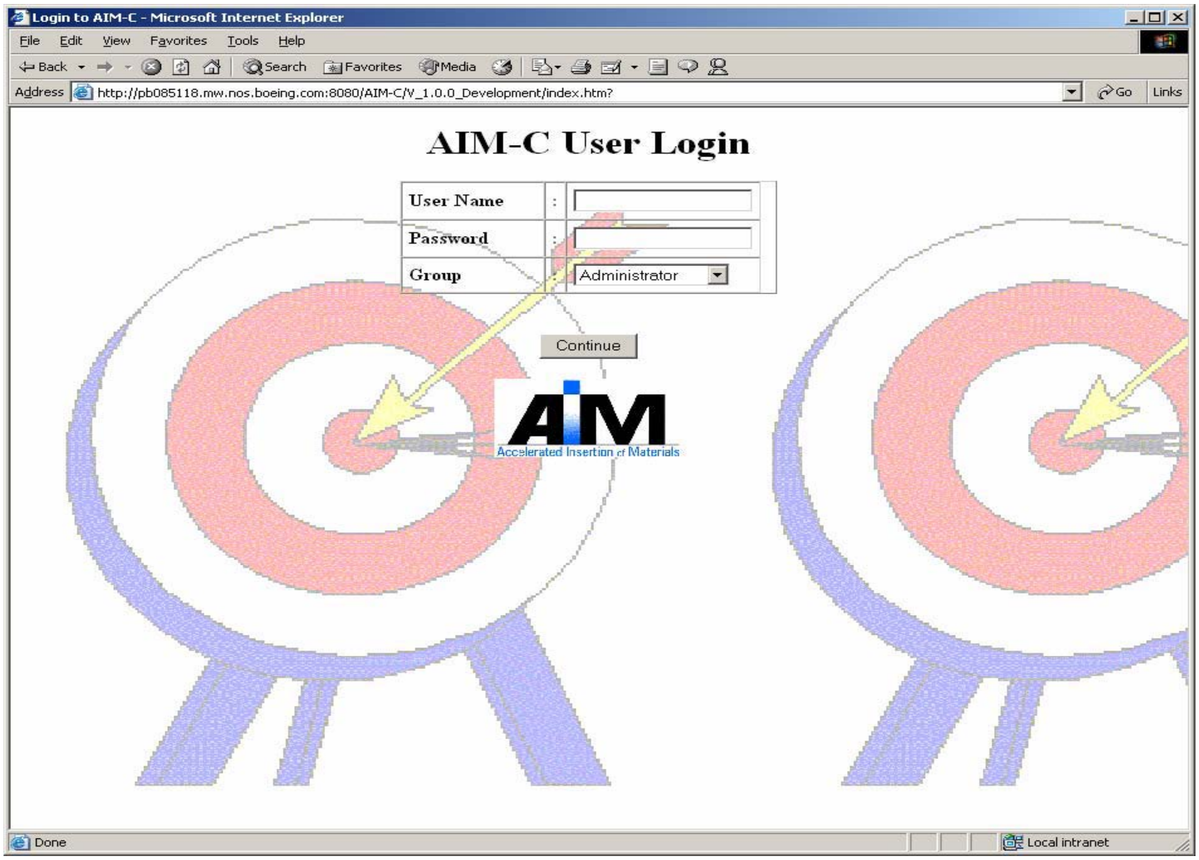



**Figure E - 6. Login Screen**

The only one who can change and add usernames, groups, and passwords is the system administrator. They will have to manually change this information in the database each time a new request for a user is made. Once the initial request has been processed, the user can access the system indefinitely.

For demonstration purposes, the following can be used to get into the system.
Username: a
Password: a
Group: Demo

After these have been typed in, the user must push the “Continue” button. A validated username and password will lead the user to the project manager.

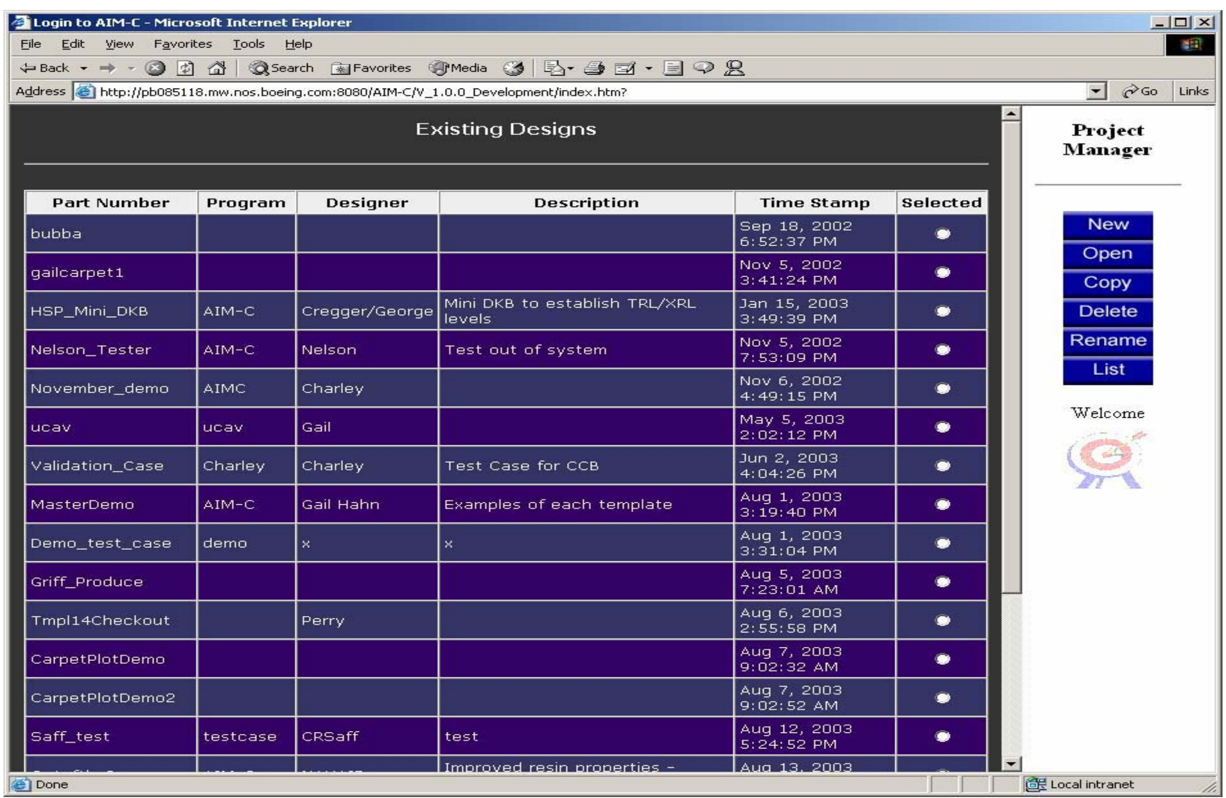
## 2.4 Project Manager

The project manager was created to give each user group a set of projects. These projects can be created or altered by only the members of that group. When a project is created, the Part Number, Program, Designer, Description, and Time Stamp are recorded. They are then used to differentiate projects. Within the project manager, the user can specify if they want to start a new project, open an existing project, copy a project to another name, delete the project, rename the project, or list all available projects in the user’s group.

It is best to choose a project name or Part Number that is very descriptive. The name cannot contain spaces or special characters. It is best to use only letters, numbers, and underscores combinations to signify project names. The Program, Designer, and Description can be used to fill in more detailed information. When building a new database for a project, it may take ten to fifteen seconds for the load to complete. Once all the data is satisfied, the process will bring the user directly to the AIM-C home page.

While these tasks are transparent to the user, a lot of work is done to the database each time one of these buttons is implemented. Every time a button is pushed, many tables in the database are touched. For instance, when a new project is created, rows in the tables in the database are created using defaults. All of these rows contain data from the user with the project name as its search criteria. Likewise, when a project is deleted, all the rows in all the tables that can be altered by the user are erased. This can cause a small wait of ten to fifteen seconds before the browser returns to a working state. In most cases, the user will select and work on the same project until that material system analysis is done. To select a project, the user must pick the radio button on the right side of the project manager in the “Selected” column and hit the ”Open” button on the right side of the menu bar. This can be seen in Figure E - 7.

The first thing that the user must do in the insertion process is to set up the DKB (design knowledge database). This can be done on the Application and Certification screens that are pull-downs from the AIM-C home page.




| Part Number | Program | Designer | Description | Time Stamp | Selected |
|---|---|---|---|---|---|
| bubba | | | | Sep 18, 2002 6:52:37 PM | |
| gailcarpet1 | | | | Nov 5, 2002 3:41:24 PM | |
| HSP_Mini_DKB | AIM-C | Cregger/George | Mini DKB to establish TRL/XRL levels | Jan 15, 2003 3:49:39 PM | |
| Nelson_Tester | AIM-C | Nelson | Test out of system | Nov 5, 2002 7:53:09 PM | |
| November_demo | AIMC | Charley | | Nov 6, 2002 4:49:15 PM | |
| ucav | ucav | Gail | | May 5, 2003 2:02:12 PM | |
| Validation_Case | Charley | Charley | Test Case for CCB | Jun 2, 2003 4:04:26 PM | |
| MasterDemo | AIM-C | Gail Hahn | Examples of each template | Aug 1, 2003 3:19:40 PM | |
| Demo_test_case | demo | x | x | Aug 1, 2003 3:31:04 PM | |
| Griff_Produce | | | | Aug 5, 2003 7:23:01 AM | |
| Tmpl14Checkout | | Perry | | Aug 6, 2003 2:55:58 PM | |
| CarpetPlotDemo | | | | Aug 7, 2003 9:02:32 AM | |
| CarpetPlotDemo2 | | | | Aug 7, 2003 9:02:52 AM | |
| Saff_test | testcase | CRSaff | test | Aug 12, 2003 5:24:52 PM | |
| | | | Improved resin properties - | Aug 13, 2003 | |

**Figure E - 7. Project Manager Screen**

The first time a user enters the Project Manager page, they should hit the "New" project button on the right side of the screen. After a brief ten-second wait, the software will open up the main page of the AIM-C GUI, and all the inputs will be set to default values.

## 2.5 Main Menu

The main menu is the place where the user should be able to get to any location within three clicks. This was designed to create a user-friendly environment where navigation would be intuitive. The user would start on the upper left menu and work their way down the first set of submenus. After they complete the information required for these picks, they can proceed to the right on the top of the menus and travel down those. The menu system across the top of the AIM-C GUI is the best way to navigate through the system. The drop-down menus serve as expandable areas where more information is located and can be reached. The first item on the menu is the AIM-C logo, which will bring the user back to the home page. As the user runs the cursor across the top of the menu structure, the categories will highlight and sub-categories will appear underneath.

The topics for the menus include Process Guidelines, Test Databases, Lessons Learned, Analysis templates, and About AIM-C. An example of this is seen in Figure E - 8.

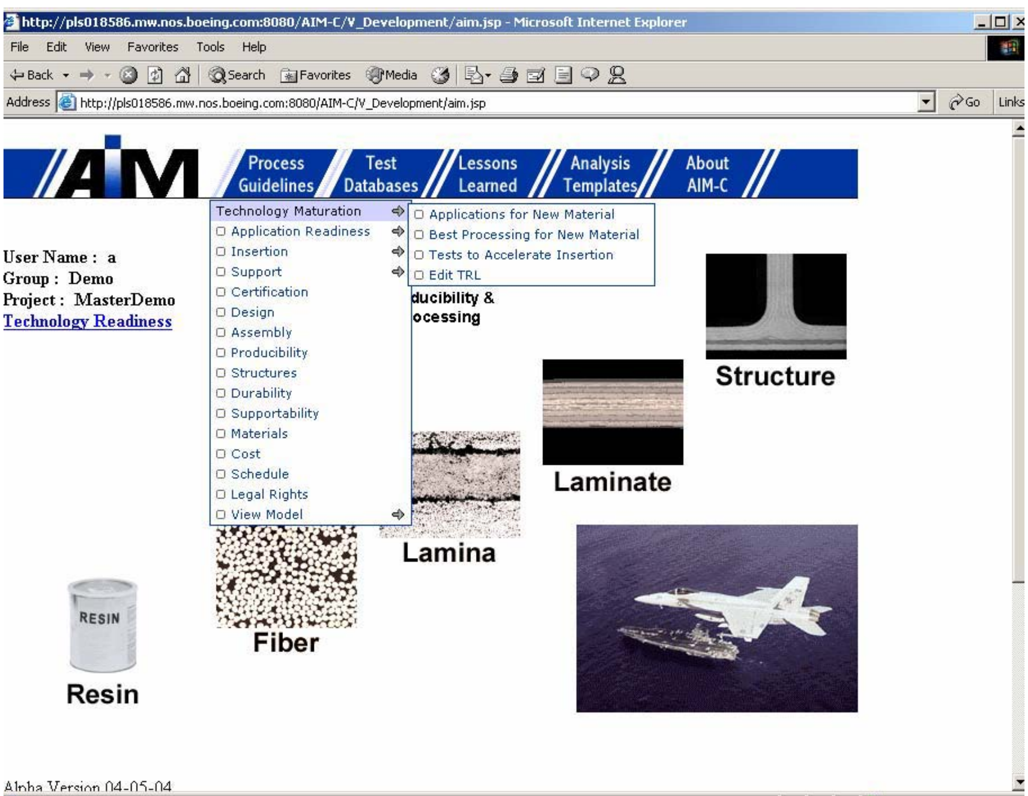



**Figure E - 8. Drop Down Menu View**

## 2.6 Home

The home screen of the AIM-C GUI is designed to help the user find their way through the system with efficiency. An example of this page is shown in Figure E - 9. The main menu is across the top of the screen. The home page also has a series of pictures representing different readiness levels for the different components of the material insertion process. If the user clicks on a picture, the software will load the readiness level for that component. These include resin, fiber, lamina, laminate, structure, durability, and producibility. Also on this page is the User Name, Group, and Project. This is to clarify which project the user is in. There is also a link to the Technology Readiness Level on the main screen. The specifics of these are describer later.

Underneath the pictures are a series of links that may help the user find information on other websites. Some of these are internal and some are external to Boeing. The links include Methodology for AIM-C documents, Test Methods for New Materials, New Process, and Second Source Data, Boeing PEPR (Production Engineering Publication Records) hotlink, MIL Handbook 5, MIL Handbook 17, ASTM documentation, EMDS - Engineering Materials Data System, Static Material Allowables hotlink which includes Boeing Design Manuals, PSDS, Engineering Sciences Data Unit (ESDU), Boeing Material and Process Specifications (BMS, BAC), Douglas Products Division Specifications (DMS, DPS), Douglas Products Division specs on Process, Material and Quality Standards site, ISDS - St. Louis Specifications (MMS, MPS), ASTM Standards, and Boeing Documents, DOD, ASTM, and SACMA Specifications.

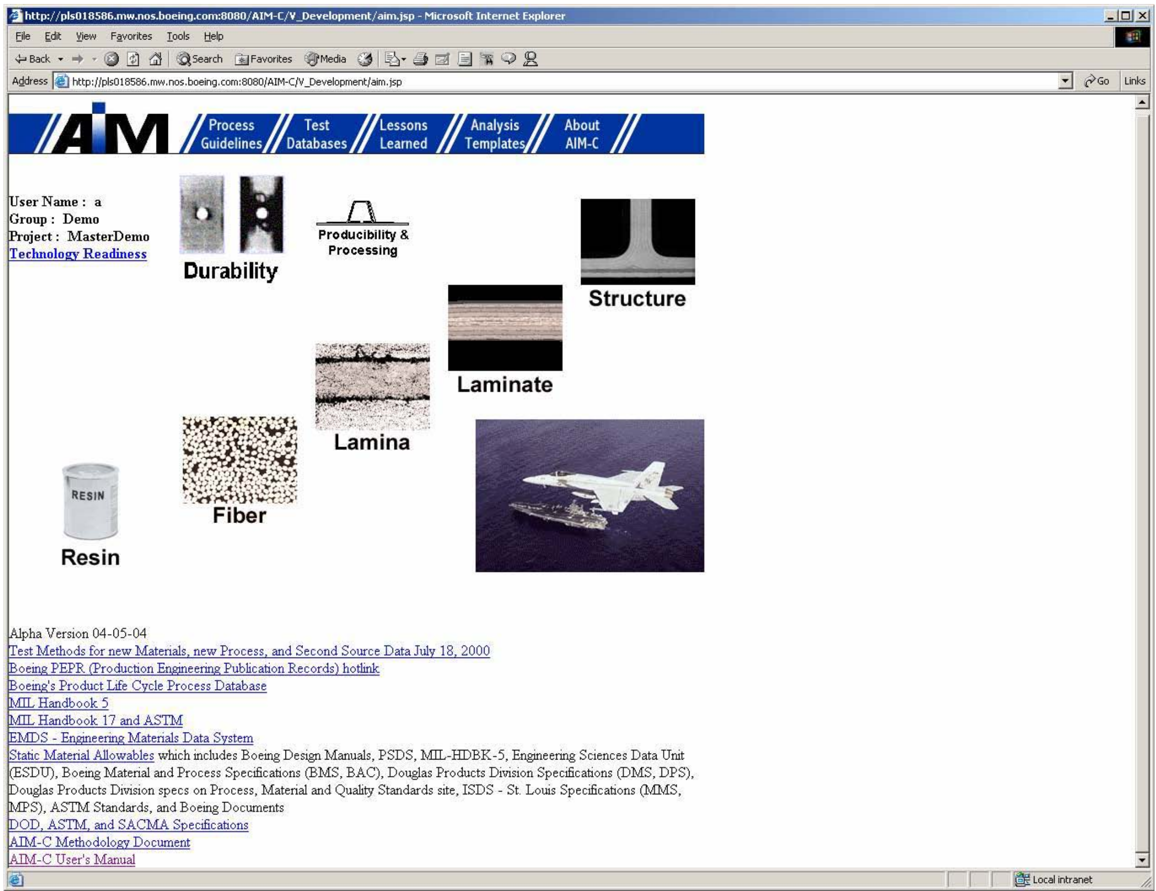



**Figure E - 9. Main Page of AIM-C Software**

## 2.7 Application

The first Application screen (Figure E - 10) asks the basic questions, such as what project, program, vehicle, component, and sub-component the user is working on. It also asks what processes are going to be used and what material system is being considered. This is the first piece in going through the methodology process flow. The process leads the user through questions at the TRL (Technology Readiness Level) and the XRL (X-underlying technology Readiness Level). At this level the requirements and major decisions are discussed. This leads down the path to properties and characteristics, which describe more information on each level. Under this level are worksheets, templates, details, and lessons learned. This methodology is used throughout each TRL level of the GUI.

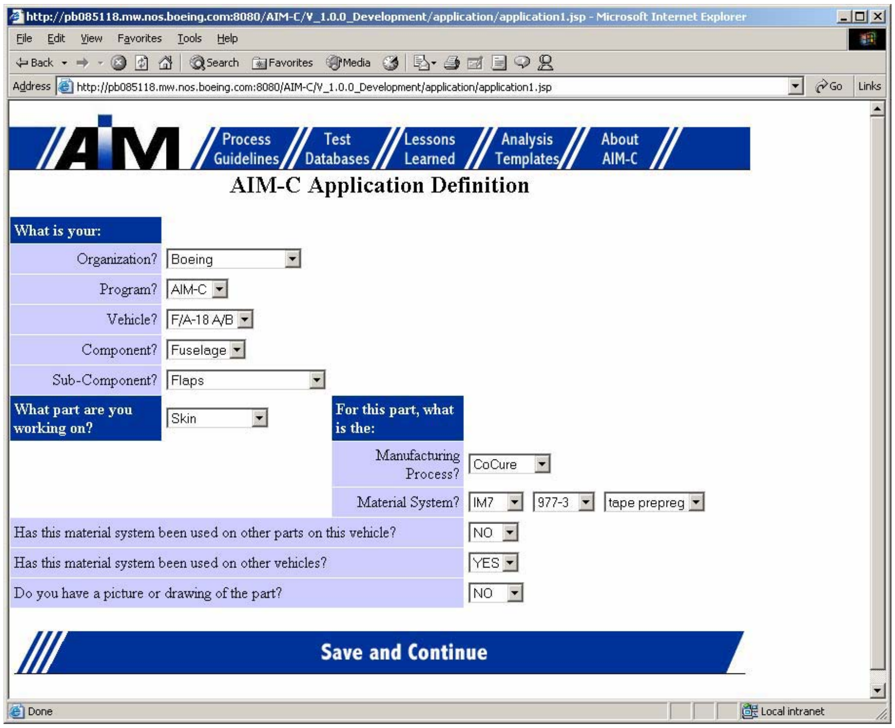



**Figure E - 10. Application Definition**

The second screen in the Application menu (Figure E - 11) asks the user what phase of production the product is in. This is represented by a series of radio buttons, which the user can change while the product is maturing. The last screen of the application section asks if there is documentation available for additional information. Eventually, the GUI will save this documentation in a version controlled directory structure.

## AIM-C Application Maturity

| | | | | | |
|---|---|---|---|---|---|
| Do you have estimated properties? | ◉ YES | ○ InWork | ○ Problem | ○ NO | ○ N/A |
| Do you have mechanical properties? | ◉ YES | ○ InWork | ○ Problem | ○ NO | ○ N/A |
| Are you documenting manufactuing processes? | ◉ YES | ○ InWork | ○ Problem | ○ NO | ○ N/A |
| Are you developing allowables? | ◉ YES | ○ InWork | ○ Problem | ○ NO | ○ N/A |
| Are you testing subcomponent assemblies? | ◉ YES | ○ InWork | ○ Problem | ○ NO | ○ N/A |
| Are you testing full scale components? | ○ YES | ○ InWork | ○ Problem | ◉ NO | ○ N/A |
| Is this product in full scale ground test? | ○ YES | ○ InWork | ○ Problem | ◉ NO | ○ N/A |
| Is this product in flight test? | ○ YES | ○ InWork | ○ Problem | ◉ NO | ○ N/A |
| Is this product in production? | ○ YES | ○ InWork | ○ Problem | ◉ NO | ○ N/A |
| Is this product out of production? | ○ YES | ○ InWork | ○ Problem | ◉ NO | ○ N/A |

**Figure E - 11. Application Maturity Chart**

## 2.8 Certification

The Certification menu is the next step in setting up the DKB. This asks the user what is documented, what is in test, and what is approved in the set up portion of the GUI as shown in Figure E - 12.

In the certification section of the GUI, there are numerous charts that reflect the inputs required for the Joint Services Specification. This leads to pages that describe the values and requirements as shown in Figure E - 13.

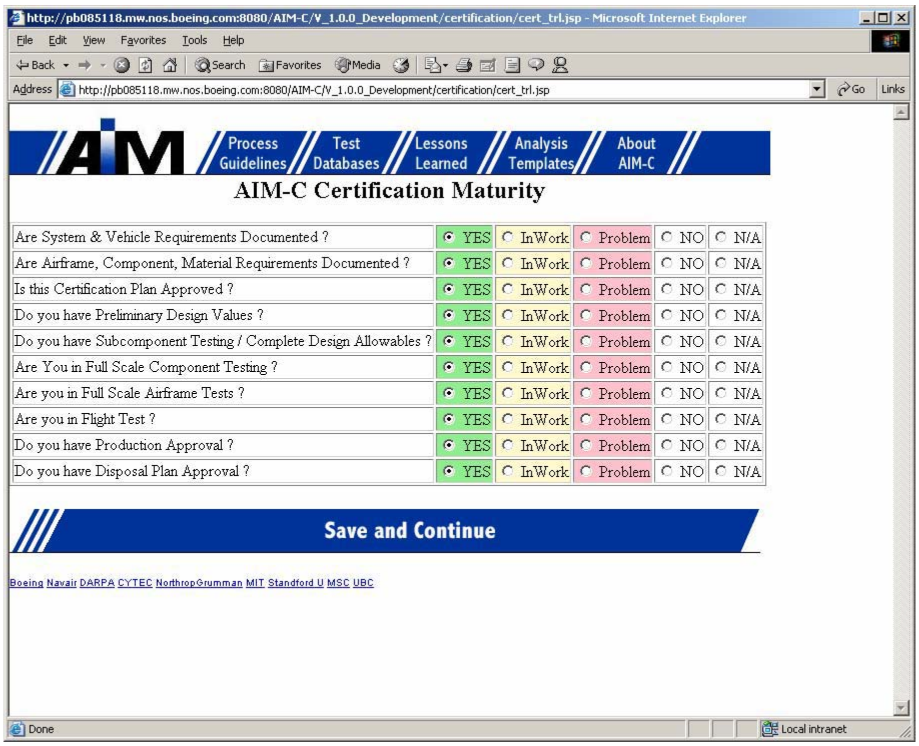



**Figure E - 12. Certification Maturity Chart**

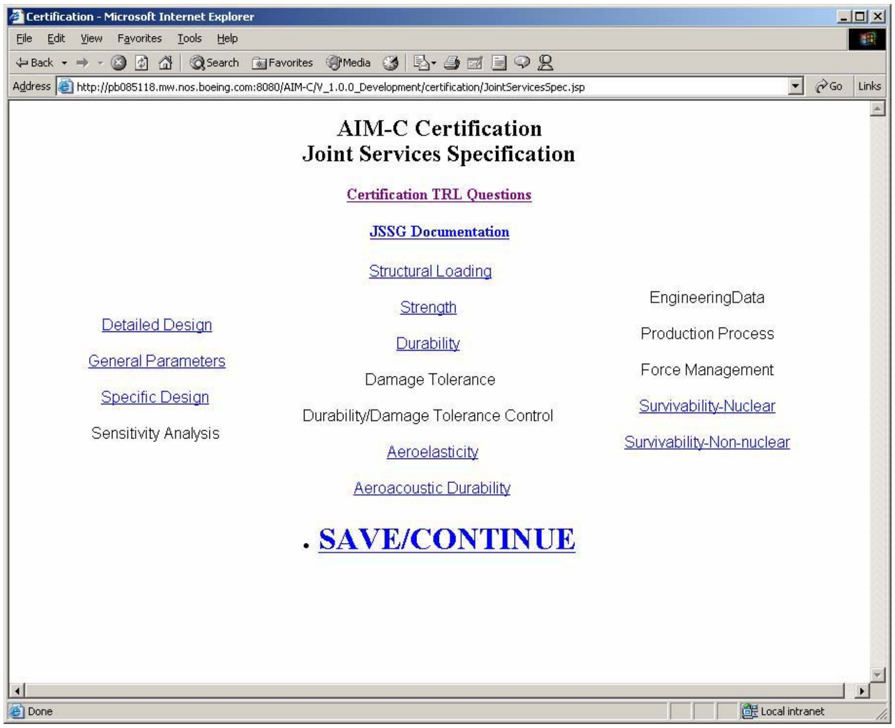



**Figure E - 13. Certification - Joint Services Specifications**

Some of the pages include detailed design, general parameters, specific design, loading, strength, durability, aero-elasticity, aero-acoustic durability, and survivability. Each of these is a link to pages below it that clarify the inputs. The general parameters link has the most information, so its detailed menus are described below.

In the general parameters sections, there are a series of pages which include airframe configurations, limit, ultimate, and design load factors, lightning strike/electrostatic charge, equipment, deformations, foreign object damage, payloads, service life and usage, producibility, weight distributions, atmosphere, maintainability, weights, chemical, thermal, and climatic environments, supportability, center of gravity, power/thrust loads, lateral center of gravity position, flight control and stability augmentation devices, replaceability/interchageability, speed, material and process, cost effective design, altitudes, finishes, flight load factors, non-structural coatings, films, and layers, land based and ship based aircraft ground loading parameters, and system failures.

## 2.9 Durability

The Durability section of the software is quite detailed. There are a series of steps that should be followed which includes a checklist, a library, guidelines, and interpretation. A picture of the first Durability pages is shown in Figure E - 14. This page shows a series of links that will display the steps, as well as the durability methodology, and links to the durability readiness level sheets.

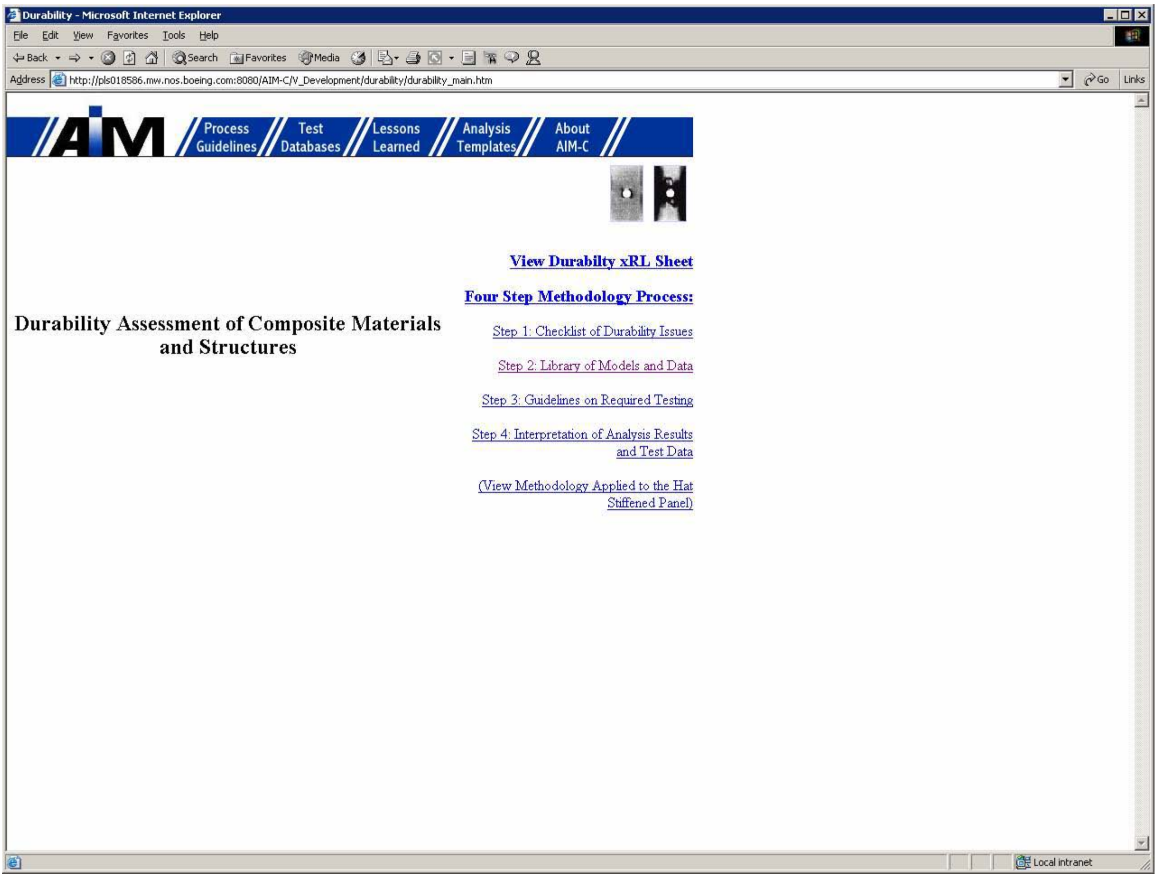



**Figure E - 14. Durability Pages**

The durability library has all the models and spreadsheet to download. Each of these has a description with the download to explain what that code includes. A sample picture of this is in Figure E - 15. On this page, many downloads are available such as Integrated SuperMicMac and DuraSoft Download, Thermal Degradation SpreadSheet, Degradation Theory Manual, Thermal Degradation Data Set, SuperMicMac SpreadSheets and Manuals (Stanford University), Delamination Tool Spreadsheet (MIT), Delamination Tool Manual, DURASOFT Download (MIT), DURASOFT Manual (MIT), and MicroCracking Data Set.

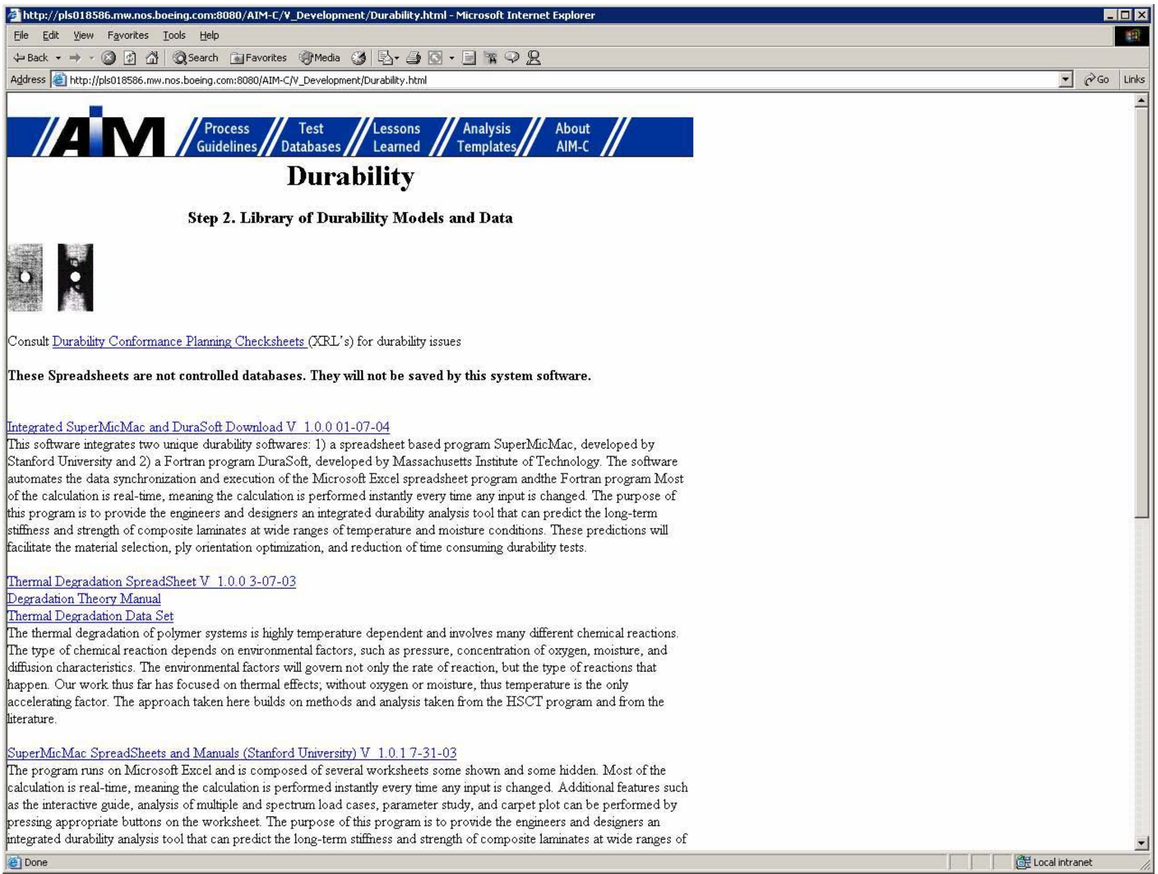



**Figure E - 15. Durability Library**

## 2.10 Design and Others

The Design maturity chart is very similar to the other maturity charts. It feeds the TRL chart. An example of this is Figure E - 16.

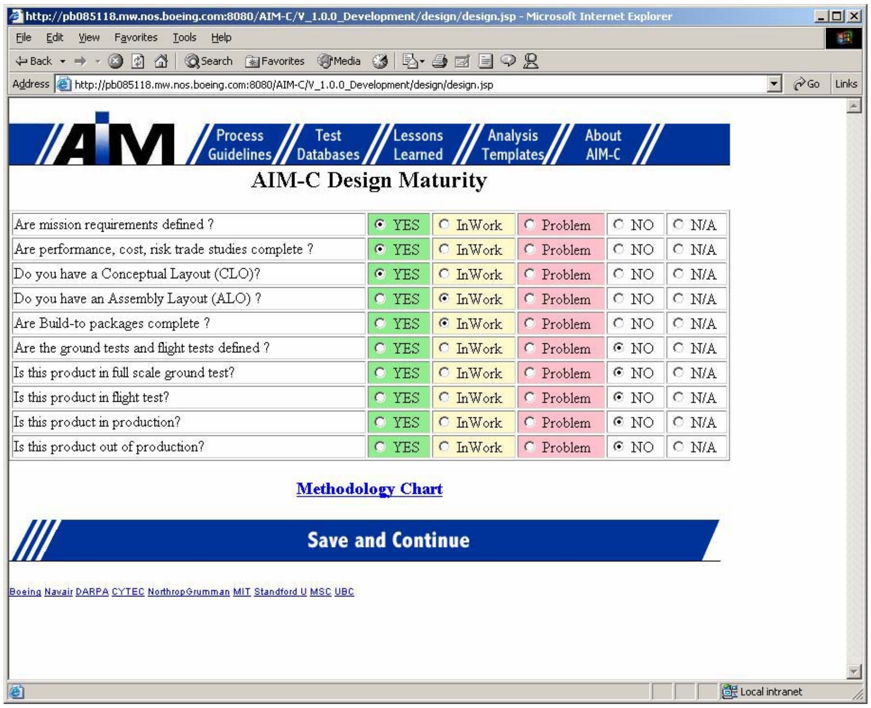



**Figure E - 16. Design Maturity Chart**

Maturity Questions exist for every topic in the TRL chart. The topics include Application, Certification, Design, Assembly, Structures, Fabrication, Cost, Supportability, and Intellectual Rights. These should all be answered to find out the location of the maturity level. The first few links under the TRL chart ask important questions for a starting point in the categories readiness level.

Each of these topics represents a line on the TRL chart and should be colored appropriately.

## 2.11 AIM-C Participants

All of the major participants have links to their websites on the participants page (Figure E - 17). This is a way for the team to find out more information about each other.

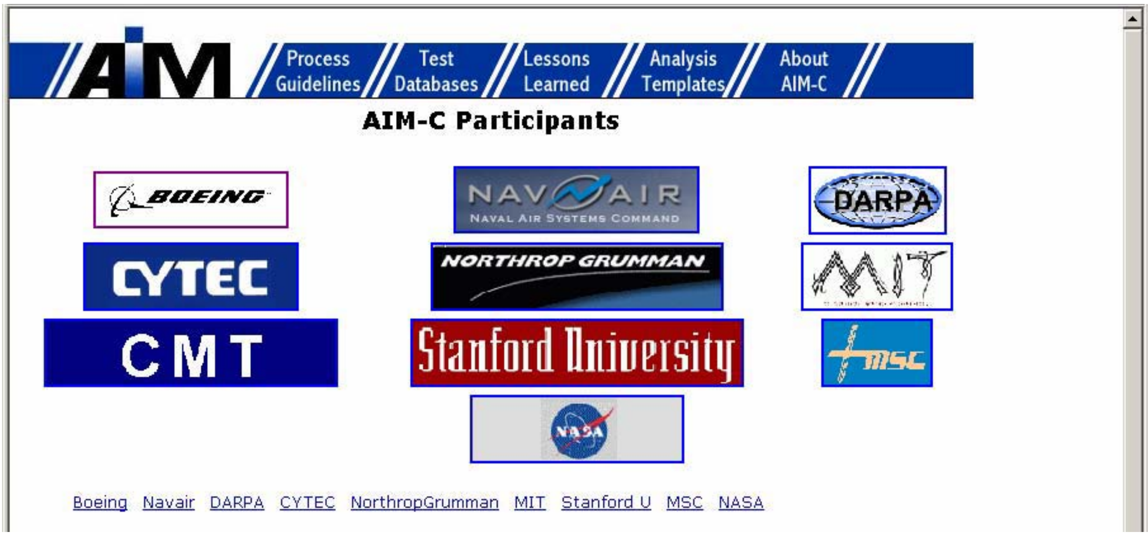
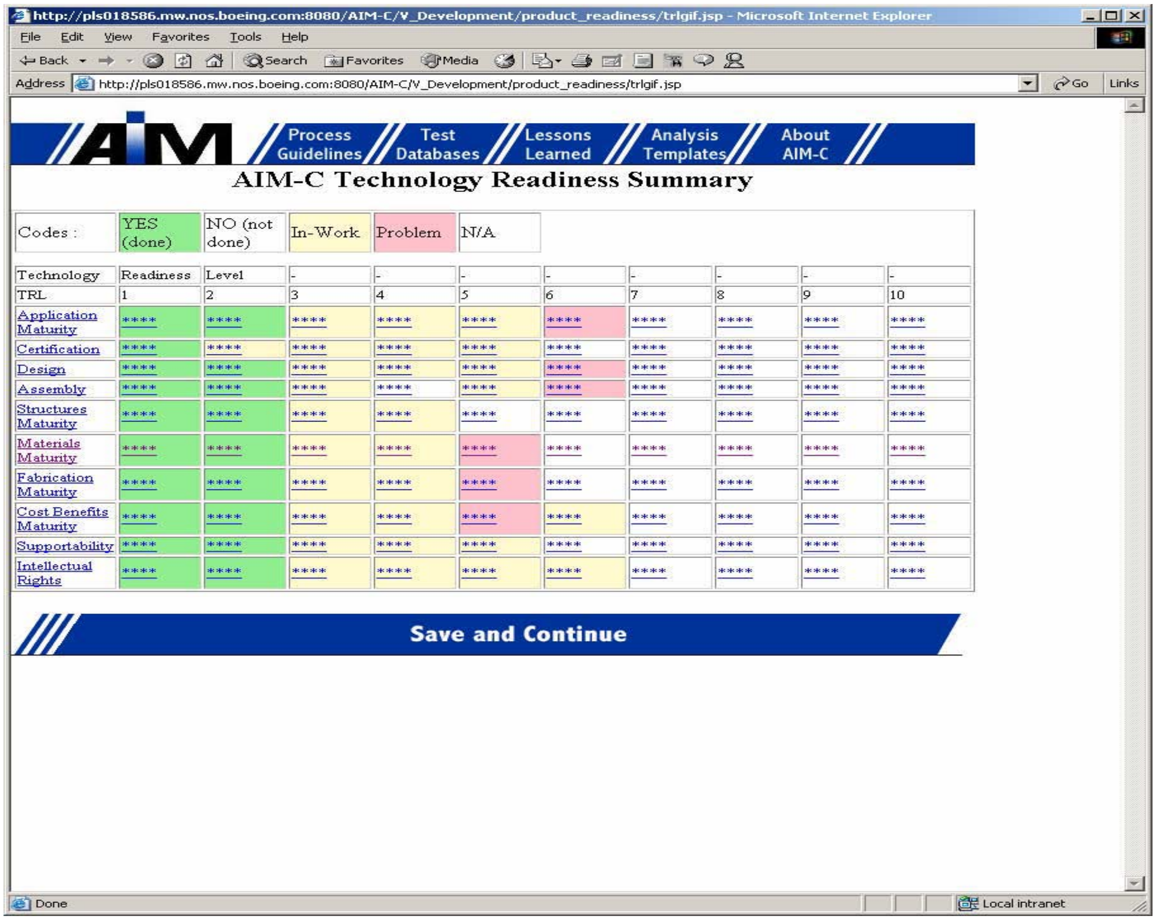



**Figure E - 17. Participants**

## 2.12 Readiness Levels through Worksheets

When starting in a new project, the default readiness level will default to one. As the user starts to fill out the data, the readiness level will increase according to the project and the required data needed to move on. There are ten different readiness levels that are tracked in the AIM-C system. They are Application, Certification, Design, Assembly, Structures, Materials, Fabrication, Cost, Support, and Intellectual Rights. Each of these categories are tracked and will color the readiness level chart with the correct information on if the process is complete, in-work, not done, not applicable, or if there is a problem in the process. They are designated by the color green if complete, red if there is a problem, and yellow if there it is in-work. White colors indicate it is not done or not applicable. The chart that shows all of this is called the Technology Readiness Level (TRL) Chart, which can be seen in Figure E - 18. It clearly shows where a major category is falling behind on its way through the maturity of the product. The color-coding on the TRL chart indicates which topics are falling behind as the insertion process progresses. Each of the "****" symbols in the colored boxes is a hyperlink to the data represented behind that box.




| Codes : | YES (done) | NO (not done) | In-Work | Problem | N/A |
|---|---|---|---|---|---|

| Technology | Readiness | Level | - | - | - | - | - | - | - | - |
|---|---|---|---|---|---|---|---|---|---|---|
| TRL | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Application Maturity | **** | **** | **** | **** | **** | **** | **** | **** | **** | **** |
| Certification | **** | **** | **** | **** | **** | **** | **** | **** | **** | **** |
| Design | **** | **** | **** | **** | **** | **** | **** | **** | **** | **** |
| Assembly | **** | **** | **** | **** | **** | **** | **** | **** | **** | **** |
| Structures Maturity | **** | **** | **** | **** | **** | **** | **** | **** | **** | **** |
| Materials Maturity | **** | **** | **** | **** | **** | **** | **** | **** | **** | **** |
| Fabrication Maturity | **** | **** | **** | **** | **** | **** | **** | **** | **** | **** |
| Cost Benefits Maturity | **** | **** | **** | **** | **** | **** | **** | **** | **** | **** |
| Supportability | **** | **** | **** | **** | **** | **** | **** | **** | **** | **** |
| Intellectual Rights | **** | **** | **** | **** | **** | **** | **** | **** | **** | **** |

**Figure E - 18. Technology Readiness Level Chart**

Some of the categories such as Materials can be tracked on a more detailed scale. Material is divided into four sub-categories called Resin and Adhesive, Fiber, and Prepreg. If there is a problem in any one of these subcategories, the Materials readiness level cannot increase unless the problem has been resolved. Some examples of these can be seen in Figure E - 19.

Each of the subcategories will bring the user to a page that contains test details, lists of properties, and their priority. These details can be further broken down into worksheet pages where the property is described and a pedigree is attached to it. Some of the information that is captured consists of approach used to gather data (test, analysis, combined approach, previous data, or heuristics), specifics about the data, assessment of the data, date this was gathered, design value, mean, units, standard deviation, norm-mean, uncertainty, minimum, maximum, notes, pedigree, comments, xRL rating for data, completeness, and if the data should be locked. All of this information is used to assess the level where the material system is. This information is collected for each property on each of the 5 readiness levels specified to complete the insertion process.

After a few of these readiness level charts are filled in, the user has the opportunity to choose which of the data is the best representation and place that data into the details page. This is the link on the far right side of the xRL sheet. This means that if one of the readiness levels was better than another, for instance, test is better that analysis, then the proper data from the test can be loaded into the details page.

Ideally, that property would be defined by the user and stored in the details page, so that the best data would be used from the details page independent of what level that property had data for.

## 2.13 Technology Readiness Level

The next step in the process is to start with the Technology Readiness Level. The user can get there by going to the Process Guidelines, Technology maturity, Edit TRL tab on the main menu or on the upper left of the home page. This will pop up the Technology Readiness Level chart. These are color coded so the user will have an idea what areas in the process need attention. The colors of this page are as follows. If everything is complete or in good status, the boxes will be green. If the box is currently in work, the box is yellow. If the box is red, a problem has been found and needs to be resolved before moving on to the next step. A white box indicates that the box still lies in the future or is not applicable. Initially, most of the boxes will default to white. Some logical rules have been applied to this page. For instance, if a box in the same column as a red box is green, the program will automatically change it a yellow box. If a green box lies down stream (to the right) of a red box, the green box will turn yellow. This is done so that the user knows he or she is no better than the red readiness level for any category. See Figure E - 18, for an example. The first box that has a problem must be resolved before the readiness level of this system can increase.

Maturity Questions exist for every topic in the TRL chart. The topics include Application, Certification, Design, Assembly, Structures, Fabrication, Cost, Supportability, and Intellectual Rights. These should all be answered to find out the location of the maturity level. The first few links under the TRL chart ask important questions for a starting point in the categories readiness level.

## 2.14 Readiness Levels Through Worksheets

The readiness level is calculated by how far along the material properties have been tested in the system. For instance a readiness level of zero would correspond with no tests or analysis performed to get good data for that property. If this test must be done and approved to move to a readiness level of 1, then that aspect must be worked to move the readiness level up.

For materials readiness, there are four sub-levels that feed the TRL chart. These levels are resin, fiber, prepreg, and adhesive. In the methodology process, these are the first charts showing XRL levels. If you click on one of these pages, the GUI will display a readiness level chart as illustrated in Figure E - 19 that gives the user the category for that item. There are a list of links on the materials page that lead the user to properties and characteristics.

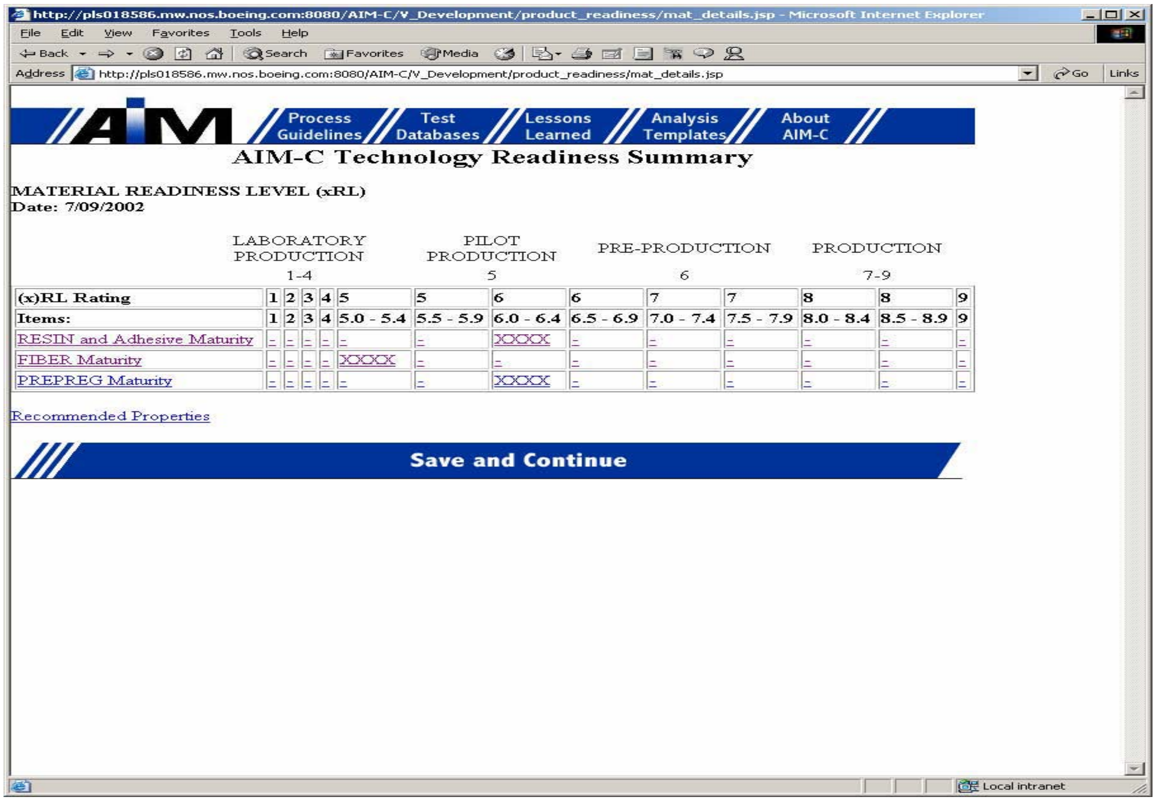


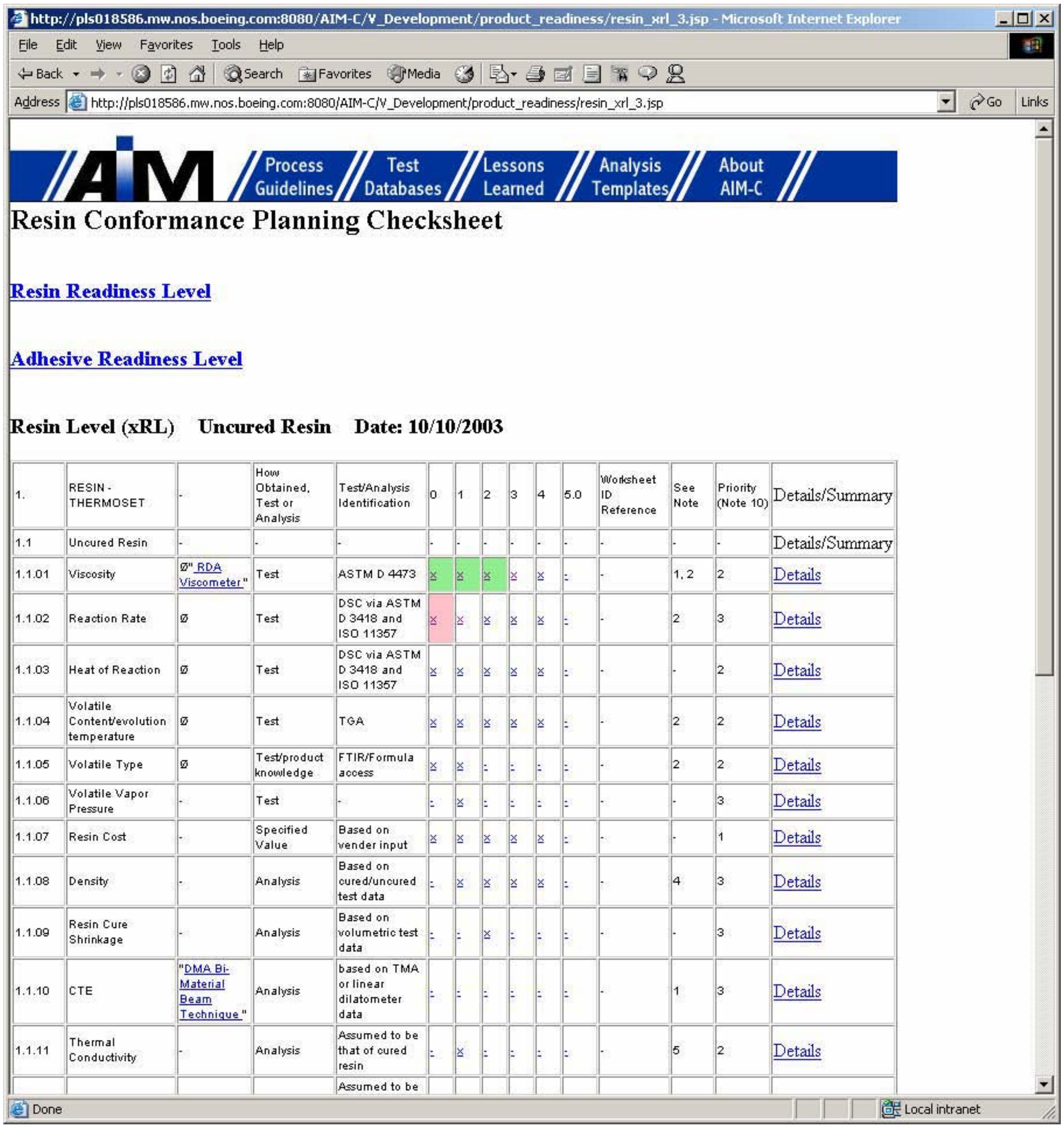

**Figure E - 19. Material Readiness Level Chart**

Each property is assigned a readiness level because some properties are important early in the insertion process and others are not. Many properties must be derived from multiple tests to get a good approximation of what that data should be. Some properties are time, temperature, or pressure dependant that requires curves to calculate. At this time, there is not a capability to incorporate these kinds of changing properties.

Overall, the readiness levels track how advanced a material is. This is assuming the user will start at a component level such as fiber and resin. They will then have to work up to the prepreg, lamina, laminate, and finally up to the structure level.

To start, the user can click on the resin can on the home page. This will lead them directly to the resin Conformance Planning Checksheet (Figure E - 20). At this time, the user should start at the first level of 0 and fill in all the properties they have. To do this, the user should simply click in the row they want to start and click on the appropriate readiness level number. This will lead them to a worksheet page (Figure E - 21 and Figure E - 22) to different approaches.

There are a total of ten approaches to use for each property. Filling in all the boxes will allow the user to capture as much data as they can for each property. When all the boxes are filled in on the worksheet page, the user can move back to the XRL sheet by pressing the Save/Continue button. If they wish in input all the detailed info, they will press the approach number and fill in the information. This process of inputting data should continue until all the known data is in the database system.  Continue through the resin, fiber, prepreg, lamina, laminate, and structures XRL sheets.




Resin Conformance Planning Checksheet

Resin Readiness Level

Adhesive Readiness Level

Resin Level (xRL) Uncured Resin Date: 10/10/2003

| 1. | RESIN - THERMOSET | - | How Obtained, Test or Analysis | Test/Analysis Identification | 0 | 1 | 2 | 3 | 4 | 5.0 | Worksheet ID Reference | See Note | Priority (Note 10) | Details/Summary |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.1 | Uncured Resin | - | - | - | - | - | - | - | - | - | - | - | - | Details/Summary |
| 1.1.01 | Viscosity | Ø" RDA Viscometer" | Test | ASTM D 4473 | x | x | x | x | x | - | - | 1, 2 | 2 | Details |
| 1.1.02 | Reaction Rate | Ø | Test | DSC via ASTM D 3418 and ISO 11357 | x | x | x | x | x | - | - | 2 | 3 | Details |
| 1.1.03 | Heat of Reaction | Ø | Test | DSC via ASTM D 3418 and ISO 11357 | x | x | x | x | x | - | - | - | 2 | Details |
| 1.1.04 | Volatile Content/evolution temperature | Ø | Test | TGA | x | x | x | x | x | - | - | 2 | 2 | Details |
| 1.1.05 | Volatile Type | Ø | Test/product knowledge | FTIR/Formula access | x | x | - | - | - | - | - | 2 | 2 | Details |
| 1.1.06 | Volatile Vapor Pressure | - | Test | - | - | x | - | - | - | - | - | - | 3 | Details |
| 1.1.07 | Resin Cost | - | Specified Value | Based on vender input | x | x | x | x | x | - | - | - | 1 | Details |
| 1.1.08 | Density | - | Analysis | Based on cured/uncured test data | - | x | x | x | x | - | - | 4 | 3 | Details |
| 1.1.09 | Resin Cure Shrinkage | - | Analysis | Based on volumetric test data | - | - | x | - | - | - | - | - | 3 | Details |
| 1.1.10 | CTE | "DMA Bi-Material Beam Technique" | Analysis | based on TMA or linear dilatometer data | - | - | - | - | - | - | - | 1 | 3 | Details |
| 1.1.11 | Thermal Conductivity | - | Analysis | Assumed to be that of cured resin | - | x | - | - | - | - | - | 5 | 2 | Details |
| | | | | Assumed to be | | | | | | | | | | |

**Figure E - 20.  Resin Technology Readiness Level Chart**

Each of the approaches will bring the user to a page that contains test details, lists of properties, and their priority.  These details can be further broken down into worksheet summary pages where the property is described and a pedigree is attached to it.  Some of the information that is captured consists of approach used to gather data (test, analysis, combined approach, previous data, or heuristics), specifics about the data, assessment of the data, date this was gathered, design value, mean, units, standard deviation, norm-mean, uncertainty, minimum, maximum, notes, pedigree, comments, xRL rating for data, completeness, and if the data should be locked. All of this information is used to assess the level where the material system is. This information is collected for each property on each of the 5 readiness levels specified to complete the insertion process.

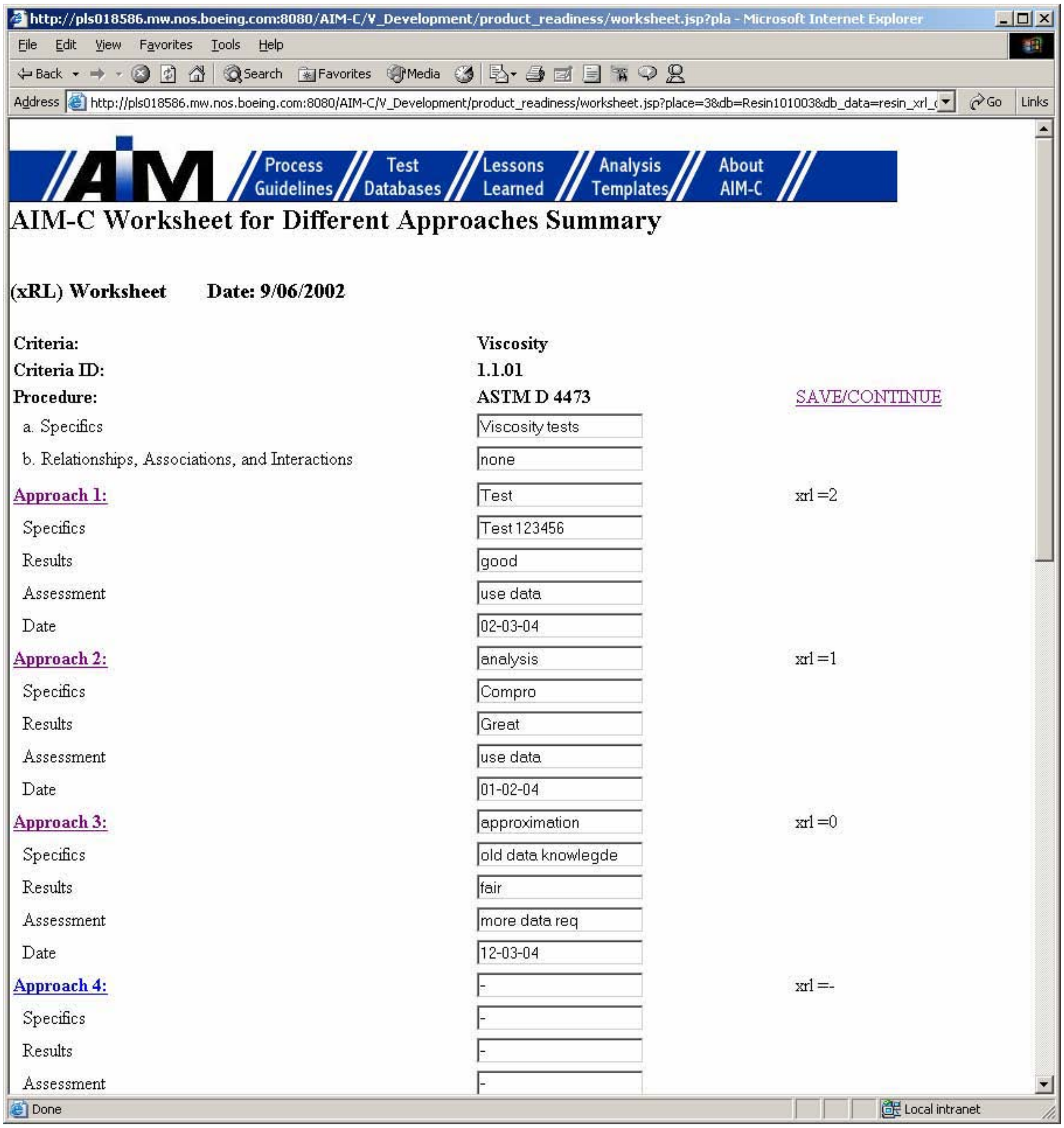



**Figure E - 21. Worksheet for Approaches**

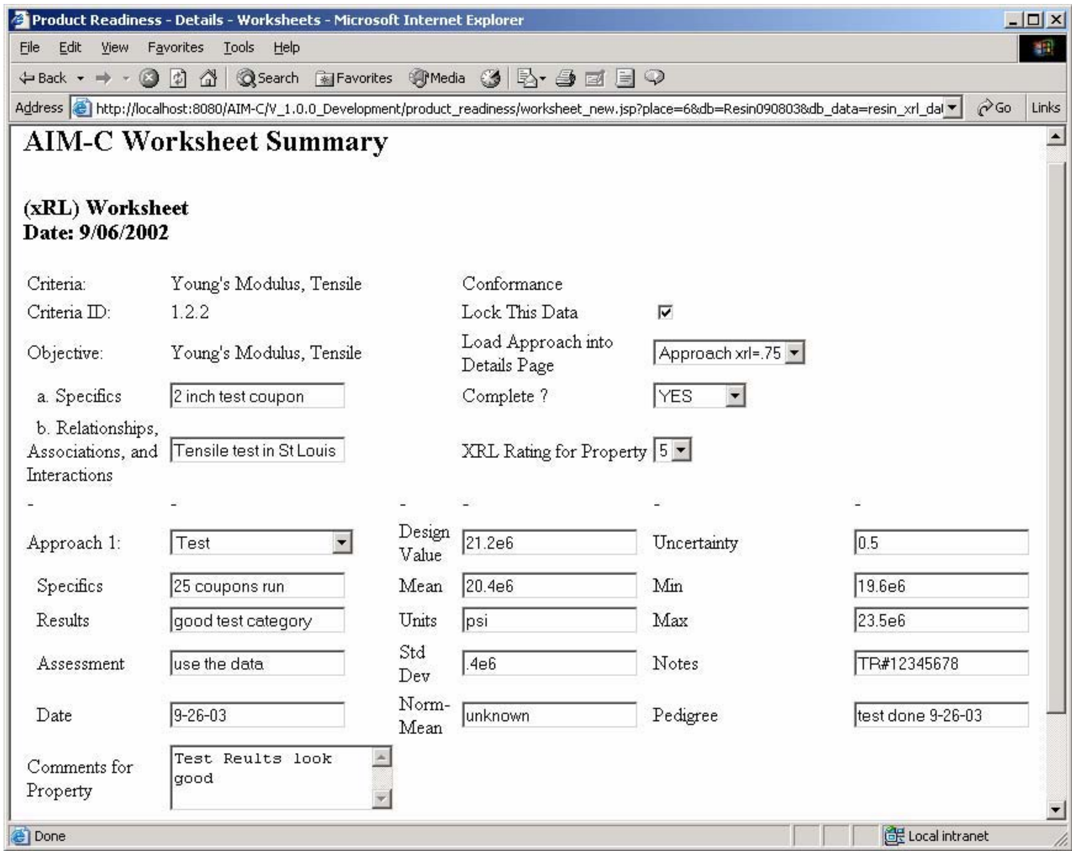



**Figure E - 22. Worksheet Summary Page**

At the time of AIM-C Phase 1 software delivery detailed worksheets exist for resin, fiber, prepreg, lamina, laminate, durability, and processing-producibility. These pages will need to be modified when properties include time or temperature dependencies. For the initial GUI, simple values were used as placeholders for more information as it becomes available.

After adding data to the system, the user may choose to run some of the templates to get more of the properties by analysis.

## 2.15 Templates

The templates are designed for the user to be able to quickly solve an analysis problem involving the insertion of materials on a new product. Many of the templates were set up for standard analysis methods such as an open-hole tests, a cure cycle optimizations, and failure prediction by using RDCS.

Currently, to create this simple RDCS run, a number of different processes are involved. Initially, the input variables for each of the RDCS projects were mapped to the TRL and XRL detailed worksheets. These values are captured from the user database and transferred to the demo page. At this point the values can be modified before the RDCS run is started. The values are then placed in the RDCS batch file. The file is transferred through an MS Exceed session in the background. The batch file is run on a UNIX or

Linux machine, and the demo page displays the running status during that time. Once the job has completed, the results are returned to the GUI. These data points can then be placed back in the database for future use. The user is also able to view simple plots within the window. The team uses GNUPLOT for this simple process.

In order to set one of these templates up to run, the user must go to the templates page and choose a template. Picking on the title or the picture of the template can do this. A description of the template follows the picture in the lower right hand corner of the each template area.

The AIM-C system has many templates, which run a series of executable codes to solve a specific problem. This page can be seen in Figure E - 23. At the time of AIM-C Phase 1 software delivery they include Template 4 (Fiber, Resin, and Prepreg Modules to Calculate Prepreg Thickness), Template 9 (Cure cycle optimization), Template 10 (Carpet Plot Generator Using SIFT), Template 11 (Interply Delamination Defects), Template 12 (Producibility and Processing modules for evaluation of heat up rate capability and exotherm potential of Hat Stiffened Panel), Template 14 (Structural Design of a Hat Stiffened Panel Using a Parameterized Finite Element Model), Template 15 (Effects of SUBLAM model of the hat stiffened panel (HSP) with fracture responses), Template 16 (StressCheck Failure Analysis by Strain Invariant Method of Hat Stiffened Panel), Template 17 (Predicting uncertainty analysis of open hole tension (OHT) coupons), Template 21 (General analyses of laminated coupons), Template 22 (Failure Loads Distributions Based on SIFT Uncertainty), Template 23 (Strain Invariant Failure Theory - Initiation Analysis of a Flange Termination), and Template 24 (Angle Mesh for Processing to calculate Spring-in and Warpage ). Each of these templates has descriptions associated with them. The templates are currently run on a Unix or Linux system that has an RDCS service. The executable codes inside the templates reside on the Unix or Linux side and they are called from the AIM-C system by a series of scripts that run after the user has placed all the input data in the appropriate boxes.

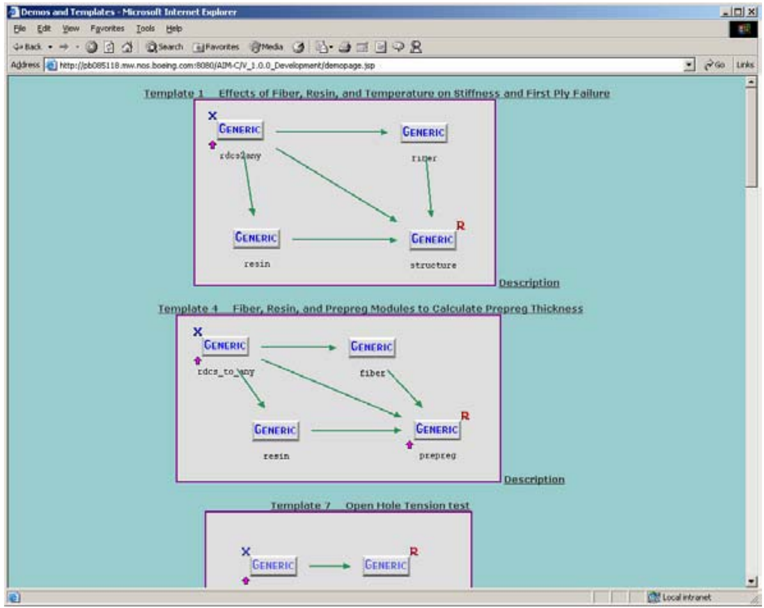


**Figure E - 23. Template Screen**

Once the user has chosen a template, a screen will come up that will allow the user to look at old runs from the view catalog button, define new inputs, view inputs, view outputs, see details, execute the template, or reset the status in the template. If this is the first time running the template, the user will have to go to the Define Input button. At this time, the template will ask for the variables that it needs to run templates. It will often present a range for the user, so that non-meaningful data is not used. Default values will populate the boxes, but the user can change the values inside.

There is a "Define Input" button at the top of the page that defines all of the inputs. If this is the first time running the template, the user will have to go to the Define Input button. This will display some information about the run, for example, the description, a default value, the units, and the range or domain that the data is valid in (Figure E - 24). The user must place a name in the Instance description box. This is how the user will designate this run from others in this project. The name should be descriptive and be followed by a date. At this time, the template will ask for the variables that it needs to run templates (Figure E - 24). It will often present a range for the user, so that non-meaningful data is not used. Default values will populate the boxes, but the user can change the values inside. After the user is happy with the data, they then either proceed to the second page of inputs or are ready to execute the template. From the last input page, they should press the "Continue" button on the bottom of the screen. The data is then registered and stored in the system. The "Execute" button on the top of the header should be chosen to send the job running on the Unix or Linux side and start the analysis. Once this button is pushed, the scripts send information in the form of RDCS batch files and XML files to the Unix or Linux side.

There is a status button on the demo input screen that tells the user the status of the project. During the definition of the input the status button will say "Being Defined". It will say "Running" if a process is running on the Unix or Linux side. When the results return, the status will change to "Complete". Occasionally if there is some interruption in the connection between the PC and the Unix or Linux box, the process may die for no explained reason. At this time, the user may need to reset the status button when the job has failed (either on the Unix side or on the PC side).

The status will change to running and the results will return after the job has finished. The status window will update approximately every 5 seconds. During the run, the user can browse the AIM-C GUI, enter new data in the system, but they cannot run another template while one is executing. If they leave this page and return, the status should return to the state of the job. Once it says "Complete", the user may view the results by "Viewing Output". The results should show up.

After the RDCS run has completed, the results are returned to the AIM-C system and are captured in the file system. These results can be viewed at a later time by going into the catalog for each of the templates. In some cases plots are viewed (Figure E - 25), but in most cases, the results are returned in the form of a CSV data file that will open up in MS Excel.

If the user wants to check old results to see if a similar run has been performed, they can click the "View Catalog" button and Define a target for a search. This will search for the information they are looking for. This will rate the previous results according to how close they match the search criteria.

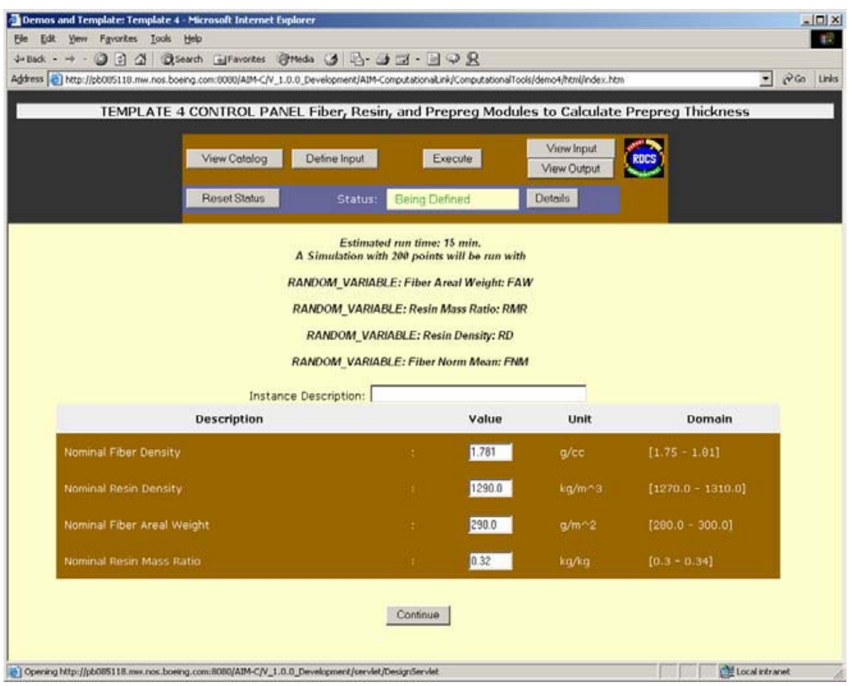



**Figure E - 24. Example of a Template Input Screen**

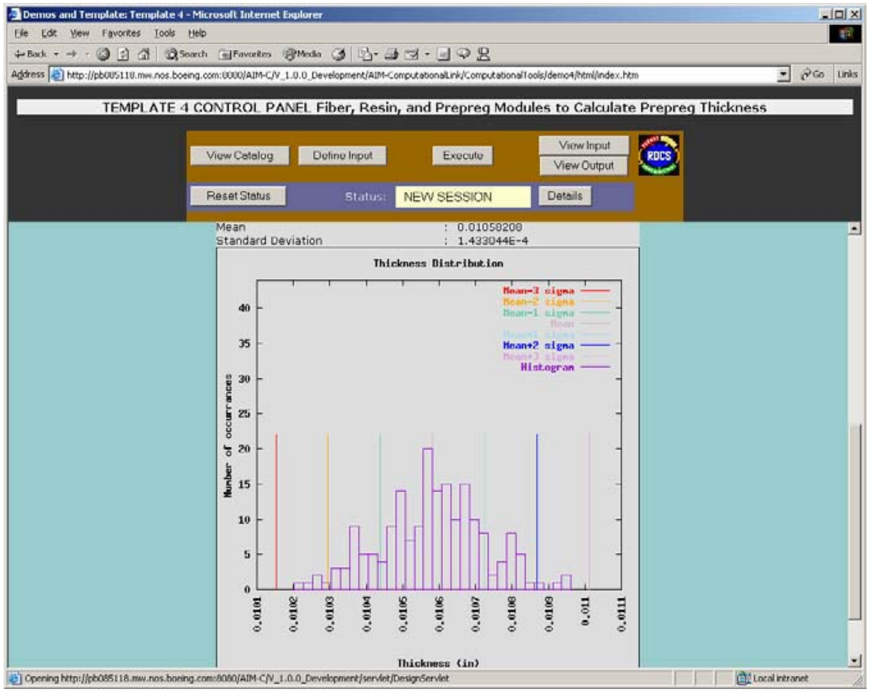



**Figure E - 25. Example of a Template Output Screen**

## 2.16 Modules

Modules are spreadsheets, executables, or the components that make up the templates. Some of these codes are licensed, some are proprietary, and some are made specifically for the AIM-C program. Each is listed according to the version number and the date it was added to the system after configuration control release (Figure E - 26). All of this software is downloadable so the user can install it on their computer and run. Keep in mind that StressCheck is a licensed product, so it will not run unless there is a license available. Each of these has a brief description underneath the hyperlinks. At the time of AIM-C Phase 1 software delivery the modules available for download are:

Compman V1.1.4 1-27-04 (Boeing Proprietary Software)
Cost Spreadsheet (Boeing) V_1.0.0 9-03-03
Delamination Tool Spreadsheet (MIT) V_1.1.0 9-01-03
DURASOFT Download (MIT) V_2.0.0 11-07-03 and V_3.0.0 2-9-04
Fabric V1.0.0 6-9-03
Fiber V1.0.0 5-12-03
Integrated Durability Download V_1.0.0 1-07-04
ISAAC V1.0.0 7-15-03
Lamina V1.0.0 5-20-03
Laminate V1.3.0 10-6-03
Laminate V1.4.0 02-16-04
MicroMechanics SpreadSheet V_1.0.1 7-31-03
Prepreg V1.0.0 7-10-03
Processing V3.1.3 5-29-03
RDCS2File V1.0.0 5-20-03
Resin and Adhesive V1.0.0 5-19-03
ResinMan V1.0.0 6-20-03
StressCheck 6.2.1 h 1-27-04
SuperMicMac SpreadSheet V_1.0.1 7-31-03

Thermal Degradation SpreadSheet V_1.0.0 3-07-03
Uncertainty Analysis of Coupon Tests V_1.0.0 02-16-04
WinASCOM Public Version 1.0 7-3-03

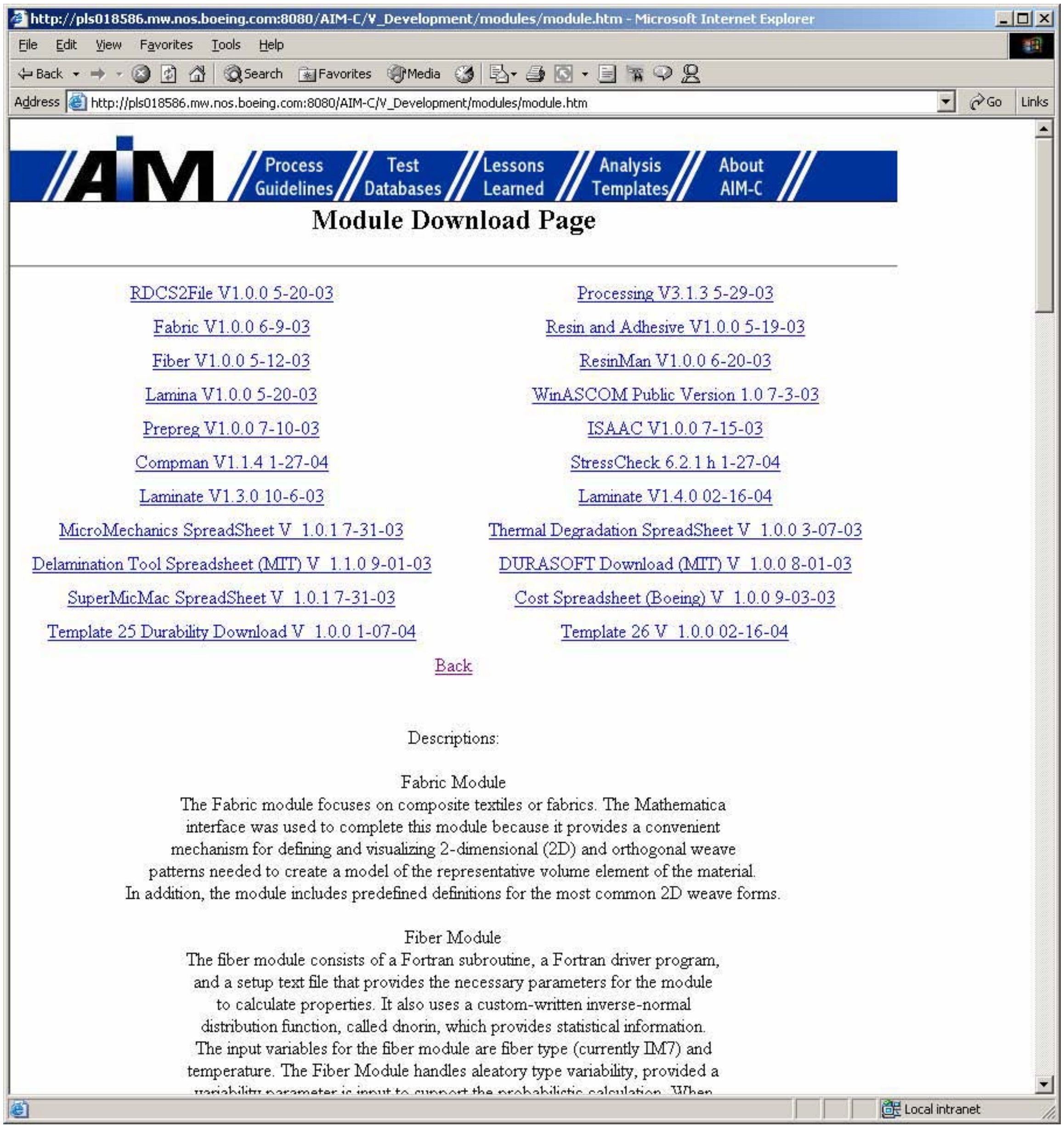



**Figure E - 26. Example of Module Download Page**

Another feature provided through the AIM-C System is the SEER Cost models developed by Galorath, the use of which requires a license. This is a cost prediction program that can calculate recurring costs. Since this is an application that Microsoft does not recognize, the mime-types have to be set for the correct file/application connection to be made in order for the SEER application to appear when clicked from the GUI. One drawback of this application in the GUI is that the SEER application executable must be resident on the users computer in order for it to work. This is a licensed product, so it will only run if the user has a valid license file. A sample screen shot is shown in Figure E - 27. SEER-H has the capability to perform non-recurring cost analysis.

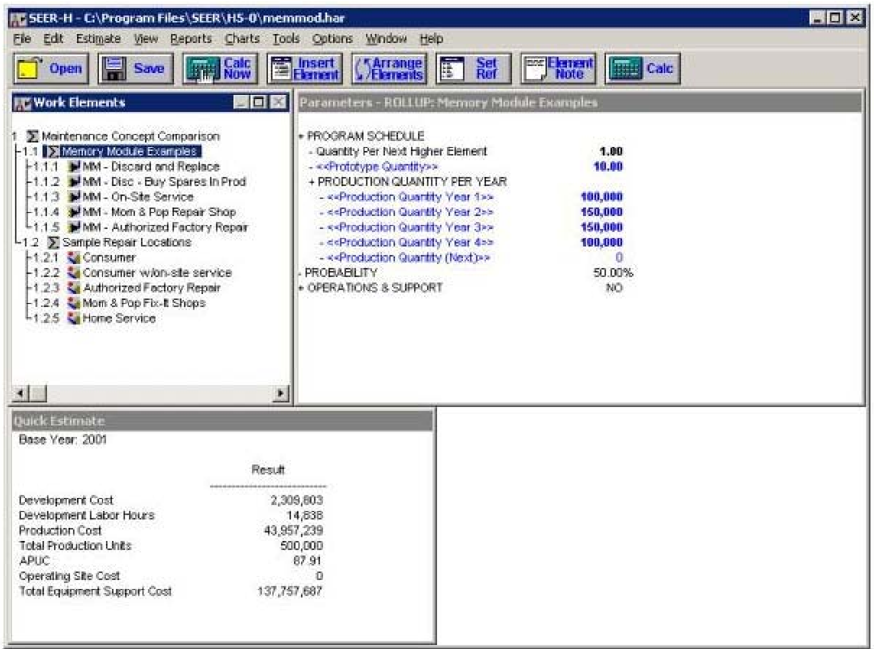



**Figure E - 27. SEER Cost Model Screen**

The Producibility Module is another part of the AIM-C system. An example of this can be seen on Figure E - 28. This module will help the user on many aspects regarding the production of parts. For instance, there are many pages that ask for information on cutting, layup, debulking, cure, bagging, tooling, and non-destructive evaluation. These procedures are defined and explained in a series of documents and presentations inside the producibility module. This module produces calculations on material per ply thickness, design nominal thickness, material average calculated thickness, material standard deviation thickness, material standard deviation minimum, material standard deviation maximum, material specification limit minimum, material specification limit maximum. These calculations will assist the user in determining if the part will be thick or thin enough for its desired use. This module also has data on voids, delaminations, porosity, inclusions, features, and distortions.

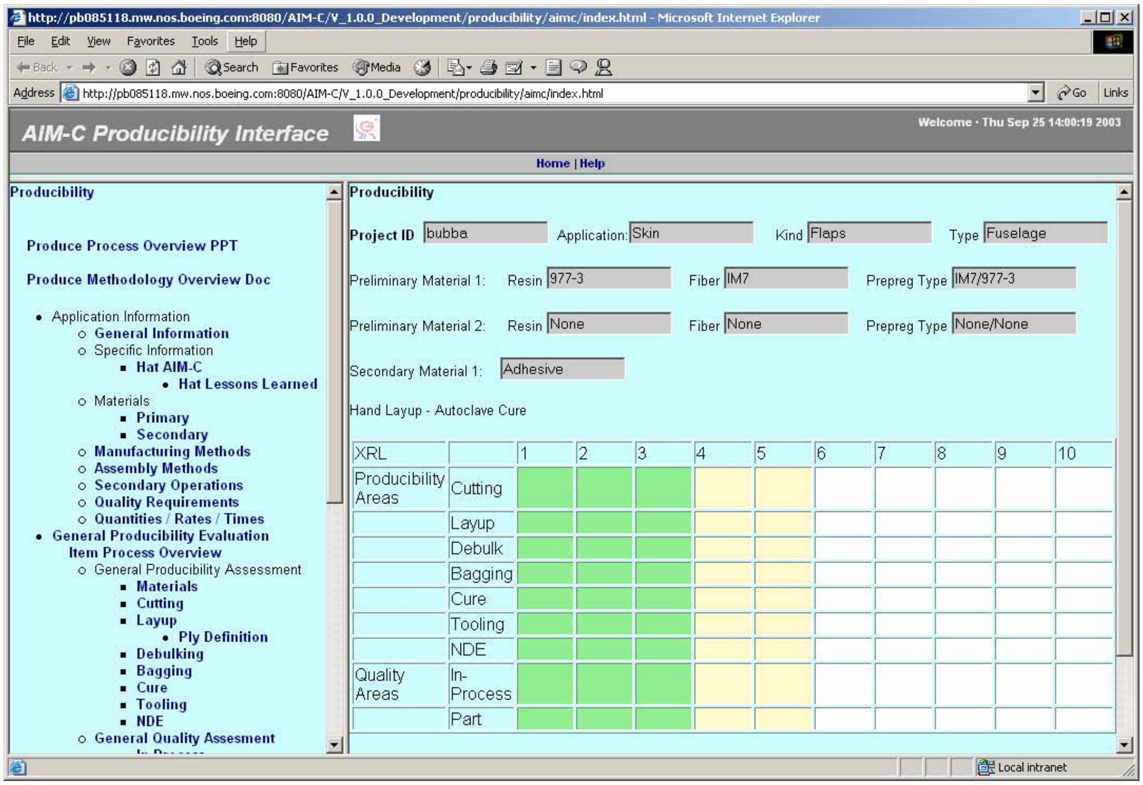


Figure E - 28. Producibility Module Page

## 2.17 Utilities

AIM-C has a few utilities that make the system work a little bit better. Some of these include the scripts such as an RDCS-to-file script that is used by RDCS to quickly transfer variable data into the RDCS run. It is used mostly on the Unix or Linux side and makes running RDCS a bit easier for the user. In most cases, the general user does not run this standalone.

The current utilities are only used if the user wants to run RDCS standalone. There is one script that is an RDCS_to_Any script that transforms parameterized data files into RDCS input files.

## 2.18 Third Party Software

AIM-C has many third party software providers. These occur on every level of the tree that makes up the AIM-C system.

For instance, on the application tier, there are codes that run behind the scenes in the software. These include Java2 Standard Development kit (J2SDK), Java Expression Parser (JEP), and Python (a scripting language).

On the web tier where the server resides, AIM-C uses COS-com.oreily.servlet, Java2 Standard Development kit (J2SDK), Java Expression Parser (JEP), WebEE (Boeing code) and Tomcat Server Engine. For Version Tracking utilities, the AIM-C system uses WinCVS and WinMerge. Microsoft Access 2000 must be installed on the server.

On the Unix side, there are many programs in the background that run strength analysis codes. They include Patran, Nastran, Compro, Ansys, Abaqus, StressCheck, RDCS, and Compman.

On the client tier or where the browser resides, there are three executables that need to be installed. These include Java SDK, Java3D for visualization, Cost Module (SEER), and Product Life Cycle Process Database (PLCP). It is assumed that the user will have Internet Explorer 6.0 installed on their machine.

Some of these can be downloaded from the following places:
•Uses Jakarta-Tomcat 4.1.24 as a server engine
Found at www.apache.org (freeware)
• Uses M.S. Access 2000 Database to store data
• Runs Java codes through JDK 1.3.1_06
Found at www.java.sun.com (freeware)
• Runs Java 3-D for images
Found at www.java.sun.com (freeware)
• Runs on MS Internet Explorer 6.0
• Uses RDCS for analysis means
• Includes Documents, Excel Files, and Powerpoints
• Runs on MS Access 2000

## 2.19 MS Access Database

The database used for the Alpha System is a Microsoft Access 2000 Database. The following information talks about the structure of the database. The general user will not need to know this information. The database administrator is the only one who will be able to see this data.

There are over 100 tables in the database. Each of these tables references a specific set of data. Many of these tables are non-changing static data. There are over 25 tables that change depending on user inputs and analysis. These are differentiated by a column named “Project” in each of those tables. There are rows in these database tables associated for every project.

If a new project is created, a java code will execute to creates a new set of rows in the changing tables called out from the table_names table that will populate the changing tables with space for new inputs. Default information will also be added to these rows from the table called table_default_proj. This will set initial information to get started. If a project is copied or renamed, the tables are altered appropriately. If a project is deleted, the rows in all of the tables from that project are wiped out all together.

Most of the tables represent data from XRL (specific readiness level) sheets. For many of these sheets, there are a ‘_data’ and a ‘_data_wkst’ table that holds the data. The initial sheet is a spreadsheet of properties, how they were obtained, test analysis, sequence number, and readiness level. The ‘_data’ sheet contains values for the property, units, uncertainty, min, max, standard deviation, and notes associated with this value. The column names are represented by field and column number, which is the default for Access. They are all ordered by ID. The ‘_data_wkst’ lists different means of obtaining the data. This may include test, analysis, combinations or those, or other means. There is also a notes column in this table. These can be found in the following tables: Durability, Fiber_interaction, mech_prop_lamina, mech_prop_lamina2, mech_prop_laminate, mech_prop_laminate2, prepreg, ProcProd, resin, and resin2. All of these tables have columns specific to each project.

Many of the xrl tables do not have other detailed data associated with them. These are Cure_xrl, Cutting_xrl, Debulk_xrl, designAllowables_xrl, Fab_Methods_xrl, Fab_Rel_Matl_xrl, Fab_xrl, Layup_xrl, Material_xrl, Structures_xrl2, Support_xrl, and Structures_xrl. These mostly describe the current state of the readiness level depending on the components inside. The column names are represented by field and column number, which is the default for Access. They are all ordered by ID.

Many of the other tables are designed for individual pages. For instance, the additional inputs table is referenced from the Additional Info button under the legacy information. It contains variable names, values, units, standard deviations, normal means, uncertainty, min, and max data. This is needed if RDCS needs more data than what the GUI requests.

A few of the tables are property data sets for existing composites materials. Some examples of these are the tables of AS4 and IM7 data. These are used only on the materials menus when a similar system is needed for reference. The values in these tables are loaded into the database if needed. The cure_recommend table is referenced from the producibility menus. These tables are ordered by ID, but have column names such as Props, neg65deg, pos75deg, pos250deg, Units, and comment. The cure_recommend has columns titles Step and value to designate each step in the cure cycle.

There are a few overlapping tables that contain info in other tables. They are Fiber_Interaction, Prepreg_Interaction, and resin interaction. They contain the same columns as in the regular xrl tables. These were created to capture the readiness level of each property in the table depending on your design. They are ordered by ID and contain Field1 and either Field2 or Field3 in most cases. These can be deleted out if the JSP are modified. The project-specific readiness levels for each property that goes along with the material are located in the interaction_data tables. These are ordered by ID and contain Field1 for the column values.

There are two very large tables that contain a large amount of data not related to xRLs. They are the user_info and text1 tables. The text1 table holds all the inputs for the pages in the GUI. This includes capturing all the user-defined inputs, text boxes, and pull-down menu options in the rest of the GUI. The user_info table is only designed to capture the responses from the user that relate to the producibility module. They were separated because there was an efficiency issue searching the long tables for specific data. Both of these tables have columns named Variable, Val, and Project. They are ordered by ID.

Some of the tables in the database were created as a part of the RDCS demo information. These include Demo1, Demo1: Geometry, and Demo1: Nomogram as well as Input,

Input:Geometry, and Input:Nonogram. They list the project name, inputs, and outputs from the RDCS run.

Many of the tables were originally created by Northrop Grumman as part of the Producibility module. These include BackingPaper, Faw, Fiber, FiberDens, FiberForm, FiberKind, FiberType, FiberYield, Indirect Material, Part, Paw, Raw, Rc, Resin Type, ResinKind, Separator Material, Spool Material, Spool Requirements, TestMethod, Viscosity Model, X-Sectional area. Many of the tables have relationship involved. A picture of this is shown in Figure E - 29.

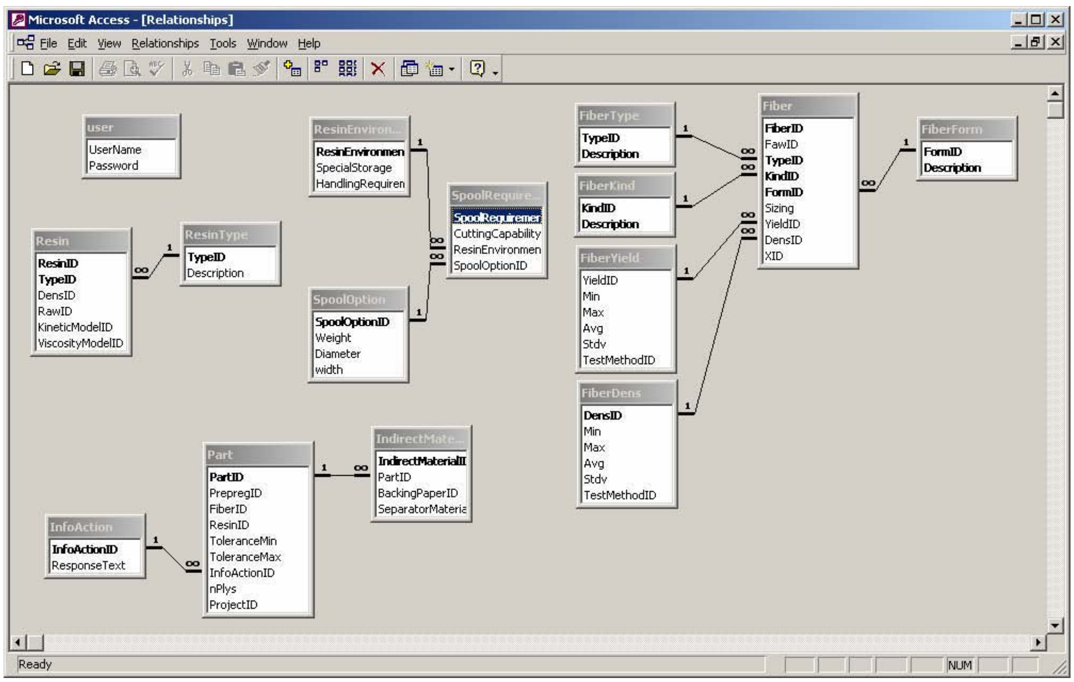



**Figure E - 29. View of Database Relationship Structure**

Tables that were all xrl tables (nonchangingdata) include applications_xrl, Cure_xrl, cutting_xrl, debulk_xrl, DesignAllowables_xrl, Fab_methods_xrl, Fab_Rel_Matl_xrl, Fab_xrl, Layup_xrl, Material_xrl, Resin_xrl_1, Structures_xrl2, Support_xrl, and Structure_xrl.

Tables that had no information include cutting_capability, Indirectmaterial, Input, ResinEnvirnmentRequirements, SeparatorMaterial, SpoolOption, and SpoolRequirements.

A sample view of the database table structure look like Figure E - 30, but this is changing all the time depending on new additions to the system.

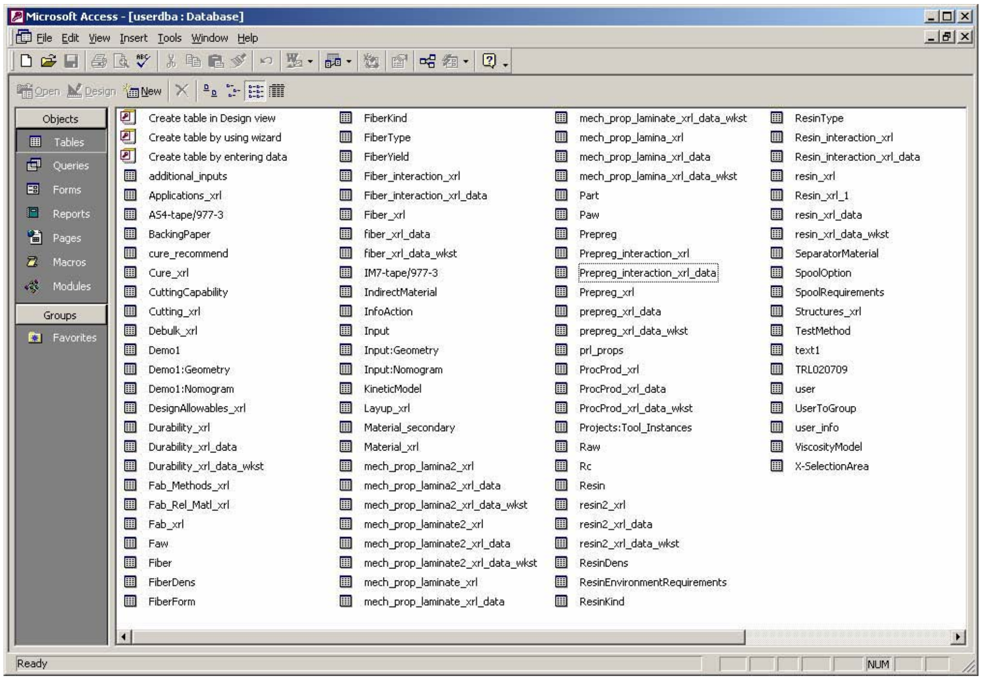



**Figure E - 30. Database Table View**

To the general user, the MS Access database acts like an information storage place. It will hold all the text input that the user is asked to put in. Since the information in the database is stored based on project name, the user should be careful to create a project name that is intuitive.

## 2.20 User Database

The user database is all the information that the user needs in order to travel through the insertion process. This information starts at the application definition and continues through testing and production.

Some of the initial data is already stored in the database. This includes data from IM7/977-3 and AS4/977-3. This data can be looked at if the user goes to the Test Database button on the top menu (Figure E - 31). Sample data 12K IM7 Fiber Property Validation Data, IM7 Fiber Specific Heat Validation Data, IM7 Fiber Thermal Conductivity Validation Data, IM7 Lamina Thermal Conductivity Data, IM7 Lamina Transverse Modulus Data, 977-3 Modulus Data, 977-3 Relative Exp Data, 977_3 Viscosity, 977-3 Isothermal Data, 977-3 Dynamic Data, 977-3 Cure Rates, 6K AS4 Fiber Property Validation Data, 12K AS4 Fiber Property Validation Data, AS4 Fiber Specific Heat Validation Data, AS4 Fiber Thermal Conductivity Validation Data, and AS4 Lamina Transverse Modulus Data.

While it may be hard to capture all the data associated with defining a new material, the AIM-C system is designed to help capture data along the insertion path. This can be done a number of different ways. Data can stored in the readiness level worksheets for each level (0 to 5) before the material is used for production. Many of the AIM-C screens gather information, which helps define the problem and the associated constraints and criteria.

At this time, the general user cannot upload files into the AIM-C system. In the future, this may be possible, but for virus protection purposes, now it is not. An administrator can only alter the database structure. However, the information inside the database is completely created by the user for each project.

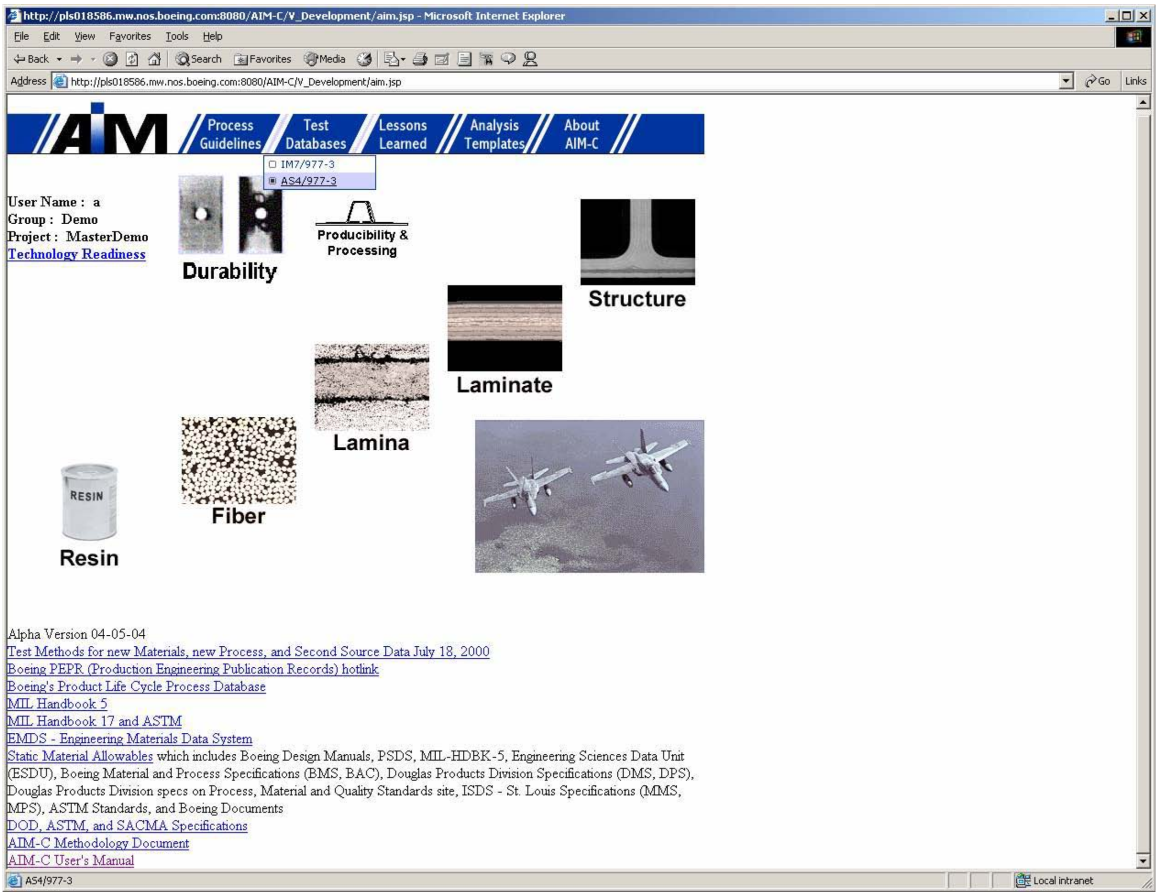



**Figure E - 31. Test Database Information**

# Appendix 1:

## A.1.0 Bug Tracker

A Bug Tracker has been installed for Boeing users to comment on bugs or features they would like to see fixed or added. This will link the user to a site at Canoga Park, CA. A series of text boxes and pull-down menus will allow the user to input the following information.

1. Category: RDCS, computational templates, database design, database implementation, distributed processing, other, or user interface
2. Reproducibility: always, sometimes, random, have not tried, unable to duplicate, N/A
3. Severity: feature, trivial, text, tweak, minor, major, crash, block
4. Product Version: V_0.0.2, V_0.0.1, V_0.1.0, …
5. Summary:
6. Description:
7. Additional Information:
8. View Status: public or private
9. Platform:
10. Operating System:
11. Step to Reproduce: