STRUCTURAL DESIGN
WITH
FIBROUS COMPOSITES

MAB

STRUCTURAL DESIGN WITH FIBROUS COMPOSITES

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The Committee on Structural Design with Fibrous Composites

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FOREWORD

Because of the great promise of composite structural materials, they have been the subject of MAB study, at the request of the Department of Defense, for almost a decade. A report, MAB-146-M, titled "Composite Structural Materials," was issued in 1958; an ad hoc Task Force produced a brief letter report, MAB-98-LM, on "Composite Materials Composed of a Metal Matrix Reinforced with Ceramic Whiskers" in 1962; and in November 1965 three reports prepared by ad hoc committees were issued--MAB-215-M dealt with "Composites" (in general); MAB-214-M with "Interface Problems in Composites"; and MAB-207-M with "Micromechanics in Composites".

Continuing advances achieved in the development of fibers, particularly boron and graphite, have brought the technology of fibrous composites to the stage where their potential as high performance structural materials can begin to be achieved in useful applications. This has stimulated attention to the design phase of the technology. Here, as was predicted by the MAB ad hoc committee study on composites in 1965, one of the obstacles is the difficulty of designing with a material whose properties can be made to be different at different positions (non-uniform) and in different directions at the same position (anisotropic) on the body. This requires, in effect, the design of the material as well as the structure.

Some rudimentary design work has been successfully carried out and the resulting structures have generally confirmed the promise predicted for filamentary composites. However, the character of these designs is generally that which occurs (1) by "substituting" composite structural elements which are typical of those constructed of more conventional materials, and (2) by using "cut-and-try" approaches to obtain a workable structure. This is to be expected at this stage in a development with profound differences from experience. Clearly much work is required before the full potential of structural composites can be achieved and before they can be applied with an economical "design-test-use" cycle comparable to that followed with metal alloy structures. Recognizing this, the Deputy Director of Defense Research and Engineering in early 1967 asked the Materials Advisory Board under Academy/Research Council aegis, to undertake a committee study. The objective was to analyze the broad design problem and identify specific areas of need that could be attacked through research and engineering or by administrative means, involving government, industry, and academic resources. This report is the result of that study. Although addressed primarily to the Department of Defense, it is hoped that its findings will be of interest to a broad audience of research people, engineers, and others concerned with advancing this new technology and applying it to the advantage not only of weapons systems but to other structures important to the national welfare.

ABSTRACT

The problem of designing structures with fibrous composite materials was examined, with the view that constituent materials and the means of forming a composite from them are well-enough established to be assured of repeatable properties. There was no intent to deal with questions of filament or matrix development, or to deal with specific materials; on the other hand, in examining design problems and potentials it was inevitable that the influence of glass, boron, and graphite fibers, and resin matrices would be strong. The advantages which can accrue from the use of filamentary composites were briefly reviewed, and confirmed as outstanding in many cases. The substantial progress made to date in limited applications is recognized, but the report concentrates on what must be done to benefit as fully as possible from these new materials and to minimize need for "cut-and-try" approaches to design objectives. Accordingly, major design difficulties were sought out and defined. Important among these is the current difficulty in standardizing on the tests needed to characterize many of the important composite material properties and in predicting them by theoretical analyses. The load transfer problem was cited as major, with only limited successes to date. Design with composites was recognized as being more intimately bound to fabrication than is design with conventional materials, and the need for design handbooks and specifications was identified as one part of an important communications, education, and acceptance problem.

No attempt was made to give priority to the various research efforts cited by the Committee as necessary. Virtually all of them are required and should receive the support necessary to bring structural composites into routine usage.

SUMMARY

Conclusions

1. Glass, boron, and more recently graphite, are now available in both filament and resin prepreg forms. Their properties are sufficiently reproducible that real components made with these materials are being, or can be, designed, fabricated, and used. It is important to note that this report focuses on the problems likely to be encountered in achieving the full potential of filamentary composite structures and in reaching the point where the fewest possible number of design - test - redesign iterations will be required. The conclusions to follow, therefore, should not be construed as deprecating the considerable progress which has been made with these materials, nor as suggesting that the advantages which can accrue from their immediate application for many systems should be sacrificed until more is known.

2. Application of composite materials to structural components to date has been largely on a substitutive basis. These applications demonstrate definite advantage for composites; however to exploit them more completely, the application of these materials should be considered in the conceptual phase of design, with the entire system conceived as one in which the geometry and the material used are chosen as jointly contributing to the optimum. More studies are needed which can guide designers in making trade-offs between material selection and geometry.

3. A large proportion of the total design effort using composites to date has been devoted to the design, fabrication, and testing of structural components. While some structural element testing has been done, these have been only pioneering efforts, and many fundamental problems remain. *

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*The term "structural element," as used herein, refers to a basic structural unit such as a tension or compression member, a torsion member, a plate, a shear-carrying panel, etc. A "structural component" implies a complete structural sub-assembly such as a wing beam-torsion box or a fuselage section between frames. A structural component can usually be idealized as an assembly of structural elements.

4. Reliable and meaningful materials specimen test methods to provide data for structural design or evaluation of structural components and elements are in need of further development. The shortcomings of present test methods are a basic cause of the paucity of reliable material characterization and structural element data. An urgent need exists for acceptable standard test methods and specimens. Since the micro-behavior of fibrous composites is inherently complex, however, specimen shapes as simple as those used for homogeneous, isotropic materials may not be suitable and a greater variety of standard specimens may be required. Whereas research efforts to date in this area have been applied to tests of prototype fibrous composite structural components, analytical tools have tended to concentrate on highly idealized structural elements. Thus, there is a need for analytical studies actively integrated with laboratory testing of basic structural elements.

5. Load transfer problems are more serious in composites than in homogeneous materials. The inhomogeneity of the composite at the load transfer point is a very important factor. As a result, what is approximately an optimum orientation and loading of fibers in areas remote from the load transfer region are usually far from optimum at the load transfer region. This may be true for both static and fatigue loads.

6. Failure laws for composites need to be defined. Micromechanics efforts to date have concentrated almost exclusively on linear elastic effects. This has been productive, for example, in arriving at the volume fraction currently used in filamentary tapes. In order to predict strength characteristics, however, it will be necessary to mount a strong attack on the behavior of composites under conditions which produce inelastic (energy dissipative) stress fields. Further, the mechanistic base of initial damage and failure theories should be sought. The use of curvefit type combined stress, ply-failure criteria as a measure must be recognized as an expedient but, in the long run, expensive approach. These considerations, of course, must ultimately consider dynamic as well as static loadings, with implications for impact strength and other phenomena where wave propogation in the composite enters significantly.

7. Designing with composites differs from designing with homogeneous materials in the degree to which integration of material design, mechanics, structural design, fabrication, and perhaps nondestructive test techniques is required as an iterative process. Therefore, a successful composite design is likely to require the combined talents of designer, structural analyst, materials and fabrication process engineers--all of whom are experienced in the field of composites--to a greater extent than has been necessary in designing with metals.

8. The importance of nondestructive testing (NDT) is greatly magnified because the final composite material is created in the part-fabrication process. NDT is, therefore, the only check possible on the quality of the material in the composite state. It is difficult to predict at this point whether this subject will always have its present importance; as experience is gained, emphasis in NDT may shift from new-part quality to considerations of integrity after severe loading in service.

9. The added dimension of variable material properties both as regards specific strength and specific stiffness, and the directionality of these properties, emphasizes the importance of structural optimization as a formalized procedure. Over and above the almost continuous range of material properties possible with composites, it is important to recognize that the filament arrangement which is optimum for obtaining one material property may not be optimum for another. It is unlikely that a design and stress analyst can approach an optimum structural design in the presence of such a vast range of variables within reasonable limits of time and resources without specialized techniques; these are likely to range all the way from improved nomograms to extensive automatic digital computer programs. The implications of this conclusion are focused on increased performance; the optimization procedures, however, will also ultimately consider economic factors.

10. Structural elements and components have been designed and built with composites, using available design approaches coupled with extensive testing, and have performed successfully in service. Reliable analytical procedures for designing to structural efficiencies approaching optimum, however, are still in an early stage of development. Widespread application of composites will require further development in analytical techniques, not only to improve the confidence in and reliability of initial designs, but also to reduce the over-all costs and to assure the use of these materials to their maximum advantage. Improvements in fundamental understanding and in analysis tools should consider the following:

10. 1 Various approximations and idealizations which are acceptable for metal structures must be reexamined when dealing with composite material structures. These include certain approximate treatments of shear and moment boundary conditions and the use of flat, finite elements to represent the behavior of shells, particularly when subject to destabilizing loads. A number of more fundamental hypotheses also remain to be proven for composites. Perhaps the most serious of these is the assumption that strains vary linearly through the depth of layered materials which have different elastic properties in adjacent lamina.

10. 2 Means of locating maximum deflection points and critical stress points in fibrous composites will require further study; not only do critical stress points occur at unexpected locations on the surface but points of critical stress through the thickness are not always at the extreme fibers.

10. 3 Until very recently, no theory has been available which is able to treat the high stress gradient problem in the areas of load transfer, although finite element methods appear to offer a promising expedient. In this and in other analysis areas, non-linear effects will probably have to be properly accounted for.

10. 4 There is increased likelihood of unbalanced laminates being used (e.g., as in lightly loaded structures due to minimum ply-thickness limits). This may make it necessary to give increased consideration to finite deflection effects and bending-membrane coupling in order to confidently evaluate designs.

Recommendations

The Committee addressed the subject "designing filamentary composite structures" with respect only to those fibers and matrices of reasonably assured quality, and only to those processes which can be relied on to form a composite with known structural integrity. The former include boron, glass, and graphite fibers, and resin matrices. This focus, however, should not be interpreted as implying that the recommended programs would be inapplicable when a newer filament-- say, silicon carbide -- reaches the same status as boron, or that research of a different nature should not be pursued to bring a newer composite -- say, silicon carbide in a titanium matrix -- to the point where it can be considered for the design of real hardware. It does seem prudent, however, to emphasize that the following recommendations apply only for programs intended to support hardware structural design with composite materials whose constituent properties have the same degree of quality assurance as boron, graphite, and glass fibers in resin matrices.

1. Conceptual Studies and Analysis

The Committee urges that composites be considered in the conceptual phase of new designs. Analyses which relate over-all system performance requirements to the material-structural-geometrical selection must be performed at the earliest stages in selecting a concept. This applies to very advanced missions which may be in an exploratory phase, as well as to more prosaic designs. In such parametric design studies, care should be exercised to insure that the methods employed do allow a free selection of component geometry as related to each of the structural-material systems considered. Fabrication and economic aspects will have to be considered in the conceptual phase, and continued in greater detail as the competing design approaches evolve.

2. Structural Element Behavior

At this writing, it is evident that to achieve the full performance potential of composite materials and to establish the economical design processes essential to widespread applications will require much experimental mechanical properties data. It is recommended that a substantial experimental program be vigorously pursued to obtain data on basic structural elements. These should include:

1. Laminates (members with very low bending stiffness)
2. Flat and slightly curved plates (including sandwich constructions)
3. Shells
4. Stiffened plates
5. Stiffened shells

The data to be obtained should describe elastic, inelastic, fatigue, and failure modes of behavior. It is important that such experiments correlate the results of tests of components, elements, and material specimens and be closely coupled with a strong effort in theory and analysis.

At the heart of the design problem is the capability to predict the response of the above elements from single ply properties. It is recommended that test specimens be developed and test data obtained therefrom, which can be used for this purpose.

3. Load Transfer

It is recommended that the design of composite structures in areas of load transfer--such as joints, fittings, and cutouts--be the subject of major effort. This should include basic investigative studies, the development of empercal data and empirically-based design techniques, and where promising, the development of theoretical joint analysis and synthesis techniques.

4. Systematic Design Procedures

It is recommended that systematic design procedures be developed to aid the design engineer in fully exploiting the greatly increased options offered by fiber composites. Efficient handling of the large number and wide range of variables--such as volume fraction, process and fabrication techniques, and geometric configurations--will require formalized procedures. A systematic approach to the design process may be based on response prediction and limiting criteria ranging from purely experimental, through semi-empirical, to highly theoretical. The resulting systematic procedures should be flexible with respect to objective; that is, alternatives other than weight minimization (such as minimum cost or maximum reliability) should be feasible.

5. Fabrication

The Committee believes that current efforts should be continued and expanded to improve basic fabrication and tooling concepts for composites. In such projects the unique characteristics of the materials involved should be constantly examined to take maximum economic advantage of the possibility of producing relatively large assemblies in a "one step" process. Automated and highly reproducible concepts should be emphasized. Application of newer filament and matrix materials (such as graphite, low temperature cure resins, etc.) as they become available with assured quality, should be pursued in parallel with the currently well-developed constituents to take maximum advantage of the potential of lower material and fabrication costs which these materials may offer. In addition, the development of rapid-cure techniques should be emphasized.

6. Nondestructive Testing

It is recommended that current efforts be continued and expanded to improve NDT capabilities for components made from composite materials. The importance of this area to the widespread acceptance of composites cannot be overemphasized. Furthermore, at this writing it appears that carefully controlled tests to establish the importance of imperfections are more crucial than the development of sensors, although continued improvement in the latter is needed.

7. Usage in Production Systems

It is recommended that deliberate measures be taken to introduce full-scale fiber composite components into advanced vehicle programs where they offer advantage over conventional metal counterparts, as parallel or preferred designs. These developments should be undertaken with appropriate contractual provisions for timely qualification, effectiveness comparisons, and judgment of suitability for use in production service vehicles, so that the over-all vehicle development will not be delayed or impaired in the event that it is necessary to revert to a conventional design.

8. Specifications, Handbooks, and Information Dissemination

The Committee recommends that the appropriate Government agencies strengthen and update specifications applicable to fiber composites usage, in consonance with the technology, in particular as regards:

a) characterization of constituent materials properties and their behavior in the environments of interest, and

b) the form, scope, and content of the contractors' process specifications and other data to be submitted for Government approval.

It is further recommended that this effort be applied to the whole specification system, including handbooks, and for each hardware system (such as aircraft, ships, ordnance, etc.). Consideration should be given to organizing the specification effort for each system on a comprehensive basis, perhaps as a unified program under the guidance of a steering group of cognizant Government people, with full consideration given to the "interdisciplinary" aspects of the design and fabrication of composite structures. It is recommended that such effort be thoroughly coordinated among all Government agencies and industry.

In the development of design manuals, test procedures, specifications and the like, continuous conscious attempts to avoid those standardizations which discourage new and improved approaches to design should be made. Especially to be avoided are standards carried over from design with metals, which tend to force composite designs to use the same concepts used in the past for metal construction. The need for standards and specifications for fibrous composites is clear and warrants careful attention; eventually, standard approaches to design problems which are encountered repeatedly, with little variation, should be sought from an economic viewpoint. The Committee, however, urges that every encouragement be given by the means referred to in this section to the continued development of new structural design concepts which take advantage of the unique characteristics available with composites.

9. Acceptance of Composites

Finally, the Committee recommends that all possible measures be taken to foster the acceptance of filamentary composites as a structural material available for hardware design. The efforts to compile useful information in specifications and design handbooks should be supported, and the resulting documents should be made known and available to structural designers. The education and continuing professional training of engineers should include information on filamentary composites where such subjects as materials, stress analysis, and structural design are normally presented.

1. INTRODUCTION

1.1 Reasons For This Study

There are several reasons why most designers will remain reluctant to take advantage of filamentary composites routinely, even after the composite properties are well defined. These reasons, which are central to this study, are: (1) the unfamiliar nature of the materials, as regards directionality and strength/density, stiffness/density ratios; (2) the problems of load transfer in inhomogeneous materials; (3) the uncertainties of fabricating with filament composites; and finally, cost. Whereas cost certainly is fundamental, it should be considered separately for at least two reasons: (1) there will be some applications where even very high costs will be justifiable, and (2) the more uses designers find for advanced composites, the greater will be the incentives to lower prices.

In designing structure with composites, an additional degree of freedom becomes available, as compared to designing with the usual homogeneous material. The usual requirements of optimum performance for given restrictions in geometry, fabrication capabilities, etc., can be approached with a new freedom as regards choice of materials and configuration, e.g., volume fraction filaments and filament orientation. To see that this is, in fact, an additional degree of freedom and not an additional constraint, it is only necessary to note that composite materials can always be configured to approach isotropy. This can be accomplished for most two-dimensional structures, for example, by orienting the filaments in three directions, 120° apart. The very fact that the designer is generally not content with this simplification is strong evidence of the benefits which accrue when advantage is taken of anisotropy.

If the solution to a structural design problem is to approach a true optimum, it must take into account two interacting factors. One is the material properties attainable with given constituents, proportions, and reinforcement configurations ("tailored" properties) and the other is the response of structure made therefrom. Prediction of this interaction between material properties and component configuration is complex. Most aerospace structures are subjected to a variety of loading conditions (for example, the shell of the rocket boost vehicle encounters axial acceleration loads at launch, bending loads due to gusts and maneuvers, pressure loads from internal fuel, etc. (e.g., see Ref. 1) and each loading condition may require a different anisotropy for optimization, which could lead back to isotropy in some cases. To cope adequately with the numerous combinations of possible designs for the best compromise, analytical design methods for both material and structure will probably have to be quite sophisticated, involving classical "analysis-synthesis" considerations (e.g., Refs. 2 and 3).

1.2 Scope Of The Study

Throughout its work, the Committee made a deliberate effort to confine the scope to problems affecting design with fibrous composites and primary attention to composites with a polymeric matrix. Hence the report does not attempt to deal with the many other important and active problem areas, such as, materials development (fiber and matrix), interfaces, environmental deterioration effects, fabrication of metal composites, etc.

1.2.1 Fibers and Matrices

In this review it will be assumed that the properties of fibers and matrix materials needed for designing with filamentary composites either are or can be made available. Proper consideration by the designer of real hardware, however, will require a more complete catalogue of properties than that which suffices for other purposes. Furthermore, since design involves fabrication and economics, some not-so-usual material property-relationships may be pertinent. Economic factors in the processing of structural fibers may result, for example, in commercial grades whose price-strength properties are related to fiber length. Bare-fiber corrosion resistance and "aging" properties may be important for fabrication processes where the individual bare fiber is wound or laid in making the part, thus requiring the ability to predict the variation of all properties as a function of "shelf life". Single fiber bending strength will be needed for handling and fabrication purposes.

1.2.2 Interface Problems

The interface is a region of microscopic or molecular dimensions between two phases (e.g., reinforcement and matrix) which have different physical or chemical properties. Its influence on the properties of a composite are profound, particularly in thermal environments, where conduction and/or thermal stresses must be considered. Since the interface integrity is a function of the fabrication process, it follows that the latter must be controllable to a degree necessary to assure acceptable bonds. Deterioration due to time or environmental exposure must also be taken into account. Many of these problems have been considered in Reference 4.

1.2.3 Micromechanics To Describe Macromechanical Properties

If any composite is to be used as a "structural material", its macroscopic properties must be available or predictable. This suggests that two courses are open to the designer. On the one hand, he can select from existing composites whose ply properties* are known and whose multiple-ply behavior is known. On the other hand, the great variety of composites which can be formed from a given fiber and a given matrix, and the intuitive appeal of being able to "tailor" a composite to the specific application at hand tempts one to postulate that ultimately the prediction of composite material properties on the basis of a well-established micromechanics theory will be an inherent part of the design process. Depending on the time and money available to a project and the degree of structural refinement demanded, some structures will be made from a composite whose ply and multiple-ply properties are known and well substantiated by test or actual use and others will be "tailored" for the specific application, requiring "design" at the micromechanics level and a substantial test program to confirm the predicted material properties.

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*Properties of a lamina of filament and matrix, one layer of reinforcement thick, which characterize that layer as if it were quasi-homogeneous.

The latter approach presages a close collaboration of structural designer, expert in solid mechanics, and materials engineer, with extensive use of large-scale digital computers, and extensive testing. Similar situations, of course, will arise when there are deviations from uniform composite properties, such as joints, cutouts, and attachments. Thus, the Committee considered the possible merit of a catalogue of ply properties for "known" composite materials, sufficiently complete to provide as much flexibility as possible in his selection of materials while at the same time limiting development costs.

1.3 Predicted Advantages

It is, by now, widely known that filaments of various materials can be made which exhibit excellent properties for many applications; glass, boron, graphite, beryllium, silicon carbide are among these. The strength-to-weight ratio for some of these materials in filamentary form can be made about an order of magnitude larger than the common structural materials such as steel or aluminum alloys. The stiffness-to-weight ratio can be four to five times that of the more conventional structural alloys. For boron and graphite, at least, both advantages accrue to a significant degree. Strength/density and stiffness/density ratios for representative filaments, composites, and metals are shown in Figure 1.

The proper combination of these filaments with appropriate binders to form structural components can lead to dramatic savings in weight and/or otherwise unattainable increases in performance. Weight is a determining factor in all aerospacecraft and some classes of submersible and surface vehicles. Stiffness-to-weight ratio is crucial in certain applications, and stiffness, per se, is dominant in others (examples are cited in later paragraphs). And sometimes strength, stiffness, and weight all enter, as in determining the maximum allowable rotational speed of a centrifuge of given size. The use of different fibers in the same composite structure, e.g., glass in the direction where tensile strength is critical and boron where stiffness governs, can often be advantageous. The superior properties of the advanced filaments, therefore, promise improvements in many applications,

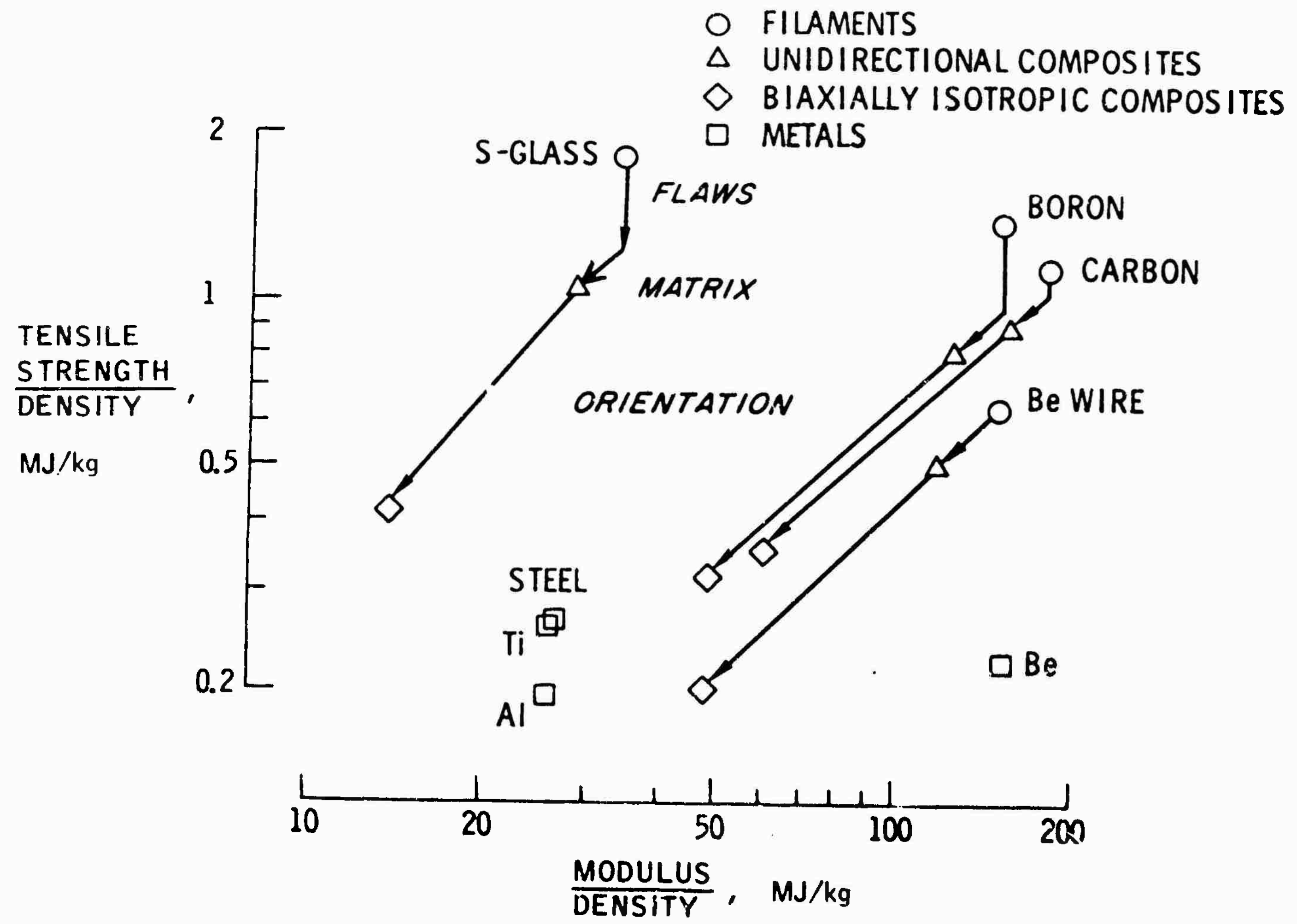

Figure 1. - Specific strength and stiffness of currently available filaments, composites, and metals. (From Fig. 2 of Ref. 20, by permission of the author.)

if the composite structure can be designed and fabricated to utilize the filament properties efficiently. It is also true that some of these materials which can be made structurally attractive only in filamentary form often have other properties of considerable utility; these include, for example, electromagnetic wave cross-section and coefficient of thermal expansion.

The directional nature of a composite formed from filaments is both a blessing and a curse -- and this will be discussed at greater length in the following paragraphs. One primary problem is in achieving the necessary strength and stiffness properties transverse to the filament axes; another is the transfer of loads in the axial direction from filament to filament, where there are changes in cross-sectional characteristics.

1.4 Review of Structures Which Would Profit From The Use Of Fibrous Composites

A number of studies have been made which show that for a wide range of structural applications the use of fibrous composites will lead to improvements in performance, savings in weight, or entirely new capabilities. Reference 5, for example, showed that for a number of aircraft structural applications advanced fibrous composites such as those utilizing boron and graphite filaments not only have the potential for substantial savings in structural weight, but further, that such new materials appear to offer the only immediate prospect of such improvement. Reference 6 indicated a similar potential for boost vehicle shells, and References 7 and 69 for deep submergence vehicles. Indeed the potential of fibrous composites has been extensively surveyed and many areas of advantageous application have been found.

1.4.1 Directionality and Strength

In general, fibrous composites are anisotropic, and this provides the opportunity to design the material as well as the structure. Reinforcements can be aligned with major load directions and be limited in minor load directions. Hence, greatest gains for the use of fibrous composites accrue when the loads to be carried are high and primarily in one direction (Ref. 8). In this case, however, one of the most difficult problems is getting the load into the structure. An application such as a ring under pressure is one example where full advantage can be taken of filament strength in a highly aligned composite. Consider a ring-stiffened cylindrical vessel capable of resisting high external pressures; here the reinforcing rings are loaded primarily in hoop compression. These rings are ideally suited for a highly oriented fibrous composite and can readily be fabricated by the filament winding process.

The concentration of highly-oriented fibers also benefits the spar caps used in the wing or tail beams of aircraft; these are generally loaded primarily in axial compression or tension. Directionally orienting the fibers in flat composite leaf-spring applications has also been proven to be extremely efficient; a similar application has been the use of composites for the landing struts of light aircraft.

For multidirectional loadings of any consequence, fibrous composites require multidirectional filament orientations, with consequent lessening of their advantages over metals of inherent isotropy. A simple illustration is afforded by a spherical pressure vessel; here, for a fibrous composite to provide a weight advantage, it must have a tensile strength-to-density ratio more than double that of a competitive metal because the filaments must be aligned half one way and half perpendicular thereto to accommodate the biaxial stresses in the shell. It has, moreover, been found that the orientation of fibers in the radial direction in spheres fabricated from glass-reinforced plastics has benefits for deep submergence applications (Ref. 70). A more favorable multidirectional load example is provided by a cylindrical pressure vessel in which membrane forces away from areas of discontinuity are twice as high in the circumferential direction as they are in the axial direction. This is readily accommodated by orienting the fibers during fabrication in a "two circumferential , one axial" configuration throughout the thickness, thereby producing material strength properties that agree closely with those necessary to carry the induced loads. Other examples include wing structural panels where fibers can be oriented axially to carry compression and tension loads caused by spanwise bending, at 45° to carry shear loads caused by torsion, and at 90° to carry loads caused by transverse bending across the chord.

1.4.2 Stiffness

The high stiffness-to-weight ratios available with reinforcements such as the boron and graphite fibers provide a major advantage by overcoming one of the long-standing limitations of glass-reinforced composites. Wherever buckling, static or dynamic deflections, or vibrational frequencies are critical, new possibilities exist. Examples include some which are almost directly dependent on modulus-to-weight ratio, e.g., static "droop" of a nonrotating helicopter blade, critical speed of thin-walled shafts, etc. The composites can now be designed, furthermore, to be compatible strainwise with a number of metals, and hence combined metal-composite structures can be considered more feasible than in the past. This can be especially advantageous in areas where joint and scaling problems exist.

For many aerospace applications, especially for spacecraft, structural index values (i.e., load intensities) are low; and here, too, the design criteria may be governed more by high stiffness than strength. Progress for space vehicle uses is being made, however, even with current composites. Through recognition of the need to capitalize on the unidirectional properties of the filaments, and proper design of the composite structure (Ref. 9), the composite is being made more competitive with beryllium and other materials for a wider range of applications, and concurrently, of course, the margin of improvement is being increased over conventional metals such as the aluminum alloys. The exacting requirements for composite design in this area are most evident; when properly executed the present fibrous composites appear attractive for spacecraft. Newer filamentary materials, such as the better graphite filaments, and improved binders will continue to enhance their relative attractiveness, inasmuch as corresponding developments in uniform, homogeneous bulk metals are not in evidence.

1.4.3 Structural Damping and Fatigue

Totally apart from strength and stiffness, fibrous composites make accessible a number of new material characteristics, heretofore unavailable, which lead to entirely new types of structural performance. These characteristics become available first, because of the wide range of matrix and filament material properties which may be effectively combined in composites, and second, because of the anisotropies which may be designed into the composite. Advantage may be taken of the differences in stiffness between filaments and binders by developing composites with high internal damping for vibration and shock applications.

Here the essentially visco-elastic response of the complaint binder material may be utilized in transferring load among the filaments to absorb energy and aid in damping-out the propagation of shock waves or vibrations of the structure as a whole.

Experiences in recent years have made it clear that resonant vibrations cannot be completely avoided even by clever design. Hence, the designer must use damping to minimize vibratory amplitudes, and thus reduce the susceptibility to fatigue failure. In many cases, however, external sources of damping cannot be employed and "material", "structural", or "internal" damping is the only source of energy absorption. Composites can display good internal damping characteristics, and yet also possess good fatigue properties. The basic fatigue strength is superior to metals, and composite susceptibility to the effects of stress concentrations such as those caused by notches, holes, etc., is also reduced as compared to metals or other homogeneous materials (Ref. 10).

One application of composites which may be favored because of internal damping considerations is for skin panels in areas of high noise intensity, where acoustical fatigue is a problem. Such areas include wing trailing edges, fuselage sides near jet nozzles, and empenage structures.

Another application for which internal damping is a primary consideration is sonar domes. In this case noise reflection, transmission and absorption are prime factors in the selection of the dome material.

1.4.4 Thermal Characteristics

The inherent anisotropic nature of filamentary composites is ideally suited to the control of thermal characteristics. Thermal conductivities may be tailored as desired, both by choice of materials for filaments and binder and by choice of reinforcement pattern to conduct, disperse, or block the flow of heat. Hollow filaments may be used to provide channels for cooling gas, or nonstructural (e.g., copper) filaments may be added in judicious patterns to provide thermal paths in desired directions. Perhaps even more important is the control of thermal expansion available to the designer, again by selection both of material and reinforcement pattern. Thus, for example, Reference 11 showed that even without special materials a wide variety of thermal expansion coefficients could be obtained, even approaching zero if desired, by choice of reinforcement pattern. Relative differences between the coefficients of expansion of filament and matrix, of course, can result in local thermal stresses and strains which must be considered in defining the total stress state including fatigue.

1.4.5 Electromagnetic Properties

Further evidence of the new latitude made available to the designer by filamentary composites is the control of electromagnetic properties. The use of hollow fibers, proposed in Reference 12, for radar transparency has yielded improved reinforced plastic radomes for search aircraft, by combining the advantageous strength characteristics of hollow filamentary materials with their low-loss response to electromagnetic radiation.

1.4.6 Ease Of Forming Complicated Shapes

Because of the various molding and winding techniques which can be employed in fabricating composite structures, it seems likely that large complicated shapes can be produced in essentially one operation. There are, at present, some difficulties with undevelopable surfaces, but these can probably be overcome. Integral stiffeners, metal inserts, thickness variations, and local reinforcements can all be formed integrally with the component, greatly reducing the number of parts involved and eliminating or minimizing joints.

Shapes that can be easily attained in the filament winding process include cylinders, spheres, conics, oblates, and prolates, and to some extent, combination of these shapes. In the vacuum bag, autoclave, hydroclave, and press molding processes, complex double-curved shapes can be fabricated with local buildups, reinforcements, and flanges as desired. In some cases, edge trim and cutouts can be accomplished during the molding cycle. In addition, sandwich structures can be molded with composites using a one-stage process, thereby minimizing bonding operations and reducing assembly time.

1.4.7 Ease Of Fabricating With Built-In Stresses

Built-in or residual stresses distributed so as to be relieved by applied loads are a well-established means of increasing structural efficiency. Fabrication variables capable of producing desired pre-stress magnitudes, directions and distributions are available to a greater extent in the filament composites than perhaps any other structural material.

One example of how residual stresses can benefit a design is provided by the thick-walled external pressure vessel. In this case, under normal pressure loads the compressive hoop stress distribution across the thickness results in higher stresses on the inner surface than on the outer surface. Therefore, the fabrication process is designed to produce tensile residual stresses on the inner surface and compressive residual stresses on the outer surface. When combined with the applied stress distribution, a more uniform net distribution results across the thickness providing a vessel capable of resisting higher external pressures without collapse.

1.5 Economics

The price of filamentary materials was alluded to in the preceding section. While it was not intended that this study treat the economics of composite design, some remarks are desirable to place the design problem into perspective.

One is likely to attempt to justify the cost of exotic raw material in terms of the "value" of the weight saved. Such evaluations of weight savings, however, will usually be done assuming "substitution" of parts made of the expensive advanced material for heavier, conventional parts on the existing system.

The benefits of designing with composite structures from the outset are more subtle and require cost-effectiveness analysis of complete systems before they can be completely assessed. Using aircraft as an example: if the structure is made of boron composite, it will be substantially lighter. Thus, the lifting surfaces may be smaller, landing gear strength reduced, and the engine(s) less powerful. For a given mission, less fuel will be needed. All of this means that the gross weight savings will be greater than just those which accrue in more efficient structure. But this is not all. A smaller, lighter aircraft is historically easier to maintain. Ground equipment, such as jacks, tows, and workstands can be smaller. Less fuel results in reduced logistic burdens. Size has an effect on detectability and vulnerability. These and other considerations can have a major effect on comparative 10-year system costs.

Finally, fabrication and tooling costs, given the complex shapes of most modern structures, may well be significantly less for composite structures than for those using conventional materials. It seems likely that inventories could be simplified a great deal, and that plant space devoted to inventory storage may be less. These last considerations are, of course, speculative. They are noted here only to emphasize the many ramifications which warn against oversimplified views of designing with composite materials solely in terms of material costs.

1.6 Usage In Production Systems

As observed in an earlier MAB report, Reference 13, composites will be used in those applications where their value for the function to be performed exceeds that obtainable from other materials. The value judgment will include considerations of performance, money, and time. In some cases where performance dominates, composites will be used where it can be shown that the performance required of the end item cannot be achieved without the use of composites.

At the present time, in the military aircraft field, both the manufacturer and customer are reluctant as regards the large-scale use of composites; the former because of having to risk competitive position in proposing departures from proven low-risk designs which are generally acceptable to the military; the latter because the uncertainties inherent in a new design and materials technology can jeopardize the success and delivery schedule of a multi-million dollar development and procurement program. This reluctance can be reduced by reducing the risks.

One approach toward this end is to invest development funds into designing and building a reasonably large quantity of substitute parts of filamentary composite construction to be used on a production system, to gain operational experience. An example of such a program is the Air Force plan to provide boron-epoxy composite outboard wing slats for one side of ten C-5A aircraft. The operational use of some reasonable number of components fabricated from filamentary composites has two advantages in addition to those which are related to giving project managers confidence as to the readiness of the technology. First, even in limited numbers, operational use is likely to uncover unsuspected environmental problems, should they exist. Secondly, even a nominal number of production-type components if they are actually in use as part of an operational system will increase the incentive of material producers to minimize the prices of filaments and matrices potentially useful for composite structures. Providing such funding from R&D resources will require imagination and a determined effort on the part of R&D managers.

A second more direct approach to overcoming the reluctance of manufacturers and procuring agencies as regards the use of structural component is as follows: Specify that some part of a system being developed--one naturally, for which the use of composite structures has clear advantages--be designed and fabricated using filamentary composites. Sufficient planning and additional funding will be required in such a case to carry a second, backup design using more conventional materials for the subject components. Tests and decision points must be scheduled so that immediately upon receiving strong evidence that the timeliness or cost of the system under development is being seriously jeopardized by the use of the advanced composites, that development can either be abandoned or relegated to an R&D basis, and the conventional design carried on at top speed. Similarly these checks should be planned so as to minimize the expense of the "insurance design", and eliminate that expense, as soon as the success of the filamentary composite components is reasonably sure.

2. DESIGN CONCEPTS AND APPROACHES FOR COMPOSITE MATERIALS APPLICATIONS

2.1 General

The conceptual or design-approach phase is critical in the design process. It is the step that blends judgment, creativity, and technology. Since in most cases the structure does not exist except as a requirement, it is not inhibited as to materials or configuration.

With conventional materials the designer begins with a concept and then, after the basic materials and configuration are selected, utilizes intricate analytical treatment to obtain a preliminary evaluation of the concept.

The designer who considers using composites, however, is faced with both the additional freedom, and the responsibility, of designing both the material and the structure. He must not only determine the external geometry of the component or structure, but the "internal geometry" as well. Motivation to consider and to develop design concepts utilizing composites will depend initially on his background and whether he has an open-minded attitude toward these new methods. Given the proper attitude, objective comparison of composites with other materials on the basis of performance parameters can follow. Thus, design with composites should entail a number of steps in which the interrelated behavior of materials and structure is continuously involved. This is certainly a different procedure than that normally used in design with conventional structural metal alloys, at least regarding the degree of material-design interrelationship. It is an aspect of the design problem that is not widely recognized by designers unfamiliar with composites; and, being interdisciplinary in nature, it tends to narrow the field of qualified personnel.

2.2 Status Of Conceptual Methods

Although parametric studies of structures to define performance requirements for materials have been used in some research studies, they are only beginning to be considered as a first step in design. Most effort today employs an evolutionary process wherein particular materials with outstanding properties are considered only as replacements in existing components. In future situations, the designer's consideration of the use of composites could be facilitated by recourse to certain parametric studies which were developed to identify areas where composites provide an advantage.

A detailed understanding of the micromechanics aspect of the material is not necessary in the design concept phase, as long as reliable tests are made available to give feed-back data to the designer. As research in analysis progresses to the point where analytical procedures for prediction of characteristics for particular composites forms are reliable, analyses can be substituted for some of the preliminary tests.

A "structural index" (Ref. 14) and a weight parameter can be combined to allow materials to be compared with regard to desired or required structural characteristics. In References 9 and 15 this method is developed with variations to show where certain composite materials can be matched advantageously to certain basic structural configurations. In general, it is shown that a high structural index is necessary to utilize composites efficiently. A very low structural index may also indicate applications where composites of the flexible type may be useful. Such methods serve as a first design clue to the consideration of composites in structures.

However, since the structural index approach is preliminary, it does not represent the multiplicity of functions a structure must provide. It also does not include any of the fabrication considerations which strongly influence design. Reference 16 shows that composites are not necessarily most efficiently applied as gross quasi-homogeneous materials over the entire structure. Quite often the material and configuration are tailored to produce a "lumped" reinforcement concept as discussed in References 8 and 9.

Advanced designs will often use concepts in which composites incorporating more than one kind of filament are used and/or where both homogeneous materials and composites are combined. Reference 17, for example, describes a system of overwrapping metal high pressure tanks with glass filaments and resin to achieve high-efficiency structure and increased reliability. In this case the entire design reflected both optimized shape and selection of compatible materials to achieve the desired efficiency.

A simple case illustrating the parametric approach is shown in Reference 18 which combines several material properties into a single parameter to compare, on a normalized basis, materials for an elevated temperature application, a large flexible rotor for reentry. This comparison showed that the vehicle could be designed advantageously with composites.

In the case of a vehicle whose external assembled form is primarily determined by aerodynamic requirements, the designer may be forced to start with a given geometry for large portions of structure. However, even here, there are cases in which deviations from assumed or wind tunnel-determined forms yielded improved structural behavior with negligible penalties for aerodynamic performance. An example is discussed in Reference 19.

For space applications, the designer has more freedom for creating concepts where the external form of the structure may be varied to better interact with new material arrangements. For example, spacecraft designed for reentry and using expandable or deployable body portions made with composite materials actually yield greatly improved aerodynamic and structural characteristics. These are discussed in Reference 20 by Heldenfels, who shows that this may be an area of undisputed advantage for filamentary composites. It is in this area where very low stresses and the ordinary "minimum gage" limitations force consideration of new material properties. Another example of this is a design concept for a large, orbital low-frequency radio telescope, described in Reference 21. This design employs a slender central mast or column 820 meters long, less than 3 meters across, and carrying an axial compression of 1.5 lbs. An additional requirement was that the column could be packaged in a length of 7 meters. The design chosen was an open lattice made of glass filament-epoxy resin composite rods, which provided both low density for efficiency and flexibility for packaging.

While the examples cited above are illustrative of concepts for application to the over-all structure, other examples can be described showing concepts which apply to details of the structure. Some of these are illustrated in various sections of Reference 22. A detailed approach is also described in Reference 16. Here an "elemental" approach is used wherein individual structural components are isolated as to structural function and then designed, using boron composites, to perform that function. The method recognizes, however, that an integration of systems and structural functions is possible, so that certain members may act as fuel, air, or electrical conduits, for example.

Research studies such as those referenced herein have evaluated the potential of certain composites in a gross sense and in terms of structural parameters. More studies oriented toward the conceptual phase of design using hypothetical or real applications would be valuable, and the results of such studies should be well distributed and read.

In order to produce engineers capable of making such studies and detail designers able to implement the results when they suggest composites, college engineering courses in materials and structures should include introductions to polymers, other nonmetals, and composites. This training would help establish an 'openminded awareness' from the beginning of an engineering career. It should also continue at the professional level with the necessary emphasis on those aspects of materials, design, or fabrication with which the professional in his organization may be concerned.

2.3 Development of a Fabrication Concept

The design concept should also consider fabrication aspects explicitly. Composite material structures are manufactured using processes quite different from those used for metal structures. As the designer progresses from basic loads and envelope restrictions to detail design configurations using composite technology, the development of a fabrication concept should evolve simultaneously with the development of the design. In most cases, it is difficult to establish the detail design configuration without first thinking of a fabrication concept with which the part can be built. The designer may often limit or restrict the consideration of a fabrication concept by his selection of shape and the basic weight and mechanical property performance requirements. For example, if a cylindrical configuration with a high strength/weight ratio is chosen, the composites engineer is likely to think automatically of the filament winding process. If a large, double-contoured part is conceived, with low void-content and rigid mechanical property control specified, an autoclave molding process utilizing cut prepreg patterns would normally follow. These examples illustrate how, in the case of composites, the development of a fabrication concept should be an integral part of the basic design determination. A specific example of this process is given in Reference 71. Thus, the designer must have an appreciation and understanding of composite fabrication technology to conceive of a practical and feasible design. As a minimum, the composites designer should be well aware, during the conceptual stage, of the peculiarities of the particular fabrication methods his shop can or does utilize, so that trade-offs may be considered. The fabrication concept development generally involves detailed analyses and laboratory experimentation to establish the most practical approach, identify critical operations, and prepare a fabrication specification. Process variables must be investigated and, in most cases, subscale and full scale prototype parts fabricated to insure the feasibility of a given fabrication concept.

If conducted simultaneously with the development of the structural design, a practical composites fabrication concept can be developed which will provide the desired balance of structural performance, cost, available facilities, and contract schedules.

2.4 The Role Of Tooling

From the foregoing discussion, it is clear that the development of design and fabrication concepts has a profound influence on the selection of the tooling approach and vice versa. Such factors as shape, size, contour surface control, tolerances, cure, and postcure temperature and pressure requirements, trim, drilling, and assembly procedures all influence the selection of the tooling concept. Most important, however, is the fact that tooling used in composite fabrication has a direct influence on the basic material properties.

Often, undesirable residual stresses can be built into the part by improper tool material selection and design, whereas a proper understanding of the problem can result in beneficial residual stress distributions that may enhance the part performance. Shrinkage, resin flow characteristics, fiber placement and control, fiber pretensioning, debulking, and cure staging factors must be appreciated by the designer to insure a tool design that will function satisfactorily to produce the desired composite end product. Hence, the tooling approach also plays an important role in the development of a product design that will meet a given performance criteria.

Other important considerations in the selection of a tooling concept include the quantity of parts to be produced, funds available, and the schedule to be met. To assure a feasible evaluation, prototype tooling must be representative of production tooling. Unless sufficient funds and effort are devoted to proper tool design and construction, the best product design and fabrication concepts have little chance of success. All too often development programs are plagued with tooling problems that derogate an excellent product idea causing it to fall by the wayside. Hence, the importance of proper tooling cannot be overemphasized in the development of a new composite concept.

2.5 Conclusions

There appears to be a large gap between conceptual design approaches and the detail design of a structure and its composite material. Whereas it is unlikely that the creative function of the designer can ever be prescribed, more guides to selection of materials and methods should be developed with the intention of making this creative function easier.

Much effort is needed in the education area. The undergraduate college curricula, as well as graduate and professional phases, have only begun to present applicable subject matter with emphasis commensurate with the promise of composite structures and in only a very few universities. An obvious place to start is within the college curricula and then continue into the graduate and professional phases.

Design with composites calls for a new combination of disciplines among designers. Experience with materials and fabrication methods as well as structural design methods is likely to be required.

3. ASSESSMENT OF THE STATE OF THE ART

3.1 Tools For Design

3.1.1 Macroscopic Composite Materials Properties

The magnitude of this problem is suggested by the fact that in place of the two elastic properties (Young's modulus, Poisson's ratio) which define homogeneous, isotropic materials, five elastic constants are needed for unidirectionally reinforced composites (two stretching moduli, one shear modulus, two Poisson's ratios), nine elastic constants for symmetrical, multidirectionally reinforced composites, and as many as twenty-one elastic constants for unsymetric reinforcement arrays. Further, the elastic properties are the simplest to determine; the vital strength, and stress-strain response characteristics which must be the basis of reliable design are more difficult to measure or even categorize.

3.1.1.1 Test Method Development

The determination of the macroscopic material properties of composites, essential for design, requires the development of new and improved test techniques. Test standards long accepted as routine for ordinary homogeneous materials are totally inadequate for composites. In this assessment of the state of the art, a complete, detailed review of the deficiencies in current methods of testing for all material properties is out of the question. Rather, an attempt will be made to show the urgency of the situation by implication through a rather detailed discussion of the problems associated with the measurement of the tensile strength of composites. Ultimate tensile strength has long been the standard material property for the design engineer by which he selected and characterized materials for design purposes. For years it has been measured by the standard 0.505 or "dog-bone" tensile test specimen. As will be shown, such a specimen is completely inadequate except possibly for the simplest, unidirectionally reinforced composites, and the presently unsettled state of composite tensile strength measurements is one of the areas critically in need of improvement. Rather complete assessments of composite material property test techniques other than those used for tensile testing have been made. Examples are References 7, 23, and 24. Suffice it to say here, these show that in general the situation is worse for other properties than for tensile strength, even to the extent that often it is not clear what property is sought. This lack of clarity, typified by "inter-laminar shear" testing, has sufficient implications for design to warrant discussion in this section along with tensile testing.

3.1.1.1.1 Measurement Of Tensile Strength

There are essentially four methods by which the tensile strength of composites is currently being measured:

1. Modified "dog-bone" type specimens.
2. NOL ring-type specimens.
3. Thin-walled cylinders under internal pressure.
4. The tension surface of a sandwich beam in bending.

Reference 25 recognizes all except the last of these methods; Reference 22 only the first and the last. All of these methods have drawbacks, and no standard has yet evolved. Flexure testing is not considered here as a method for determining tensile strength. It is the consensus of the Committee that flexure tests for this purpose are generally misleading.

Data acquired to date should be regarded as preliminary for the following reasons:

a) For advanced, high modulus filamentary composites there exist no reliable standard test methods.

b) The art of processing composites is new for at least the advanced systems and only in a few examples do different facilities actually produce identical laminates from the same incoming materials.

c) Complex test specimens, such as wide specimens (Refs. 26, 27, 28), have been developed which do not produce the stress field reported; hence, the data are inconclusive.

"Dog-bone" specimens -- The problem with dog-bone specimens is primarily associated with end-reinforcement to preclude "grip failures" or the introduction of local stress concentrations. For filamentary reinforcements parallel to the axis of the specimen, the problems are minimized and grip failures can generally be avoided by the use of cemented-on reinforcing tabs, as recommended in Reference 22. These tab-reinforced, unidirectional specimens are probably the least unsatisfactory of any for composite tensile testing. Unfortunately tensile strength data must also be obtained for other than the filamentary direction, and the dog-bone, because of edge and width effects, is unsuited for use when the filaments run transversely. The dog-bone is also not amenable to fabrication by filament winding.

NOL-ring-type specimens -- The Naval Ordnance Laboratory ring was devised as a simple specimen for filament winding and testing in an ordinary testing machine. Analysis (Ref. 7) shows that substantial bending moments develop at the edge of the loading fittings during test, however, and while these can be reduced (at the penalty of increased manufacturing complexity) by elongating the ring into a race track shape, they are not eliminated. Another approach to avoiding bending is to load the NOL ring with a uniform internal pressure using a device such as that described in Section VIII-A of Reference 29. Furthermore, of course, the ring does not contribute to establishing strengths other than in the filamentary direction.

Pressurized cylinders -- Pressurized thin-walled cylinders have been used successfully for tensile testing (for example, Refs. 30 and 72). Potentially, such specimens offer the greatest promise. When testing in a combined-load machine while subjected to internal pressure, they permit determination of strengths in any direction relative to unidirectional reinforcement. Machines capable of applying the desired loads, axial plus torsion, unfortunately are not presently available as standard equipment. Cylindrical specimens are also suitable for filament or tape winding and for testing multidirectional reinforcement configurations.

In addition to suitability for tensile strength determinations, they are useful for measuring all elastic constants and the "failure surface" for combined stresses. Development of standardized specimens of this kind, including the associated fabrication techniques and testing equipment, is required before it can be determined whether the full potential of this specimen can reasonably be achieved.

Sandwich beams -- Sandwich beams, also more complicated to construct than "dog-bones" or NOL rings, do permit tensile testing for both unidirectional and angle ply composites. The properties of the core material must be altered for different facing properties and a set of standard beams for any composite strength or stiffness has yet to evolve. A sandwich cross beam has also been developed to study biaxial and shear stress states. A summary of the sandwich beam development, still a somewhat controversial approach, may be found in Reference 31.

In summary, tensile testing of composites must be considered as still evolving. The fact that the fundamentally attractive, pressurized cylinder specimen is receiving little emphasis (it is not even mentioned in Ref. 22, for example) is perhaps an indication that without substantial theoretical support and thoughtful direction the evolution of satisfactory tensile test methods for yielding adequate design data will take a long time.

3.1.1.1.2 Measurement Of Other Properties

Test methods for properties other than tensile strength are generally less advanced than those for tension. Shear testing cannot be made to yield reliable design values with short beams such as the "interlaminar shear" specimen of Reference 22. Torsion loading of tubes is more desirable. Compression testing requires even better end-support conditions than tension and even more careful specimen and test design to insure that an intrinsic material property rather than a specimen instability is being measured.

Further discussion in more detail, such as has been done above for tension, would simply emphasize the shortcomings of present procedures and the need for substantial additional research directed toward improved techniques. Until composite material property test techniques have improved sufficiently to supply reliable data, satisfactory structural designs will probably be achieved only through prototype test and subsequent redesign.

3.1.1.1.3 Conclusions

In the execution of test programs aimed at improvement of techniques, careful attention should be given to the following points:

1) All test data should be accompanied by a thorough description of the test specimen, including the method of manufacture.

2) All specimens should be thoroughly analyzed, both theoretically and experimentally, to insure that the stress state is known and intrinsic properties are measured.

3) As acceptable specimens emerge, a set should be standardized to allow better materials comparisons. Correlation of independent test techniques is very important during the period of confidence and standards development.

4) A point that should be kept in mind is the danger of applying test results from specimens fabricated by one technique in the design of parts that will be fabricated by another technique (see Section 3.2).

3.1.1.2 Theoretical

The ability to describe mathematically the load-deformation characteristics of a material as a function of environmental conditions is the basis of rational structural design. Whereas control of the volume content, physical properties and geometry of the physically distinct constituents which make up a composite has clear advantages, it also adds a new dimension to the design problem and the required mathematical description of the gross properties is much more difficult.

As mentioned earlier, both micromechanics (the study of the composite properties through constituent properties and constituent geometry) and macromechanics (the study of the composite properties under the assumption of quasi-homogeneity) have been studied previously by the Materials Advisory Board (Refs. 13 and 32). Recent and current developments in these fields, however, warrant some additional study, and the pertinence of both disciplines to the problem of structural design needs to be addressed.

3.1.1.2.1 Micromechanics

The micromechanics problem may be subdivided into two general areas: a) the consideration of problems for which the constituents may be assumed linear (stress-strain, time and temperature) and b) problems involving nonlinear constituents. The linear micromechanics problem is, of course, the one for which useful solutions would be expected to exist. Even in the linear case, however, the effect of time-dependent material properties has not been assessed. Some essential theoretical analyses of a general nature have been reported in References 33 and 34. The non-time dependent, linear case is discussed first in the following paragraphs.

Elastic properties of composites in the direction of the reinforcement have been found to be essentially as predicted by the "rule of mixtures" (Refs. 35 and 36). The elastic and strength properties transverse to the filaments and in shear, however, cannot be predicted as reliably. A unidirectional composite, stressed uniaxially transverse to the filaments and in shear, has been attacked by a number of investigators as recommended by the Materials Advisory Board (Ref. 32). The approaches to the transverse case assumed a perfect, doubly periodic array of filaments, i.e., periodic in two directions, and include finite differences (Ref. 37), finite elements (Ref. 38), stress functions (Ref. 39), and collocation (Ref. 40). In general, these various analyses provide uniform results but poor agreement with the test data and therefore, by themselves, are inadequate for design.

The shear problem has been attacked using finite differences (Ref. 41), stress functions (Ref. 42) and finite elements (Ref. 43). Elastic properties are in good agreement, but again the strength is not accurately predicted with sufficient accuracy for design purposes.

Two other works of interest are the extension of the computation of elastic properties to three dimensions (Ref. 15) and a proof (Ref. 44) that, for an arbitrary composite material under plane deformation, the stress-state is a function of only two independent elastic constants (for bonded and smooth interfaces plus interfaces with friction).

Definition of the stress-strain response of a composite with nonlinear constituents has only recently begun. Computation of the shear stress-strain curve with a matrix modeled by the Ramberg-Osgood equations is presented in Reference 43. Although a unidirectional composite, stressed in the direction of the filaments was analyzed in Reference 45 including the effect of matrix plasticity, an accurate model for the strength of a composite material with nonlinear constituents remains undefined.

The design of a composite structure, of course, may proceed without the addition of micromechanics to the design process. In fact the first highly efficient structural use of composites, in filament-wound pressure vessels, depended only on "netting analysis"* in the structural analysis and design of the structures. The environment and constraints which dictate the design of pressure vessels are much simpler than those defined for complex advanced systems. The need for a continuum model for composites has become necessary to analyze composite structure properly.

It has been noted that the majority of contractors performing current advanced composite programs have determined a need to utilize anisotropy in the design of composite structure. This usually manifests itself as the use of filament orientation as a continuous design variable. The willingness of the designer to introduce anisotropy through orientation into the design problem is indicative that it may, in fact, eventually come to pass that the design of the material will be part of the design process. Before this will become practical, several goals must be achieved; namely, a) digital computer-aided design to remove the tedium of the many calculations which would be necessary, b) refinement of the theoretical micromechanical tools, and c) accumulation of supporting experimental data.

For immediate application of composites, an experimental materials characterization will be necessary, because the available theories will not allow the confident prediction of composite properties. However, even the present imperfect micromechanical analyses provide an important tool for the reduction of acquired data and the identification of the modifications needed for material performance improvement. In short, the links between micromechanical analyses and product design are in thorough materials characterization and development.

Micromechanics is usable today as a means for tailoring constituent volumes as loading demands are changed for some filament-binder applications, assuming that at least one or two binder volume-fractions are characterized.

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*Analysis which accounts only for filament strength in its axial direction, neglecting all matrix contribution to composite strength.

3.1.1.2.2 Macromechanics

Macromechanics may be divided into the general categories of: a) the definition of the appropriate constitutive relationships for combinations-orientations of composite materials, plus b) the definition of the failure modes for the same combinations-orientations of composite materials. Two sections in the recent state-of-the-art review by the MAB (Ref. 32) were devoted to macromechanics; one under the title, "Macromechanics", the other in a section titled "Laminates".

Most of the recent work has been formulated utilizing Love's first approximation for defining the strain-displacement equations. This may be traced chronologically in References 46, 47 and 48. Even though the resulting plate and shell equations have not been solved in general, and few approximate solutions are available, the basic constitutive equations are in wide use for the definition of laminate stiffness properties. It is now common (Refs. 31, 49, and 50) to have the equations programmed for a digital computer and available to aid the designer in the evaluation of stress in a single lamina for given laminate stresses or strains. The ability a) to reduce the computational tedium associated with this problem in laminates consisting of anisotropic layers, and b) to determine gross laminate properties from lamina properties is essential to the development of a composite design technology.

An extensive literature review of available strength theories, both yield and ultimate, was cited in Reference 51. The author concluded, after reviewing thirty-one pertinent articles, that:

1) Most theories were primarily mathematical.
2) Experimental data were not obtained in a manner or quantity which could be related to mathematical models.
3) Apparently little experimental-theoretical correlative effort was indicated.

The majority of the theories reviewed dealt with computation of yield or the onset of inelastic action in a lamina or laminate. The existence of a yield surface (Ref. 52) has recently been questioned because it has been experimentally observed that for a thin, orthotropic lamina of boron epoxy, the shear stress-strain curve is continuously nonlinear.

Nonlinearity has also been observed for time dependent behavior. It has been observed (Ref. 53) that for an 0-90 degree crossplied glass-epoxy, tested in uniaxial tension at the reference axes and at intermediate angles to the reference axes, that as the loading axis approaches 45 degrees to the reference axis, nonlinearity was significant and at a maximum. For the 45-degree loading axis, a 0-90 degree crossplied material has deformation dominated by the reference axis shear stress-strain behavior (Ref. 52).

The development of macromechanical mathematical models, both for constitutive equations and failure theories, is a necessary task in the development of rational design procedures for composite materials. While micromechanics may be circumvented by macroscopically characterizing the composite a macroscopic modeling technique is necessary to formulate a mathematical model for a structural element. These models must be verified with experimental work so that they can be regarded as something more than speculation. Mathematical simplicity is desirable, but with the current availability of digital computers, is not necessary.

3.1.1.2.3 Conclusions

Micromechanics research should be continued in the areas of:

a) Inelastic stress fields.
b) Failure mechanisms and modes.
c) Nonuniform arrays.

Considerable attention needs to be focused on the testing required to obtain reliable data. The minimum test data necessary to characterize a plane sheet of composite material consists of the longitudinal, transverse, and shear properties for the lamina. Such data are also very helpful in providing accurate micromechanical correlations. Thus, if properly executed, the tests necessary to support component development programs can also contribute to the data necessary to enlarge the scope of the composite material design process.

Macromechanical analysis efforts should be continued until mathematical tools are available, verified, and in a form suitable for predicting the effect of the following situations accurately enough for design purposes:

1) Stresses and strains for:
   a) Static linear behavior (conservative).
   b) Static nonlinear behavior (conservative).
   c) Dynamic loadings (vibratory, impact, and other transient effects).
   d) Thermal environment.
2) Failure theories under:
   a) Static loadings.
   b) Dynamic loadings (fatigue, impact, and other transient effects).
   c) Thermal environment.

A concerted effort is necessary to provide the needed tie between theoretical and experimental efforts at the microscopic level. Attention should be directed toward maintaining wide communication among the various hardware developments, obtaining guidance from specialists, and requiring periodic evaluation from external sources.

3.1.1.3 Accumulation Of Data

Much of the data accumulated so far is unaccompanied by adequate description of test methods. Reliable interpretation to allow characterization of constituent materials for design purposes is, in such cases, impossible. Even with greater fastidiousness, the acquisition and organization of well-accepted data on composites will be slow, for a number of reasons:

1) Materials are still being evolved--matrices particularly, as well as interface improvements. Even good data rapidly become obsolete.

2) Processing can have a major effect on properties; e.g., through collimation, spacing, voids, hardening failures, temperature-pressure processing time histories.
3) Uncertainty as regards standard test specimen and test techniques.
4) The vast number of possibilities (e.g., volume fraction, filament orientation, numbers of plies, edge effect) reduces duplication in testing, so that the rate of accumulation of corroborative or statistical information is retarded.
5) The difficulty and comparatively primitive state of theoretical analyses inhibit prediction of property data, interpreting test results, and correlating test results--especially those performed by different organizations.

One substantial attempt to establish a design handbook for filamentary composites has had only very limited success (Ref. 22). It has emphasized the necessity of having designers--that is, people charged with the task of conceiving and fabricating useful hardware--intimately involved, if not responsible for, the preparation of such manuals.

3.1.1.3.1 Conclusions

Reasonable progress will be made only with a strong and continuing effort of considerably greater magnitude than that customarily applied for conventional materials.

3.1.2 Structural Element Behavior

3.1.2.1 Theoretical

A substantial portion of the structural design process has traditionally been carried out assuming linear elastic static behavior and treating more complex behavior subsequently as deemed necessary. Dynamic and thermal response are being considered more frequently in structural design, but still within the framework of linear behavior. Thus the following discussion will emphasize the aspects of static linear macrostructural analysis which predict stress and displacement distributions as an essential part of structural design. Although an attempt will be made here to summarize only a) the status of the analytical efforts performed to date, and b) the implications of most important results, a rather complete review of this field is included as Appendix A.

Fundamental structural elements may be considered to include frame members, membrane plates, plates, membrane shells, and shells. Frame members are understood to be those with two dimensions small compared to a third; plates and shells are flat and curved structural elements, respectively, capable of supporting bending and with two dimensions large compared to a third (i.e., the thickness). Membrane plates and membrane shells are simply plates and shells which, for practical purposes, carry no moments through their thickness.

Many applications of composites to beam and truss type structural elements (i.e., frame members) require only slight modification of conventional methods of analysis. Some progress has been made, but general and reliable methods for dealing with frame members constructed of anisotropic materials are not available. As a minimum such methods must account for the coupling between the axial loads, bending, and torsion that is likely to exist for minimum weight frame member designs. These effects will require reexamination of instability failure modes.

In the analysis of plates made of laminates of filamentary composites, it has generally been assumed that linear line elements perpendicular to the plane of the underformed plate remain straight and perpendicular to the tangent to the deformed plate. Thus, strains are assumed to vary linearly through the plate.

Tests are needed to validate this assumption or establish limitations on its applicability. As in the case of frame members, plates whose laminations are not elastically symmetric about a mid-plane through the plate thickness will have coupling between bending and membrane action. When equilibrium equations are based upon the deformed geometry, nonlinear terms arise even though the strain-displacement and stress-strain relations have been assumed to be linear. In many cases it may be necessary to consider finite deflections, thus introducing additional nonlinearity through the strain-displacement relations. These nonlinearities as well as the influence of initial imperfections lead to substantial computational difficulties. It is noted that initial imperfections must be carefully considered in both analyses and tests, since a) truly flat, balanced laminated plates are difficult to fabricate, and b) initial imperfections lead to bending deflections even when only membrane loads are applied.

A number of important cases have been dealt with in the literature. For example, numerical methods and computer techniques have been used to obtain stress and deflection predictions for plates exhibiting linear bending-membrane coupling, neglecting initial imperfections and stability considerations. Solutions useful for predicting buckling loads of flat, orthotropic balanced-laminate plates with various boundary conditions subject to compression, shear, and combined compression and shear are available. Predicting the buckling loads of balanced, anisotropic plates is a more difficult problem, since it takes the form of a general Eigenvalue problem, but it has been dealt with adequately. However, some further study of methods for handling prescribed moment and shear boundary condition is needed. The influence of known inplane loads on the behavior of balanced anisotropic plates subject to transverse loading can be handled adequately using existing numerical techniques; however, here again further study of methods for dealing with prescribed moment and shear boundary conditions is required. For balanced plates subjected to multidirectional loadings of sufficient magnitude to require many plies in several (at least two) directions, it may often be possible to simplify the analysis task substantially by treating the laminate as an equivalent homogeneous (isotropic or orthotropic) plate. For those lightly-loaded elements where composites of relatively few plies may suffice, current analysis capabilities must be significantly extended, especially as regards bending membrane coupling, initial imperfection effects, and finite displacement considerations.

Anisotropic shells have received considerable attention, for cases where the bending-membrane coupling is either nonexistent or negligible. Pressure vessels, however, as perhaps the most successful application of filamentary composites to date, are the most amenable to analytical design. Since they may be treated as statically determinate membrane shells, the membrane force distribution is independent of the stiffness distribution and the fiber orientation can be selected directly on the basis of carrying the known loads more efficiently. "Netting analyses", which assume that the matrix has no strength at all, have been carried out with considerable success, leading to designs which approach the state of being uniformly stressed, called "isotensoid".

The design of externally-loaded pressure vessels, for example, deep-submergence submarine vehicles, requires that prime consideration be given to buckling failures. Here a considerable literature dealing with the elastic stability of orthotropic shells can be drawn on, so long as the structure can be considered symmetric through the shell thickness (i.e., balanced laminae). Recent work on cylindrical shells subject to axial compression suggest that pseudo-isotropic filamentary arrays are best for resisting buckling. Where membrane-bending coupling, as due to unbalanced laminae, cannot be ignored, it is likely that it will be necessary to include pre-buckled bending response in shell stability studies.

The numerical methods used to obtain solutions for the complex equations generated by anisotropy and coupling among axial, bending, and torsion behavior often have as their basis the use of idealized structural elements. The latter are mathematical "building blocks" which can be "joined" to represent a continuous structure. Planar membranes and frame members are frequently used. Several flat triangular and quadrilateral discrete elements suitable for the static elastic analysis of fiber composite structures have been developed. Uncoupled bending-membrane behavior has been assumed within these elements and most of them have been generated within the framework of the displacement method of structural analysis. As would be expected, displacement predictions with these methods are generally superior to stress predictions.

It is likely that many of the current gaps in the ability to analyze composite material structural components will, at least temporarily, continue to be filled by the generation of computer programs based on numerical methods. Further effort will be required to provide operational static structural analysis capabilities useful to the designer, that:

1) include linear bending-membrane coupling for unbalanced laminates.
2) include nonlinear strain-displacement relations (for postbuckling load displacement behavior).
3) predict stress distributions with sufficient accuracy.
4) avoid modeling shell structures with flat discrete element idealizations.

In filamentary composites a much greater difference is likely to exist between tensile, compressive, and bending properties on the one hand, and shear properties on the other; the former are supplied by the fiber and the latter by the matrix. This means that transverse shear effects are likely to be more pronounced than in equivalent structures using isotropic materials. The likelihood of having adjacent laminae with vastly different elastic properties in a composite probably aggravates this situation further. Thus, transverse shear deformations may have to be considered more carefully in structural design using composites.

Finally, it should be noted that sufficient work has been done in the analysis of laminae with membrane-bending coupling to show that this is more than just an effect to be considered in predicting the macroscopic response of the particular structural element in question. For example, the critical stresses through the thickness in such cases are not necessarily at the extreme fibers, nor are bending curvature and moment related by a simple constant of proportionality.

Furthermore, it will frequently not be apparent where the maximum deflection will occur and establishing the location (with respect to planform and through the depth) of the critical combined stress state will in the general case require further study.

3.1.2.2 Experimental

Experimental work in composite materials to date has essentially centered on the proof testing of representative components and the evaluation of new constituent materials. A large amount of experimental data is available in both company and Government reports on such topics, subject to the limitations discussed earlier in Section 3.1.1.3. A comprehensive summary and evaluation of experimental investigations of filament reinforced plastics for deep submergence applications is given in Reference 73. References 54 through 57 are typical reports on the testing of prototype fibrous composite structures.

Very little experimental effort has been devoted to the understanding of the macroscopic response of orthotropic structural elements. Experimental data on general anisotropic structures exhibiting both in-plane shear/direct-stress coupling and bending-membrane coupling are nonexistent. References 58 through 62 are representative of the types of programs that should be conducted for a complete verification and understanding of the constitutive relationships and the structural response of composite materials.

Reference 63 is cited as an example of progress being made in the development of nondestructive testing methods for providing quantitative material/energy interaction response indications that can be correlated with mechanical properties. As capabilities increase in the field, the use of NDT techniques to measure actual properties of the composite material composing the structure, as part of experimental structural testing will enhance verification and understanding. Further discussion of NDT techniques as they are used in end item testing is contained under Section 3.3.3.

3.1.3 Joint Analysis and Design

3.1.3.1 Theoretical

The theoretical problem of macroscopic load transfer is closely related to the theoretical task in Structural Element Behavior. Here the element becomes a detail of the component, but many such elements must comprise the whole. The complexity of these analyses has been such as to require substantial time and dollars, and unfortunately, the accuracy of the results has often been in doubt. Past design techniques, therefore, have been largely empirical even for metals. It follows that composites-oriented joint development to this time has also been primarily empirical. Theoretical analyses have been developed, however, for special cases; these include the analysis of stress distributions in bonded joints. An annotated bibliography of both mechanical and bonded joints is given in Reference 64. Also, the Goland and Reissner lap joint analysis (Ref. 65) has been programmed for a digital computer and is being used to aid data reduction and interpretation (Ref. 64).

The majority of examples found in the literature (Ref. 64) employ elasticity solutions of a closed form for the analysis of stress distribution in joints. Recent programs (Refs.64, 66, and 67) have used finite elements to model the complex loads and boundary conditions encountered with pin-loaded and bonded joints. Finite element techniques appear to have considerable promise for obtaining solutions with the complexity (anisotropy, complex boundary conditions) encountered in composite joint analysis.

Analytical techniques in structural synthesis have also been applied to the problem of joint design using multiple metal inserts for composite metals (Ref. 67).

The problem of designing a joint for composite materials is among the most critical factors in the development of this technology. Mathematical analyses are always desirable because of the flexibility they provide. Certainly the evaluation of joint efficiency would be more easily and inexpensively performed, as new materials are developed and characterized, if a reliable joint analysis were available. Even if the analyses of composite joints cannot be developed to the point of providing accurate absolute structural response, they could still prove valuable in interpreting the results of tests. Such aids are almost certain to be required, since tests are likely to involve the large numbers of variables typical of joint design with composites.

3.1.3.2 Experimental

The testing of composite structural joints that has taken place is predominantly in the class of empirical measurements of gross failure loads, with--unfortunately--little attempt to correlate the stresses predicted by the advanced analytical procedures with the actual stresses in the failure area. Of the many reasons for this, the most significant is a lack of adequate techniques for measurement of stresses (or strains) on a very local basis, in the vicinity of the load-transfer area. This is not a completely new problem. The need to understand load-transfer in metal structures has been a driving force in establishing the field of experimental stress analysis, and techniques exist for solving most of such problems. These techniques provide the basis for investigations of composite materials, but do not provide a direct solution.

Most methods used for metals assume linear, elastic behavior and homogeneous, isotropic materials. Even where they have been successful in the plastic region, they assume homogeneous behavior. Many of the successful techniques involve measuring external strains (i.e., strain gages, stress coat, etc.) and the ability to extrapolate these strains to the interior of the structure.

Composites do not readily fit the assumptions and criteria associated with metals. Their anisotropy is a problem in itself, since the materials used for conventional photo stress (i.e., frozen stresses) are isotropic. Modeling of composites not only requires anisotropic materials but the directional properties must be in the correct relationships. Composites are much more likely than metals to be used in applications where they exhibit nonlinear behavior at low strains.

There have been some notable successes in the application of experimental stress analysis to composites. A number of investigators have established the relative strain relationship between the matrix and the fibers under various loading conditions and these techniques are readily extended to the bond lines between simple lap joints. Simple models simulating the two elements of composites, the plane of the fibers and the plane of the matrix have been useful in showing relative load paths. However, these studies have been confined almost entirely to the microanalysis of the composite itself. Practically nothing exists in the literature on load transfer of complex real structure such as encountered in cutouts, concentrated load attachments, change in load paths from element to element, etc.

In brief, there has been essentially no significant experimental work in load transfer of real composite structures. The lack of experimental verification of load transfer techniques and analysis methods is likely to be a major roadblock in the broad application of composites to primary structure.

The importance of load transference, and its corollary, load introduction, is clearly demonstrated by the history of honeycomb structure. The potential of this type of construction was recognized many years ago, with clear advantages promised over more classical structures. However, it has taken many years to capitalize on this potential, due to an inherent difficulty in transferring the load to honeycomb structure without negating the weight advantages.

These difficulties are now demonstrated by present attempts to design primary aircraft structure using advanced composites. Statements to the effect that, "The primary stress and deflections were as predicted but the part failed at less than design load due to premature failure at load introduction or load transfer points." are common in the literature.

The need for a capability to predict analytically the performance of load-transfer structure has been discussed in the preceeding section. Perhaps paradoxically, this requires experimental proof of the analysis techniques. If experimental data are not accumulated, design conservatism in load-transfer areas may neutralize the weight advantages promised by composite materials. This problem is particularly severe in aerospace composite applications. The generally increasing complexity of systems will almost certainly lead to increasing access requirements for assembly, equipment, and maintenance in the future. All of these involve the use of load-transfer mechanisms of some type.

3.1.3.3 Conclusions

Development of empirical data and methods for designing efficient load transfer structures should be continued. Theoretical analyses should accompany these empirical development programs. Emphasis should be placed on data-analysis correlation to develop confidence. Specific areas needing research concentration include:

1) Reinforcement of cutouts
2) Joints
   a) bonded
   b) mechanical
3) Concentrated load introduction

An intensive program should be initiated for applying experimental stress analysis techniques, and the structures community should be alert to opportunities to develop such techniques and the appropriate associated instrumentation suitable for complex composite structures, with particular emphasis on load transfer areas.

Design studies to establish proven load transfer techniques need to be accelerated and extended; these should deal with structural problems as encountered in real systems.

Studies to determine the effects of defects (i.e., partial voids, non-uniform fiber content, etc.) on load transfer need to be undertaken. These should encompass the nature of the performance degradation, elimination of the defect and means of minimizing its effect short of eliminating the defect.

3.1.4 Integrated Structural System

3.1.4.1 Analysis

Because of the added complexity of design with composite materials, the development of automated techniques for accomplishing virtually all phases of the design-analysis cycle is necessary. This is certainly true for the integration of various components into a structural whole. While assumptions as to the location of optimum solutions (simultaneous failure modes) suffice in some instances for pre-design judgments, the problems caused by multiple environments, multiple loadings, and the possibility of failures off the primarily-loaded axis because of highly anisotropic material properties dictate the development of better techniques. Structures using composite materials are not, however, being developed in a design vacuum and some contemporary techniques being developed for complex design problems in metals might prove to be adaptable.

Techniques such as structural synthesis (Ref. 68) or improved man-machine communication in computer-aided design should be vigorously researched. Much progress has been made in automated design, and exploratory efforts to apply structural synthesis concepts to design with composites are under way (Ref. 2). However, much development and training of engineers will be necessary to make the automated techniques available for the average designer's repertoire.

The integration of automated design techniques, and the subsequent evaluation of these techniques, should be encouraged in hardware development programs.

3.1.4.2 Test

The need for testing integrated structures stems from a) the load transfer problem at joints, and b) uncertainties regarding the relative stiffness of components comprising the integrated structure and hence the distributions of loads among them. It is rarely sufficient to test only components, even with metal structures. For composites, of course, the joining of one part to another particularly where more than one material is involved, can be relied upon only after a test program which is commensurate with the anticipated operating conditions. Furthermore, the complexity of such problems will probably preclude the use of scaled models as a final demonstration of the structural integrity of a design. It follows that structural substantiation of composite structures will be a costly matter, --as it is for metallic structures. High costs are associated both with fabricating the test structures, in the facilities investments, and in performing the full-scale structural tests. Accordingly, this type of testing will normally be limited to evaluating the capability of a specific design to perform its intended mission.

The nature of composites makes the attachment of equipment, control surfaces, actuators, secondary structures and the like considerably more critical than it is in the case of isotropic materials. A composite structure optimized for major structural loadings, which include only small-magnitude loads "off-axis", may become overloaded in the off-axis direction by an inconspicuous load associated with some non-primary structural item which happens to be attached to it. Greater care than is now taken to test a complete major structural assembly, therefore, may be required with structural composites.

All this is not to say, however, that sub-assemblies and small-scale sub-assemblies are not useful. In fact, the majority of integrated composite structures work has been and undoubtedly will continue to be of this kind. Box-beam work with GFRP (glass fiber reinforced plastics) has been conducted at the Aero Structures Department of the U. S. Naval Air Development Center; development of a two-thirds scale bending spar-torsion box with boron-epoxy skins for the F-111 tail was carried out under a USAF Materials Laboratory program. Such efforts are useful to show the applicability and/or limitation of fundamental structural component data and of simple specimen (small coupon) test data, particularly as regards fatigue properties. It is also necessary to provide the correlation of such sub-assembly and/or small scale test data, with those from complete, full scale tests.

3.2 Fabrication Processes

3.2.1 General

With composites, "fabrication" generally includes an important step in the preparation of the structural material. Thus, the fabrication process plays a particularly critical role in the appearance and performance of the end item, and the selection of an appropriate process is an important consideration in design. Adequate process development and prototype fabrication, utilizing experienced personnel must be accomplished before acceptable production parts can possibly be produced.

Basically, the current fabrication processes involve a form of either winding or molding. The winding process can be considered to include filament winding, tape winding, and cloth winding or wrapping. The molding process generally consists of a hand or automated layup followed by a vacuum bag, autoclave, hydroclave, or matched tool press molding cycle. Secondary fabrication operations may include machining, post-curing bonding, coating, and assembly to other components.

Some of the considerations in the selection of a fabrication process follow:

a. Quantity of Parts - Is the process to be capable of high production? This also influences the tooling selected.

b. Quality Required - This generally determines the selection of materials as well as the fabrication process, and includes structural performance, surface requirements, and dimensional control.

c. Size and Shape of Parts - This has a great influence on the selection of the fabrication process. The winding process appears to have definite shape limitations and the size of part influences the type of tooling and molding process, depending on the available facilities.

d. Cost Restrictions - The cost of a metal item with which the composite is competing can influence both material and process selection.

e. Schedule Restrictions - A short delivery schedule will limit the time available to obtain certain types of tooling and facilities, and hence, will influence the fabrication process selection.

f. Past Experience - Past experience and the availability of capable personnel and facilities are certain to have an influence on the approach taken by the various fabricators.

The development of specific designs will require the designer to acquire intimate knowledge of fabrication capabilities and to maintain a close working relationship with the materials and manufacturing engineers. A brief discussion of the principal processes available is contained in Appendix B.

3.2.2 Conclusions

The techniques for fabrication and repair and their influence on the design of structure for desired properties and predictable integrity will require an extensive and continuing research and development effort to fill in the existing gaps in knowledge and experience and to resolve problems that arise as the technology of composites progresses. Some of the technology gaps and problem areas and the kind of research and development effort needed are described hereafter.

3.2.2.1 Automatic and Controlled Process Techniques

It appears that handwork in the fabrication process will have to be minimized if uniform high quality is to be achieved. Filament winding and prepreg tape layup machines are steps in the right direction; however, automation should be extended to sandwich composites, bagging and cure operations, and subsequent adhesive bonding procedures. Equipment should be developed which effectively assures rigid quality control while establishing a production process capable of rapid and consistent fabrication at minimal cost. Extending filament winding techniques to a greater variety of shapes may also produce beneficial results. It seems clear that anticipation of automated techniques will have an influence on the designs proposed for composite structures.

3.2.2.2 Attachment and Joining Techniques

Additional effort is required to develop a better understanding of the action of fasteners used and planned for use with advanced composites. Unique problems concerning minimum edge distances, end distance, diameter/thickness ratios, fastener patterns, spacing and joint failure modes need to be investigated.

New attachment concepts that will assure high joint efficiency by properly introducing loads into the reinforcing fibers need to be developed. For each new concept, fabrication problems associated with drilling, countersinking, fastener installation, etc., must be investigated to prevent delamination and guarantee that close tolerances can be held.

3.2.2.3 Residual Stresses

Residual stresses in composites should be studied to develop a better understanding of the role played by shrinkage, fiber orientation, fiber pretensioning, fiber compaction, and resin flow. The effect of variables such as filament size, shape, spacing and filament and resin moduli should be studied. Both the beneficial and deleterious effects of residual stresses must be understood before they will be satisfactorily predicted during design and controlled during fabrication. The problem of residual stresses will become even more severe as the thickness of the structure increases for applications such as deep submergence pressure hulls. To advance current knowledge in this regard, subscale and full scale structures should be fabricated and tested to determine scale effect on shrinkage and residual stresses.

3.2.2.4 Repair, Rework and Sealing

Local repairs or rework techniques will have to be employed to some degree, especially in the case of very large hardware items. Structural evaluation of techniques presently associated with glass reinforced plastics will be required before such techniques can be applied to advanced composite primary structural components. New techniques uniquely suited to the advanced composite will have to be developed in many cases.

Edge and surface sealing techniques will have to be developed, especially in the application of composites to long-life deep submergence structures. Work with glass composites has shown sealing to be a critical problem, particularly when structures are subjected to cyclic pressure loads for extended periods. The sealant must be compatible with the composite under biaxial and triaxial loading conditions and be especially resistant to abrasion, corrosion, and wear.

3.3 Quality Assurance

3.3.1 Raw Material Control

In most cases, the organization responsible for design and fabrication of fiber composite end items will procure the raw material in the form of fiber or filament, resin system, or prepreg, from vendors. This is accomplished by procurement specifications that define limits for the properties and characteristics known to be related to the quality of the end item. Conformance is determined through sampling, inspection, and test by vendor, or purchaser or both. These matters are essential to competent structural design. Brief discussion of pertinent aspects as regards filamentary composites is contained in Appendix C.

It must be concluded that, in general, the current capability to specify, measure, and control raw material variables is not adequate to assure uniformity of quality in the end item. Additional research is needed to establish better understanding of the effect of raw material variables on the fabrication processes and on the quality and performance of the end item so that more effective specifications can be prepared. Procedures and methods for sampling, inspection, and test should be developed with the objective of assuring that raw materials conform to specifications. Continued developmental work should be encouraged to control material variables during the prepreg operation through the use of equipment that can make the measurements dynamically and continuously.

3.3.2 New Part Quality Control

Typical defects to be controlled are:

- Interlaminar voids caused by air entrapment, blistering, resin pockets, gaps, delaminations, etc.
- Wrinkles or ridges caused by compaction, improper winding, tension, mismatching, etc.
- Orientation misalignment of skin plies or core.
- Unacceptable joints in skin plies or core.
- Foreign material or inclusions.
- Matrix void content and porosity.
- Uncured or incomplete resin cure.
- Damaged filaments.
- Buildup and thickness taper locations.
- Discoloration.
- Drill and fastener damage.
- Machining and trimming errors.
- Unbonded areas in adhesive joints.

3.3.2.1 In-Process Control

Meticulous quality assurance measures must be imposed during fabrication to control the numerous in-process variables. Because the design details of a particular end item will have a strong influence on the details of the fabrication process, the in-process quality control measures required for each part will have to be carefully studied and planned during the design/fabrication development, and the design may be modified to conform to the existing quality assurance technology. Several aspects of in-process quality control are discussed in Appendix D.

Through rigorous in-process quality control techniques, fabrication defects can be minimized. Realistically, however, some of the above defects will be present in completed parts. In such cases, critical areas will have to be defined and acceptable tolerances or limits established on the size, nature, and number of defects allowed. Where acceptable limits are exceeded, parts will be either scrapped or reworked by detailed and controlled repair techniques.

3.3.2.2 Conclusions

Additional research and testing is required to study and measure the effects of defects on the properties and integrity of fiber composites; this is re-emphasized in the following section on Nondestructive Testing. It is important that development of rework and repair procedures be based on the results of research and testing concerned with the effects of defects, and on the same high standards of engineering as those employed in developing the design and the fabrication processes. Quality control techniques should be incorporated more completely into in-process quality control monitoring so that defects can be detected early enough to prevent the rejection of parts after considerable materials and fabrication costs have been invested.

3.3.3 End Item Testing

The statistically unavoidable possibility of defects in a finished part obviously leads to the requirement for end-item testing. As an example of practice in one industry, destructive and nondestructive tests (NDT) are presently performed on all types of helicopter roter blades, and some of their subassemblies (i.e., faring assemblies) to assure that all critical characteristics are in accordance with prescribed engineering requirements. The sampling plan that is normally used is to randomly select a blade out of every 100 blades manufactured. However, on new production blades, until a sound statistical history has been established, the rate is one out of every 50 blades. The following is a list of the characteristics for which tests are performed on the random sample, along with the methods used.

Characteristics	Test Methods
Adhesive Beads	Visual
Voids	Visual
Glueline Thickness	Magnetic and Eddy Current
Porosity	Visual
Bond - Trailing Edge Strip to Box	Physical to Failure
Bond - Trim Tab to Trailing Edge	Physical to Failure
Bond - Box to Spar	Physical to Failure

It is noted that the above tests are in addition to comprehensive in-process inspections which are performed throughout the fabrication cycle to assure the integrity of the various materials, processes, and subassemblies. Some of the areas covered are those discussed in the preceeding sections; e.g., in-process control of adhesives, solution control, heat and pressure surveys, etc. These combined with the regular inspection methods are the normally applied quality control disciplines employed on all rotor blades.

3.3.3.1 Nondestructive Testing (NDT)

Nondestructive testing takes on additional importance in the quality assurance of components fabricated with composites. It has been noted that "the material is made with the making of the part", so that the probability of voids, disbonds, inclusions, etc., is greatly increased. Moreover, the internal structure of the composite prevents the use of conventional NDT methods or forces major modifications in such methods. A survey of NDT methods currently used to test advanced composite materials and a few of the more promising techniques which have been studied for future applications, is presented in Appendix E. These are listed and briefly commented on as follows:

Coin Tapping - easy and quick, but insufficiently accurate, therefore of limited usefulness.

"Crackling" Tests - Detection of sounds generated by the composite material itself when placed under load, with the unaided ear or listening devices, has provided a qualitative indication of composite behavior in some applications, notably pressure vessels.

Ultrasonics - widely used inspection technique for voids or unbonds and delaminations. Several different techniques are available, they are generally quite sensitive, often require highly-trained personnel and sophisticated fixtures, but in some cases lend themselves to automation.

Infrared - still in developmental stages, current limits include some maximum depth or thermal conductivity of the laminate; now capable of sensing voids, future systems may measure resin content, degree of cure, glueline thickness, etc.

Radiography - Radiography and fluoroscopy are successful in defining fiber orientation, honeycomb core damage, etc. Advanced versions will include x-ray sensitive vidicon and image intensifier systems. In an exploratory stage is neutron radiography for bond line structure measurement.

Microwave - these techniques promise to monitor the chemical composition of the nonmetallic components as well as their voids, delaminations, etc.

Eddy-sonic -	for composites in which one constituent is metal; generates sound waves which can be analyzed, hopefully, to determine structural quality.

3.3.3.1.1 Conclusions

1) The adequacy of the resolution provided by commercial non-destructive test equipment currently available is a controversial subject among various researchers active in the field. Many methods for improving sensitivity have been suggested in the literature, but most involve nonstandard modifications. A specific research effort is needed to establish minimum performance capability acceptable for use of NDT methods for quality assurance.

2) The literature indicates that, technically, the best NDT results for fibrous composite structures would most often be obtained by a combination of ultrasonics and radiography; the ultrasonic test for delaminations and voids and the x ray for fiber breaks and misalignment.

3) Extension of the function of nondestructive testing from the detection of defects to the determination of actual physical properties of composites would be of major assistance in design as well as in assuring conformance of the finished part to design properties, and is badly needed. Interesting work in this field has been described in Reference 63.

4) More research into the applications of the more promising new techniques, such as neutron radiography, eddy sonics, and microwaves, is needed.

5) The majority of fibrous composite nondestructive testing has been performed on simple sheet specimens with parallel fiber orientation. Application of NDT techniques to more complex geometries should be investigated.

6) Much more correlation between NDT results and failure data should be attempted for the purpose of defining defect criteria. Unless meaningful criteria for the various kinds of defects which are peculiar to composite materials are established, there is little reason for further refinement in NDT resolutions, with perhaps the following exception: There has been little or no work done to develop NDT methods capable of detecting such defects as wrinkled fibers or residual stresses, both of which can seriously degrade the ultimate strength of the composite.

3.3.3.2 Failure Testing

Failure testing is a necessary part of the quality assurance procedure for any composite structure for the following reasons:

a) Production tolerances can be compared with design tolerances.

b) The quality of workmanship may be examined.

c) Internal defects may be detected which have escaped nondestructive detection.

d) Material strengths are obtained which may be compared with design strengths. This is a most important feature of failure testing since, at present, nondestructive test methods do not yield quantitative strength results.

e) An objective correlation is provided between the nondestructive test results and the actual physical condition of the structure. This fact may be used to establish defect criteria by failure testing components which have previously been nondestructively tested.

In short, because the state of the art in NDT is not adequate to establish actual strength, destructive tests and proof tests will be required for some time to come. It would be worthwhile to establish general criteria and specifications for destructive testing and proof testing as a function of component use, critical nature, redundancy, and fail-safety characteristics.

3.3.4 Integrity In Service

In-service inspection is necessary to detect incipient failures in critical structural components. In a broad sense, in-service inspection techniques may employ any of the nondestructive techniques used in the detection of defects in new parts. Ultrasonic techniques, for example, (Ref. 75), have been used successfully to determine the effect of cumulative damage on the fatigue life of external pressure vessels. In practice, however, component accessibility and equipment portability usually limit the use of these methods. Often a detailed visual inspection is the only recourse. Unfortunately, composite defects may not always be as easily detected visually as defects in corresponding metal components.

Integral fail-safe systems are sometimes used in conjunction with conventional nondestructive testing techniques. This is, of course, a matter for consideration at the earliest stages of structural design. In contrast with conventional inspections which are usually performed at some prescribed interval, the fail-safe mechanism maintains a continuous check on the structural integrity of a part. Fail-safe systems are being developed which utilize the special properties of fibrous composite materials. The most notable of these is the incorporation of crack wires in the layup of composites which have a nonconducting matrix. The wires are electrically energized and when excessive deflections are experienced, the circuit is broken. When the composite consists of metal fibers with nonconducting matrices, the composite fibers themselves may be used as crack wires. The same principle is used in the application of conducting coatings to nonconducting composite components.

The ultimate success of composites clearly will depend upon their ability to perform reliably in use. The materials, as a class, provide a significant potential in fail-safe systems and better long-term integrity than metals. These characteristics have been only partially exploited. Active programs are required in:

a) Development of procedures for in-service inspection which will assure continued structural integrity.

b) Development of fail-safe concepts which are applicable to and exploit the unique characteristics of composites.

4. SPECIFICATIONS

Three general questions concerning specifications may be addressed, as follows:

1. What is the role of specifications in the design of structures with fiber composites?
2. What is the current specification situation in this field including major problems?
3. What can be done to improve the situation?

4.1 Definition of Terms

The specifications of concern are those used to control the procurement of weapons systems of all kinds and personal equipment. Customarily such procurement is controlled by a family of specifications, or specification "system", consisting, in most cases of a general specification which in turn invokes the application of hundreds of other specifications, standards, handbooks, technical orders and notes, drawings, and other reference documents.

We have considered, for example, the specification system used in the procurement of aircraft; other specification systems for ships, ordnance, missiles, etc., follow a somewhat similar pattern. Included are: the Federal, the MIL-Specifications, and MIL-Handbooks, the specifications of the individual Services (Army, Navy, and Air Force), specification series of professional societies such as the AMS series, and very importantly, the contractors' specifications.

The subjects covered include: the end-item weapons system (general and detail specification), design criteria, materials, processes, test methods, technical data, inspection, and significantly, form and subject matter requirements for the preparation of contractors' specifications, which will be subject to Government approval, for subjects not covered by Government specifications. It will be observed that this last subject (for contractors' specifications) renders the specification system open-ended to embrace new technology as it evolves.

4.2 The Role Of Specifications

The primary role of specifications is to establish the technical agreement between the procuring activity and the contractor as to what is wanted and what quality will be accepted. Among the other roles of specifications, the following are cited as significant in the context of this study:

- Specifications serve as effective instruments for organizing and evaluating new data as they accumulate.
- Developing and using a new specification helps to identify gaps and deficiencies in the technology.
- Specifications provide the basis for a Qualified Products List certifying quality and performance.
- Specifications foster and facilitate test method standardization.
- Specifications provide an efficient means of disseminating information to secondary industry (transmitting technology to subcontractors).
- Specifications provide an efficient communication device between those concerned with advanced systems development, with supporting technology, and with fundamental research,--and between individual disciplines within the technology area.
- Specifications provide a convenient means of identifying and referring to a particular material, process, or test.

Thus, specifications serve not only procurement but also the effort to develop advanced materiel and techniques.

From the foregoing, it follows that successful application of composites in weapons-systems structure will depend to a considerable extent on the availability of suitable specifications. While the over-all effect of the specification control of composites will be the same as for other materials, the technique of control will probably be somewhat different due to the unique nature of composite materials. While there is likely to be some usage of "stock" composite material in the form of rod, sheet, tubing, etc.--covered by a specification similar to specifications for metals--and some MIL-specifications giving representative properties for glass laminates, much, if not most of the high performance composite material used in primary structure will not be of the "stock" category. Since the in situ properties are not known until the part is designed and fabricated, the Government specification is likely to be constrained to deal with the constituent fiber and matrix materials, the fabrication process, and the means of inspection and testing. Methods proposed by the contractor for acceptance will almost certainly require more elaborate explanation and justification than for metal practice, at least for some time.

It should be noted that the general problem of controlling the use of a new material is not new. The specification systems already provide for the introduction of new materials, including composites. Nevertheless, composites cannot be considered merely as a new aluminum or titanium alloy not yet defined by specifications. The special nature of the composite material properties, i.e., "tailored" to provide the desired structural behavior of the part, will largely preclude the preparation of materials specifications for composites equivalent to materials specifications for standard materials such as metals.

4.3 Current Status

It is likely that specification control for composites will be provided through modification of, and addition to, existing systems of specifications. A brief survey of the aircraft system of specifications indicates that a start has been made but much more work remains to be done. A similar situation appears to prevail with respect to other weapons systems.

4.3.1 General Specifications (Such as the Handbook of Instructions for Aircraft Designers and SD-24)

Although the current general specifications allow the use of composites, there is little information given as to what kind and amount of information the contractor should offer to justify his composite design and construction for a particular application, or how the information should be presented.

Revision of the general specifications to clearly state the Services' requirements for the information needed from contractors to approve a given design using composites is in order. This would facilitate communication and control. These requirements should be the same for Army, Navy, and Air Force.

4.3.2 Detail Specifications

Until the specifications systems as a whole are expanded and modified to accommodate composites, many of the requirements pertaining to composite structures will be written into the detail specifications, thus making them an important instrument of control of new applications.

4.3.3 Material Specifications

Material specifications for the constituent materials, fiber and matrix, represent the one area in the specification systems where specification control is exercised for composites in the same manner as for other materials.

MIL-specifications exist for some constituent materials such as glass fiber, yarn, tape, and cloth, and for various polymeric matrix materials. There are also MIL-specifications for the composite fabricated from constituent materials such as glass cloth or mat with polyester, epoxy, and phenolic resin. These specify properties for the composite based on a low pressure laminating process. MIL-specifications also exist for sandwich core materials (foam, honeycomb) and the composite structure resulting from the use of these materials in conjunction with faces of glass/resin laminate.

There are as yet no MIL-specifications issued for the high-modulus fibers. Although preparation of MIL-specifications would be pointless for many of the advanced fibers now in the developmental stage, such work should be undertaken as soon as it is clear that a fiber can be useful. The AMS-series specification now in preparation for boron filaments, the existing contractors' specifications, and the materials requirements written into other documents, provide a good start in this direction.

In the preparation of material specifications, emphasis should be placed on characterization of the materials. Lack of this is an overwhelming handicap to reliable analysis of composite behavior and to reproducibility.

4.3.4 Process Specifications

There is some MIL-specification control of processes for fabrication of glass laminates. Specifications such as MIL-P-17549B (Ships) provide for qualification of contractors' processes. However, since the process used for the fabrication of parts from composites is directly and radically affected by many factors, including the configuration of the particular part, the constituent materials, the proportions and arrangement of the constituent materials, the equipment and facilities, and the quality control requirements, it is difficult to establish MIL-specification process control of very broad applicability. The Services can contribute very significantly to the effectiveness of control through the contractor's specification by maintaining up-to-date requirements covering the form, scope, and content of the contractors' process specifications. MIL-P-9400B is an example of the kind of specification that is intended to serve this purpose. Preparation and maintenance of these specifications should be carried out in close collaboration with industry organizations who are actively engaged in structural applications of composites. This seems to warrant concentrated effort by the Services.

4.3.5 Acceptable Materials Properties for Design

The Committee believes that the general scheme of providing uniform data on the allowable stresses and other related properties of materials and structural elements, as exemplified by MIL-Handbook 5, will find only limited application in the case of fiber composites.

MIL-Handbook 5 data apply to specific materials defined by procurement specifications. These materials are available to any contractor, and their properties are established by test methods which are standard or at least accepted with a high degree of confidence. Similar data, e.g., MIL-HDBK 17 and 23 can be established for the "stock" class of composite referred to previously and for some noncritical or very conservatively designed composite material structure. The composites of high structural efficiency, however, are designed to provide the properties desired for a particular application and the properties and quality actually achieved are strongly influenced by the fabrication process. For one contractor to use the properties of another contractor's composite material, it would be necessary for him also to duplicate the fabrication process; in many cases, where the structure has a unique shape, for example, this will probably not be possible. The need to establish design values for composites similar to MIL-HDBK 5, e.g., MIL-HDBK 23, is probably a real one, so long as it deals with frequently used composite configurations of well-defined fabrication processes. Beyond this, such a task should, at least for the present, be given relatively low priority.

On the other hand, the Committee recognizes the need for efficient means of disseminating information on properties that have been achieved in specific applications, especially for the benefit and encouragement of those who are considering the use of composites in high performance structure for the first time. For such purpose, the most suitable document may be a handbook of the type now under preparation (Ref. 22) or MIL-HDBK 23, oriented to information rather than specification requirement. A specification guide for presentation of composite materials property data, adapted from Technical Report AFML-TR-66-386, "MIL-HDBK 5 Guidelines for the Presentation of Data", would also be helpful.

4.3.6 Requirements For Structural Design, Analysis, Test, and Data Thereon

For aircraft, the requirements for strength and rigidity are covered by the specifications of the MIL-A-8860 series. Again, the existing specification system admits the use of composites but leaves much to be desired in the way of guidance as to test and structural analysis method and the kind of data on composite structure that is required to be submitted by the contractor for evaluation and acceptance. It appears now that the necessary requirements, as they are developed, can be incorporated into the existing specifications of this series. As the number of composites applications increases, however, it may be found that the developing specification requirements, by virtue of their nature or volume, would be more effective in a specification or specifications devoted exclusively to composites. Requirements pertaining to test specimens, test methods, and quality control, including NDT, are examples of subjects for which separate specifications may be desired.

4.3.7 Action To Improve Specification Coverage of Composites

Obviously the initiative and the burden of the work in improving the specification coverage of composites rest with the Services. Such responsibility, in general, is widely dispersed in the military Services in accordance with internal organizational grouping and to some extent with disciplines. In specifications that concern composite material, it is important to recognize that composite structure in a subject that usually requires the joint attention of the designer, structural analyst, composite materials engineer, manufacturing engineer, quality control engineer (especially for NDT) and other specialists. Consequently, close coordination or collaboration in specification preparation becomes important.

With these considerations in mind, it appears that the total effort to strengthen the Services' specification coverage of composites should be organized on a comprehensive basis, perhaps as a unified program under the guidance of a steering group of cognizant Government people. The objective of such an approach would be to facilitate the planning and execution of the work of the separate segments of responsibility and to provide a channel for an orderly input of information from industry. In any event, the total task of providing up-to-date specification treatment of composites should be recognized as an important matter deserving serious attention and timely action.

4.4 Conclusions

Adequate and appropriate treatment of specification requirements peculiar to composites will facilitate the successful introduction of composites in structure. Conversely, inadequate treatment of specification requirements will tend to impede such introduction.

An important role of specifications is as an accumulation of the latest technology in an organized form ready for immediate application.

The specification systems, as they are now, admit the use of composites but, because they do not yet contain sufficient requirements and guidance applicable to composites, do little to establish their acceptance as useful structural materials. Nevertheless, specification systems provide an appropriate and highly effective framework for the introduction of requirements for composites. A start has been made but much more remains to be done before the specification systems can serve to control and encourage the use of composites as effectively as they do for other materials.

No major problems in the accomplishment of what needs to be done in the specifications field are foreseen provided the importance and magnitude of the task are realized and adequate effort is applied.

beam under the influence of a bending force applied at the free end was analyzed in Ref. 3; plane anisotropic beam analyses are reported in Ref. 4; and the same problem for the special case of orthotropic plane rectangles in Ref. 5. Solutions for particular problems in this class given in Ref. 6, however, are reported in Ref. 4 to be in error.

Many of the common instability failure modes for conventional frame members need to be reexamined for composite material frame elements. With composites it is very likely that coupling will exist in minimum weight designs between axial, transverse, and torsional load-deflection relationships. An anisotropic rod subject to a uniform axial stress is not only lengthened in the direction of the applied load and shortened in the transverse directions, but also bends and twists (see p. 76, Ref. 3). Local buckling of the individual elements or collections of thin-walled elements making up a cross section requires further attention. Developments in plate analysis can be expected to provide insight and solution methods for these local buckling problems. A linear small deflection and a finite deflection development for frame members with general coupling is likely to be needed for dealing with future problems.

A.1.2 Plate Members

Flat structural elements with two dimensions large compared with the third dimension are referred to as plate elements. In most aerospace applications these plate elements will be "thin"; still, composite plates of this kind will consist of several individual plies or laminas. Within a ply the composite is assumed to be homogeneous, with the filaments oriented in a single direction. However, since the individual plies may be oriented at various angles with respect to a reference coordinate system in the plane of the plate, the material is heterogeneous in the direction perpendicular to the plane of the plate. For thin plates it has generally been assumed that linear line elements perpendicular to a reference surface in the undeformed flat plate remain straight and perpendicular to the reference surface after deformation. Experimental evidence is needed to support this basic hypothesis for laminated plates and establish its limitations, if any.

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3.2 Fabrication Processes
3.3.1 Quality Assurance--Raw Material Control
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APPENDIX A

Review of Structural Element Behavior Theory

A substantial portion of the structural design process has traditionally been carried out assuming linear elastic static behavior as primary, treating more complex behavior subsequently as deemed necessary. While it may be argued that dynamic and thermal response are more frequently playing a direct role in structural design, this is generally still within the framework of linear behavior. In any event, it seems reasonable to initially place emphasis on what is needed to carry on structural design within the framework of static linear elastic behavior. The objective of static macrostructural analysis is to predict stress and displacement distributions throughout the structural element.

A. 1 Basic Fundamental Elements

A. 1. 1 Frame Members

Frame members will be understood to be straight members with two dimensions small compared with the third. Many applications of composite materials to beam and truss type structures will require only slight modification of conventional methods of analysis. For example, in Division IX, Section 5 of Ref. 1 the elementary beam theory is modified for the analysis of beams constructed of layers of orthotropic material where the natural axis of each layer has an arbitrary orientation with respect to the axis of the beam. The classical Euler column buckling formula is modified for the same class of composite beam members in Division IX, Section 6 of Ref. 1.

Solid and hollow rectangular beams, solid and hollow circular shafts, and hollow elliptical beams have been evaluated under bending, axial, torsional, and shear loads on a stiffness to weight basis, by extending elementary beam theory (Ref. 2). Both unidirectional and crossply fiber layups were treated.

The general anisotropic elasticity problem encountered with composites has also been considered for frame members. An anisotropic cantilever beam under the influence of a bending force applied at the free end was analyzed in Ref. 3; plane anisotropic beam analyses are reported in Ref. 4; and the same problem for the special case of orthotropic plane rectangles in Ref. 5. Solutions for particular problems in this class given in Ref. 6, however, are reported in Ref. 4 to be in error.

Many of the common instability failure modes for conventional frame members need to be reexamined for composite material frame elements. With composites it is very likely that coupling will exist in minimum weight designs between axial, transverse, and torsional load-deflection relationships. An anisotropic rod subject to a uniform axial stress is not only lengthened in the direction of the applied load and shortened in the transverse directions, but also bends and twists (see p. 76, Ref. 3). Local buckling of the individual elements or collections of thin-walled elements making up a cross section requires further attention. Developments in plate analysis can be expected to provide insight and solution methods for these local buckling problems. A linear small deflection and a finite deflection development for frame members with general coupling is likely to be needed for dealing with future problems.

A.1.2 Plate Members

Flat structural elements with two dimensions large compared with the third dimension are referred to as plate elements. In most aerospace applications these plate elements will be "thin"; still, composite plates of this kind will consist of several individual plies or laminas. Within a ply the composite is assumed to be homogeneous, with the filaments oriented in a single direction. However, since the individual plies may be oriented at various angles with respect to a reference coordinate system in the plane of the plate, the material is heterogeneous in the direction perpendicular to the plane of the plate. For thin plates it has generally been assumed that linear line elements perpendicular to a reference surface in the undeformed flat plate remain straight and perpendicular to the reference surface after deformation. Experimental evidence is needed to support this basic hypothesis for laminated plates and establish its limitations, if any.

Force-displacement relations are readily obtained (see p. IX-38, Ref. 1 for example) if it is assumed that the strains vary linearly through the depth of the laminate. In general, the bending and membrane action will be coupled. That is, either forces in the plane of the plate or bending or twisting moments will induce both linear strains in the plane of the plate and bending and twisting curvatures. A computer program based on a finite difference formulation which solves the equations characterizing these effects, using a fixed, twenty-five point grid, is reported in Ref. 7 and summarized in Ref. 1.

In cases where both bending moments and membrane (i.e., in-plane) forces exist and the equilibrium equations are based on the deformed geometry, nonlinear terms appear in the vertical equilibrium equation. This nonlinearity appears even though the strain-displacement and stress-strain relations have been assumed to be linear. Since bending and membrane behavior are coupled for plates whose laminates are not symmetrical through their thickness, it is suggested that such plates under the action of destabilizing loads require further investigation. It is also suggested that studies of this sort include the influence of initial imperfections since truly flat unbalanced laminated plates are not easily fabricated. Consideration should be given to treating unbalanced imperfect plates subject to destabilizing loads as a nonlinear finite-displacement response problem.

Consider now flat, balanced laminates, i.e., laminates that are symmetric with respect to a mid-surface reference plane. For plates of this class, the thickness and solutions may be sought by expressing inplane equilibrium equations in terms of displacement variables (u and v) or by expressing the inplane strain compatibility expression in terms of a stress function that identically satisfies the equilibrium conditions, (see Chapter 2, Ref. 6). The stress function formulation is given by Eq. IX 96 of Ref. 1 with the coupling coefficients (b) set to zero.

If for a balanced laminated plate the distribution of the membrane force resultants is known, the possibility of plate buckling may be examined. Employing small deflection plate bending theory and taking into account the possibility of a transverse displacement distribution in writing the equilibrium equations leads to a linear homogeneous partial differential equation

$$D_{11} \frac{\partial^4 w}{\partial x^4} + 4D_{13} \frac{\partial^4 w}{\partial x^3 \partial y} + 2(D_{12} + 2D_{33}) \frac{\partial^4 w}{\partial x^2 \partial y^2} + 4D_{23} \frac{\partial^4 w}{\partial x \partial y^3} + D_{22} \frac{\partial^4 w}{\partial y^4} - N_x \frac{\partial^2 w}{\partial x^2} - N_y \frac{\partial^2 w}{\partial y^2} - 2N_{xy} \frac{\partial^2 w}{\partial x \partial y} = 0 \qquad \text{Eq. (1)}$$

For the special case of orthotropic plates (for example plates made up of many plies alternately oriented at $\pm\phi$ to the x axis of the plate) the terms D_{13} and D_{23} essentially vanish. In Chapter 13 of Ref. 6 several orthotropic plate buckling problems are treated. The results for several important special cases useful for design applications are given in Division IX of Ref. 1.

(1) Plate under compression N_x;
  (a) simply supported on all edges,
  (b) simply supported on the loaded edges clamped on the unloaded edges,
(2) Long plate a >> b subject to shear N_{xy};
  (a) simply supported on all edges,
  (b) clamped on long edges parallel to the x axis,
(3) Long plate a >> b subject to combined compression N_x and shear N_{xy};
  (a) simply supported on all edges.

The post buckling behavior of balanced orthotropic plates is governed by a set of two partial differential equations in terms of the Airy stress function and the transverse displacement (see Eq. IX 133 Ref. 1). These equations are coupled and nonlinear due to the use of finite displacement strain-displacement relations. For the isotropic case they reduce to the well known von Karman equations (see p. 417-418 Ref. 8).

The buckling analysis of balanced laminates subject to known in-plane load distributions is complicated by the presence of the coupling terms that arise when D_{13} and D_{23} are non-zero in Eq. (1). This same difficulty is introduced by the shear (N_{xy}) load terms when the dimension (a) is not very large compared with b. The difficulty is that the usual series expansions used to represent the possible transverse displacement (w) leads to a general Eigenvalue problem of the form $Ax = \lambda Bx$ where neither A nor B is diagonal. Furthermore it becomes more difficult to select series expansions for w that satisfy the various boundary conditions. It may be necessary to use functions that satisfy only the imposed boundary conditions while not satisfying the natural boundary conditions. The buckling analysis of balanced laminates subject to known in-plane load distributions can be achieved using numerical techniques. However, further study of methods for handling prescribed moment and shear boundary conditions is required.

The small deflection bending theory of anisotropic plates is reviewed in Chapter 8 and solutions for several specific problems (principally balanced orthotropic rectangular plates and strips) are presented in Chapter 9 of Ref. 6. In Division IX Section 4.4 of Ref. 1 the approximate static deflection response of a simply supported rectangular balanced orthotropic plate subject to a uniform transverse load is given based upon a single assumed mode in a minimum energy formulation. The formulas for approximating the maximum deflection for this special case may be useful to designers.

The influence of known membrane forces on balanced anisotropic plates subject to transverse loading is an important problem. This problem may be viewed as a two dimensional generalization of the beam-column problem. The known in-plane forces modify (increase or decrease) the effective bending stiffnesses of the plate. The plate behavior is governed by Eq. 1 with the right-hand side set equal to q, the intensity of the distributed load, rather than zero. This general problem can be dealt with using numerical techniques, however, further study of the methods for treating prescribed shear and moment boundary conditions is required. In Division IX, Section 4.6 of Ref. 1 the influence of a uniform mid-surface force resultant N_x on the approximate static deflection response of a simply supported rectangular balanced orthotropic plate subject to a uniform transverse load is given using a single assumed mode in a minimum energy solution. It should be noted that the convenient formula given by this approximate analysis (Eq. IX 125 Ref. 1) may be used to estimate the influence of a uniform inplane load N_x and a uniform transverse load q on balanced orthotropic rectangular plates with other boundary conditions, provided the buckling load corresponding to the particular boundary conditions of interest is available.

In principle once the deflection response of a plate has been determined, the strain distribution over the planform and through the thickness is known. It should be noted, however, that the strains depend upon the second derivatives of the transverse displacements. Therefore, if the displacement distribution is only known approximately, the stress distribution predictions will be substantially less accurate than the displacements. Even for the case of plane stress membrane behavior, with no bending, the stress distribution depends upon first derivatives of the displacement variables (u and v) or upon second derivatives of the stress function. In seeking experimental correlation of plate analyses stress correlation (strain measurements) should be pursued in addition to deflection correlation.

It will frequently not be apparent where the maximum deflection will occur and establishing the location (with respect to the planform and through th depth) of the critical combined stress state will in the general case require further study.

In certain special cases of importance, the location of maximum deflections and stresses will be facilitated by treating the composite plate as an equivalent homogeneous material. In Division IX, Section 4.10 of Ref. 1 a comparison is made between the maximum deflection and stress results obtained in Ref. 9 and the predictions of the same quantities obtained by treating the composite plate as an equivalent homogeneous material. Comparative results for two specific examples are given in Division IX, Section 4.10 of Ref. 1. The following conclusion is quoted from the foregoing reference:

> "It has been shown that for composites made up of many layers cross plied at alternate angles of 0° and 90°, or at alternate angles of ±45°, the behavior of the composite may be adequately approximated by considering it to be a homogeneous isotropic material. It would seem to follow, as a corollary, that a composite made up of many layers cross plied at alternate angles of $\pm\phi$ could be approximated by considering it to be a homogeneous orthotropic material, where ϕ is any angle."

For highly loaded structural elements, where composites made up of many layers occur the possibility of being able to use balanced layups and treat the material as an equivalent homogeneous (isotropic or orthotropic) material simplifies the analysis task substantially. On the other hand for lightly loaded structural elements where composites made up of relative few plies may occur, it will be necessary to extend current analysis capabilities to include bending membrane coupling. Furthermore, the location of maximum deflection and critical combined stress states could require substantial effort.

A.1.3 Shell Members

This section deals with anisotropic shells laminated from unidirectional composite layers. The effects of bending membrane coupling are either eliminated due to a symmetric construction or approximated as being negligible. In Ref. 10, Ambartsumyan gives a rather thorough survey of the state of analysis of anisotropic layered shells up to 1962. This survey includes the analysis of anisotropic shells utilizing the Love-Kirchhoff hypothesis and new theories allowing for the deformation of normals to the reference surface. Recent additions to the work on multi-layered structures was surveyed by Habin (Ref. 11). The first six chapters of Ambartsumyan's test (Ref. 12) on the "Theories of Anisotropic Shells," serves as the most complete single document on the fundamental analysis of this type of structure.

G. G. Love (Ref. 13) presents a method for the stress analysis of axisymmetrically loaded orthotropic shells of revolution. The differential equations are solved by numerical integration for filament wound pressure vessels containing discontinuity stresses at points of juncture between cylindrical and spherical sections. Solutions for homogeneous anisotropic shells of revolution are also presented by Kingsbury and Brull (Ref. 14). The solution for the symmetrically loaded circular cylindrical shell is obtained by a perturbation method based on the earlier works of Vinson and Brull (Ref. 15) and Dong and Dong (Ref. 16). In all of these papers, the effects of bending membrane coupling have been neglected. Many other papers on the analysis of anisotropic shells subjected to both static and dynamic loads can be found referenced in the surveys by Ambartsumyan (Ref. 10) and Habin (Ref. 11).

Pressure vessels have been the most successful single application of fibrous composites. Most pressure vessels are analyzed as statically determinate structures, and therefore, the orientation of the stiffness does not affect the stress distribution. The concept of orienting the fibers to carry the load is easy to exploit for statically determinate structures. This class of shells, whose design is fully stressed, is called isotensoid. Due to the fact that the internal pressure load provides a stabilizing force, these structures fail when the ultimate load of the material is reached, i.e., buckling limitations need not be considered. Based on netting analysis, Read (Ref. 17) develops a set of simultaneous differential equations to determine the shape of isotensoid pressure vessels. Greszczuk (Ref. 18) discusses the analysis of isotensoid structures. Gerard (Ref. 19) gives a comparative efficiency study of aerospace pressure vessel design concepts for various materials including glass and boron fibers and oriented whisker composites. Johns and Kaufman (Ref. 20) presented the idea of over-wrapping an isotropic metallic cylinder with fiberglass to provide a two to one strength ratio for an isotensoid design. Schneider and Miller (Ref. 21) studied noncylindrical fiberglass pressure hulls for applications to deep submergence. In this study, buckling failures under hydrostatic loads became a prime design consideration. Several stress analyses for thick-walled cylindrical shells under external hydrostatic pressure generated in the course of an investigation of advanced design concepts for deep submersibles are reported in Ref. 22. In Ref. 23 Dow and Rosen study the structural weight-axial buckling load efficiency of fiber reinforced composite cylinders. They found the pseudo-isotropic fiber configuration most effective in resisting the destabilizing axial loads. In this situation, the structure carries the load in a membrane manner, but the bending response must be completely understood in order to properly analyze buckling failures. The elastic stability analysis of orthotropic shells has been available for some time. For example, linear small-deflection theories for orthotropic circular cylinders subjected to external pressure, torsion, or axial load can be found in Ref. 24. The subject problem of this study derived its orthotropicity from the stiffening provided by integral or fabricated rings and longitudinals. Nevertheless, the general methods of buckling analysis for orthotropic shells has been established. Hess (Ref. 25) derived the equations for the stability of orthotropic cylindrical shells under combinations of axial compression and external pressure. Schneider and Hofeditz (Ref. 26) studied the analysis of cylinder stability under external pressure for various fabrication patters of fiberglass structures. Schneider (Ref. 27) did a similar study for fiberglass cylinders under axial load. Singer and his colleagues at Technion have done extensive work in recent years on the stability of stiffened and unstiffened cylindrical and conical shells. Ref. 28 provides a summary of some of their work, both analytical and experimental. Block et al., Refs. 29 and 30 derive equations for the stability of eccentrically stiffened orthotropic cylinders under axial, circumferential and pure bending loads. These papers provide an adequate basis for studying the stability of orthotropic shells subjected to various loading conditions, so long as the shells are orthotropic and symmetric about the reference surface. If the shells are generally anisotropic, a torsional deflection can accompany an axial load and this phenomenon must be accounted for in the differential equation through the introduction of in-plane shear stress-direct stress coupling. If the pattern of unidirectional fibers is not symmetric with respect to the reference surface, then a bending-membrane coupling phenomenon arises. In such situations, it may be necessary to include the prebuckling bending response in a stability study.

A.2 Numerical Methods

In predicting the behavior of composite material structural components, it will frequently be necessary to have recourse to approximate numerical techniques. The basic formulation governing the static behavior of these structural systems usually take the form of differential equations and associated boundary conditions. It should be noted that assuming conservative material behavior, there usually exists a corresponding energy formulation such that the stationary conditions on the energy are equivalent to the field equations and boundary conditions.

Approximate numerical solutions can be obtained by discretizing the problem in several ways. For example the field equations and boundary conditions can be cast in finite difference form. Series expansions for the dependent variables may be employed in conjunction with the Ritz technique or the Galerkin technique. The various finite element methods of structural analysis may also be used to predict the behavior of composite material structural components.

An example of an application of the finite difference technique to composite material structural analysis is the computer program for approximate solution of the generalized Poisson-Kirchhoff equations reported in Ref. 7 and summarized in Ref. 1. This computer program is based upon a fixed twenty-five point grid finite difference formulation of the two linear coupled partial differential equations in which the transverse displacement (w) and the stress function (U) are the dependent variables. The program can accommodate clamped or simply supported boundary conditions and uniform specified values of the force resultants on the edges. It should be noted that the accuracy of the ply stresses and strains can be expected to suffer from the fact that they depend upon second derivatives of the stress function and the transverse displacement variable. The Poisson-Kirchhoff formulation assumes that the equilibrium equations can be based upon the undeformed geometry and therefore this particular formulation does not consider buckling instability. This formulation is not well suited to treating the problem when boundary conditions on the in-plane displacements are specified.

Bushnell, in Ref. 61, has developed a buckling analysis of general stiffened shells of revolution using the finite difference approach. Nonlinear prebuckling effects are accounted for, and stability is treated as a linear Eigenvalue problem. In Ref. 31 energy formulations and Ritz-type solutions are presented for the analysis of balanced anisotropic rectangular and skew plates with various boundary conditions. Buckling analysis, determination of the natural frequencies and mode shapes, as well as the prediction of the static displacement distribution due to transverse loads are dealt with. The influence of known uniform in-plane loads on the behavior of plates with uniform flexural properties over their planform is included. The Ritz technique is used to cast the problem in matrix form as either a set of linear simultaneous equations or as a linear Eigenvalue problem. The transverse displacement (w) is approximated by a series expansion involving the products of beam mode shape functions. Numerical results and experimental correlation are shown for the buckling load on a twenty-ply, unidirectional composite plate with fiber orientation of 60° to the N_x loading. A numerical example is presented illustrating the rapid convergence of the approximate buckling load as the number of degrees of freedom is increased. Numerical results and good experimental correlation are shown for the first four natural frequencies and mode shapes of square cantilever plates. These numerical and experimental results are given for an isotropic aluminum reference specimen and two balanced 12 (twelve) ply glass-reinforced epoxy resin composite plates with the following layup patterns (1) (+30, -30, +30, -30, +30, -30; -30, +30, -30, +30, -30, +30) and (2) (-60, +60, -60, +60, -60, +60; +60, -60, +60, -60, +60, -60). The treatment of prescribed moment and shear boundary conditions for skew and anisotropic rectangular plates requires further study. The difficulties of obtaining accurate stress predictions using approximate displacement type methods for isotropic plate problems may be expected to persist for this class of composite plate problems and these difficulties may be aggravated by approximate treatment of prescribed moment and shear boundary conditions.

Several finite elements have been generated in response to the need for analysis tools suitable for dealing with composite material structural systems. In Ref. 32 two planar membrane type elements are introduced. The strain in these elements is assumed to be uniform through the depth and they are suitable for the analysis of balanced laminates subject to in-plane loading. The triangular element provides for anisotropic elastic behavior and it is based upon the assumption of linear variation of the stresses over the region of the element. The stress assumptions employed satisfy both equilibrium equations and the compatibility equation within the element. The quadrilateral element provides for orthotropic elastic behavior and it is based upon an incomplete quadratic stress assumption that satisfies both equilibrium equations and the equation of compatibility. Numerical verification of these two elements is illustrated by comparing some stress results for orthotropic and anisotropic beams with results based on Ref. 6. These elements were used for the structural analysis of a 2/3 scale F-111 horizontal tail. The idealization employed led to a system with 479 displacement degrees of freedom. A comparison of calculated and experimentally determined results is given in Ref. 32. As would be expected, the displacement predictions are superior to the stress predictions.

In Ref. 33 several discrete elements applicable to the analysis of composite material structural systems are described in outline form. For example, a flat triangular plate element in which uncoupled bending and membrane action are represented is outlined in Ref. 33 and described in detail in Ref. 34.

The material properties accommodate general anisotropy. Membrane displacements within this element are approximated by quadratic polynomials. Transverse displacement is represented by cubic polynomials. Under normal circumstances, three corner points and three midside points participate in establishing continuous connection of this flat triangular element with adjacent elements. The variation of strain within the flat triangular element is implied by the assumed displacement functions and leads to corresponding stress variation. A flat quadrilateral plate element in which uncoupled bending and membrane behavior is accounted for is also outlined in Ref. 33 and this discrete element described in detail in Ref. 35. Here, too, the material properties take general anisotropy into account. The membrane displacements are approximated by quadratic polynomials and the transverse displacement is represented by cubic polynomials. The four corner points and four midside points participate in establishing continuous connection of this flat quadrilateral element with adjacent elements. It should be noted that two additional elements with application possibilities are outlined in Ref. 33:

(1) Triangular flat plate - uncoupled bending membrane behavior orthotropic, in-plane displacements approximated by linear polynomials, transverse displacement is approximated by a cubic complete except for x^2y.

(2) Quadrilateral flat plate - uncoupled bending membrane behavior, orthotropic in-plane direct stresses vary linearly and in-plane shear is constant, transverse displacement is represented by a complete cubic with the addition of the terms x^3y and xy^3.

These two discrete elements are described in detail in Ref. 36. The development of incremental stiffness matrices that take into account the influence of known midplane forces is included in Ref. 36. As another example, Gifford (Ref. 62) employed a ring element of triangular cross-section to analyze stresses in thick-walled orthotropic shells of revolution.

It is likely that many of the existing gaps in analysis capability of composite material structural components will at least temporarily be filled by the generation of computer programs based on numerical methods. Further effort will be required to provide operational static structural analysis capabilities useful to the designer that:

(1) include linear bending-membrane coupling for unbalanced laminates.

(2) include nonlinear strain-displacement relations (for post-buckling load displacement behavior).

(3) predict stress distributions with sufficient accuracy.

(4) avoid modeling shell structures with flat discrete element idealizations.

A.3 Plate and Shell Theory

A unidirectional fibrous composite may be viewed as a transversely isotropic elastic solid with the section normal to the fibers being the plane of isotropy. The stiffness and strength properties in the direction parallel to the fibers are generally much greater than those in the plane of isotropy. When fabricated into a two-dimensional structural element, the cross-section has one of its dimensions reduced so that when the Love-Kirchhoff assumption is invoked, the resulting planar structure is orthotropic, with respect to the set of orthogonal axes colinear and perpendicular with the fiber direction. The material is anisotropic when referenced to any other set of axes in the plane of the reference surface. Rarely do structural applications require an element with virtually all of its stiffness and strength in only one direction. Most plate and shell elements must serve a multiplicity of functions requiring only a minor imbalance in stiffness and strength in mutually perpendicular directions in its plane. Current methods of fabrication, therefore, lead to the superposition of plate and shell elements into a layered construction. The validity of the Love-Kirchhoff hypothesis, particularly for laminated plates with vastly different elastic properties in adjacent lamina is questionable. Therefore, the introduction of transverse shear deformations in the analysis model should be investigated.

A.3.1 Effects of Transverse Shear

Ambartsumyan (Ref. 37), Peshtmaldzhyan (Ref. 38), and Osternik and Barg (Ref. 39) have investigated new theories for anisotropic plates and shells allowing for normals to the reference plane to deform but assuming that the transverse shear and corresponding strains vary according to a given law. The problem of transverse shear in sandwich panels of isotropic constituents has been investigated previously (Refs. 40 and 41). It has been observed that the effects of transverse shear deformation in the analysis of sandwich shells laminated from isotropic constituents are not as great as that observed for plates of the same constituents. Benson and Mayers (Ref. 42) found that the inclusion of transverse shear lowered the uniaxial buckling load of a simply supported sandwich panel of isotropic constituents by about 18%. Ren and Yu (Ref. 43) studied the flexural and extensional vibration of a two-layered composite plate including bending-membrane coupling coefficients. While the extensional mode frequency was unaffected by the introduction of transverse shear, the bending mode frequency was changed by as much as 10% due to transverse shear effects. These results are in agreement with the results of Benson and Mayers (Ref. 42) since the buckling load is related to the square of the flexural frequency.

Established analysis (Ref. 37) capabilities should be investigated for adaptation to laminated composites where the individual lamina are orthotropic rather than isotropic. These theories have been developed to the point where the governing differential equation and corresponding boundary conditions have been established. In order to evaluate this approach, selected problems have been examined. Unfortunately, transversely isotropic materials with their plane of isotropy being parallel to the reference plane are the only problems investigated thus far. Even for this restricted class of problems using mildly dissimilar materials in a laminated configuration, significant deviations from classical theory have been observed. The effects of clamped boundary conditions seemed to cause further deviation from classical theory. These studies should be conducted for both plate and shell elements where the individual plies are highly orthotropic as is the case for high performance composites. If found applicable to current and future aerospace structures, these concepts should be extended to determine the effects of transverse shear deformation on load carrying characteristics such as the buckling load of laminated fibrous composites. The investigation should further attempt to distill the results into meaningful analysis capabilities suitable for use in design.

A. 3. 2 In-Plane Normal Stress-Shear Stress Coupling

Frequently the principal directions of elasticity of the individual lamina are not colinear with the structural axes. This introduces a normal stress in-plane shear coupling not present in orthotropic lamina. When a plate is fabricated from individual lamina of this type, it is possible that the gross properties of the resulting plate may also display this coupling. The result of this coupling is to distort the wave pattern or natural modes of the plate or shell. The assumed mode for a displacement, buckling, or vibrational response should accommodate such a skewed wave pattern in order to obtain sufficiently accurate results using a reasonable number of terms.

Dong and Dong (Ref. 16) developed a perturbation method of analysis for slightly anisotropic shells based on an extension of the work of Vinson and Brull (Ref. 15) for orthotropic plates. The amount of computational effort involved makes a method impractical for design application in its present state of development. References 44 through 51 also report on the effects of in-plane coupling along with a coupling between bending and membrane response.

A. 3. 3 Bending-Membrane Coupling

Frequently in the design of high performance composites, very few layers are needed to sustain the loads. The resulting structure cannot be approximated as homogeneous in the direction transverse to its plane. In these situations a coupling between the bending and membrane response is possible so that when a membrane load is applied to the structure, it undergoes both a bending and membrane displacement response (Refs. 44 through 47).

The result of including the bending-membrane coupling in the analysis of plates and shells has been examined for only a few limited examples. It is easily shown that critical stress conditions are not necessarily located at the extreme fibers nor is the curvature and the bending moment related by a simple constant of proportionality. Concentrations of stress or strain have been observed for both plate and shell structures with the bending-membrane coupling (Refs. 45 and 46) when compared with similar uncoupled systems.

Bending-membrane coupling can influence the flexural stability of plates and shells. If the structure undergoes substantial bending deformation prior to buckling an Eigenvalue analysis serves only as an upper bound to the stability limit. Tasi (Ref. 48) reported an Eigenvalue solution for the axial buckling of cylindrical shells possessing bending-membrane coupling effects. The effects of such coupling decreased the axial buckling load capacity. References 49 through 51 present the buckling analysis of anisotropic cylinders under combined loads. Bending-membrane effects are included and the Eigenvalue solution is found. The effect of bending-membrane coupling is analogous to the effect of initial imperfections. For imperfection sensitive structures, a complete load displacement response curve is necessary to ascertain the stability limit (Refs. 52 and 53). Thurston (Ref. 54) presented a method of solution including prebuckling deformations based on the work of von Karman and Tsien (Ref. 55).

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APPENDIX B

Typical Fabrication Processes and Illustrations of Current Capabilities

The following brief discussion is intended to introduce those who are unfamiliar with the subject to the principal processes available and some of the problem areas associated with each.

Filament or Tape Winding

Filament winding is one of the more recent techniques developed for the fabrication of composites. It can be designed to be almost completely automatic, thereby assuring reliable and reproducible structures. Utilizing either roving or tape in wet or prepreg form, it is capable of producing some of the highest mechanical properties of any known composite structure and is particularly well suited for the fabrication of pressure vessels. Shapes that can readily be accommodated are the cylinder, sphere, oblate and prolate ellipsoids, and various conics.

Tool design has a considerable influence on the parts produced by this process. The usual tool is a mandrel and may be either a rigid metal type or the wash-out or melt-out type composed of plaster, salt or low melting-point metal. The rigidity of the tool influences the magnitude and distribution of the resultant residual stressed induced in the cured part, hence a detail residual stress analysis should be accomplished as part of the tool design and processing parameter selection. This process requires special winding machines and let-off systems capable of handling and positioning numerous spools of roving or tape under controlled tension on the mandrel at the desired spot--without twisting, breaking, gapping, or overlapping the basic material. Process parameters that affect the end item include pretensioning, resin content, void content, proper fiber placement, flow and resin shrinkage in cure, and proper cure and postcure. These will vary with each material system applied and considerable additional development needs to be accomplished with some of the newer advanced reinforcements such as the boron and high modulus graphite filaments.

Cloth Wrapping

This process involves the positioning of a bidirectional or unidirectional woven cloth about a mandrel or in a tool until the desired part thickness is obtained. The part is then vacuum bagged and cured in an oven or autoclave. In this process a large amount of material can be applied in a short time, however, the resultant part properties are presently lower than those typical for the filament or tape wound process. Wrinkling in thicker parts caused by compaction during cure can be a serious problem. In some cases the cloth wrapping process is combined with the filament winding process, and hoop windings and pressure bags are used to alleviate the wrinkling problem and enhance the hoop properties.

Vacuum Bag Molding

In this process the reinforcement is positioned in a mold and liquid resin added. A vacuum bag is then applied over the surface, a vacuum drawn within the bag, and the excessive resin and air are worked by hand to the edges of the part and extracted by the vacuum system. This tends to create a relatively void-free part with properties, of course, depending upon the type of reinforcement used. Generally the reinforcement is in the form of woven cloth, unidirectional unwoven fibers or mat. Once the void-freeing operation is completed, the part is cured in an oven under vacuum pressure.

The tooling required for this process usually involves female molds and the process is readily adaptable to parts with double contour. In addition, the process is commonly used on parts using sandwich construction where core materials may consist of honeycomb, fluted core, or foam. Normally, the only size restrictions are set by the availability of facilities necessary to cure the end items.

Some of the process problems involved in this technique include resin content control, resin drainage control, reinforcement distortion during layup and the voiding operation, void content, resin flow during cure, multi-stage curing, and postcuring. Many of these problems have been resolved for non-structural glass fiber reinforced composites, but only limited experimentation has been conducted to date utilizing advanced high modulus reinforcements. Additional problems arise in the fabrication of large thick parts where usually a prepreg is used in preference to a wet layup. In this case, proper prepreg tack and flow are required to obtain a wrinkle-free, void free laminate and problems of compaction and stage-curing become more critical. These are often cases where more than vacuum pressure is required and an autoclave is used to augment the differential pressure provided by the vacuum.

Autoclave Molding

The autoclave molding process is similar to the vacuum bag molding process except that greater curing pressures are used. Better resin flow can be obtained with this process and void free laminates can be fabricated with a minimum of rubout effort. Laminates made from prepreg will be more consistent in resin content and thickness, with properties somewhat superior to those commonly associated with the wet layup vacuum bag process. The use of prepreg is a much cleaner and more controllable operation than the wet layup, and patterns can be more readily cut and positioned on the mold with a minimum of fiber distortion.

The process problems in this method are similar to those of the vacuum bag molding operation, except that greater range is available in selecting the curing pressure. Generally this is in the 50 to 300 psi range. Higher pressures can be obtained with a hydroclave, if desired. Proper selection of resin solids, volatile content and flow in the prepreg to produce the desired a) tack for layup, b) flow in cure, and c) final part resin-content requires developmental study for larger parts.

Matched Tool Press Molding

In this process the material is positioned between two matched metal dies in a press and cured under pressure and temperature. Generally the material utilized is in the form of a "preform". Patterns may be cut from woven or unwoven sheet stock, or the material can be placed in the molds in sheet form and trimmed during molding with shear-off edges. Short-fiber molding-compounds are also used where property requirements are less severe and part complexity makes a sheet type reinforcement impractical. Cure cycles being much shorter, it is a fabrication process capable of relatively high production; however, tooling and developmental costs are greater than with other molding processes and must be justified by large quantity orders. Also, the size of part is limited by the size and capacity of available press facilities.

Process variables concern proper preform and prepreg selection, cure and post-cure cycles, fiber washing, proper material positioning and mold design to obtain desired fiber alignment, and degassing operations with certain resin systems.

Machine Lamination

Numerically controlled, tape-layup machines presently under development are designed to eliminate the time-consuming and often crude hand-layup techniques. Computer-developed design data will be fed into these machines with instructions for the required position and direction of each length of prepreg tape. With this data on punched tape, such machines will automatically lay up the prepreg tape in the proper sequence in a positioned mold or on a mandrel. The completed part can then be bagged and cured under vacuum or augmented pressure in an oven or autoclave. These machines are designed to handle flat panels, compound curves, complex curves and bodies of revolution. As an indication of the promise of automated techniques, it is estimated that approximately 70% of the F-111 surface area and 60% of the material in a composite rotor blade are suitable for the machine layup process.

Machining, Drilling, Sawing

A considerable technology has been developed for glass composites and it has been demonstrated that diamond-faced tools can be applied to the advanced composites employing boron and graphite reinforcements. Cured laminates can be machined, drilled and sawed by methods somewhat similar to those for metals, however, turning speeds and tool feeds will vary considerably. Carbide and diamond-edge tools are the most practical. Care must be taken to prevent forces being applied which tend to delaminate the composites. Conventional tools tend to dull rapidly and must be frequently sharpened to prevent gouging and rough surfaces; this is more of a problem with boron than with graphite fibers, but not an overriding one with either. Experience has also been gained with ultrasonic drilling and appears quite promising.

Adhesive Bonding

Adhesive bonding is used extensively with composites and provides attachments with good fatigue life. Adhesive films are also readily used in composite sandwich structures. Surface preparation is not nearly as critical as with metals and often bonds may be obtained which are stronger than the interlaminar strength of the basic laminate. However, control of glue line thickness is one of the important remaining problems. In some cases the required application of heat and pressure to cure the adhesive may be accomplished during the molding cycle of the composite. Both room- and elevated-temperature curing epoxy adhesive systems are available in a paste, liquid, or film form, all of which have performed remarkably well in the relatively limited composite fabrication done to date. Here again, considerable development work must be accomplished with advanced composites before adequate data can be accumulated to reliably design and fabricate various joints incorporating an adhesive.

Typical Costs and Applications

Constituent Materials

The purpose of the following data on materials is solely to convey a general understanding of the approximate cost of various materials, as of early 1968. Whereas the cost of glass fibers and resin is relatively stable, this is not the case for boron and graphite. The trend for the latter has been downward and is expected to continue, but just how far costs will decrease, and how rapidly this will occur, depends on advances in the production technology which are unpredictable. Availability of the new filaments may be expected to increase, but again, this will depend on the technology.

Material	dollars per pound
E-Glass Roving	.30 - .60
E-Glass Cloth	.90 - 1.65
S-Glass Roving	3 - 4
S-Glass Cloth	5 - 7
Boron (Tungsten) Filament	300 approx.
Graphite Filament (Thornel 40 grade)	325 "
Graphite Filament (Thornel 50 grade)	350 "
Polyester Resin	.30 - .40
Epoxy Resin	.60 - 1.00

Cost of Fabricated Structures

Information on cost of structure fabricated with composite material is difficult to obtain and to evaluate. Many factors are involved such as the constituent materials and the volume fraction, tooling, engineering and development, quality assurance standards, and, of course, the number of parts produced. Unless all the relevant factors are known and taken into account, misleading comparisons may be drawn. Further, as discussed under Economics in the Introduction of this report, cost-effectiveness of composite structure is a complex evaluation in which cost of material is only one factor.

Size of Fabricated Structures

The size of glass-reinforced plastic structures has been limited primarily by the capacity of available facilities such as lathes, winding machines, ovens, autoclaves, hydroclaves, etc. The following list is offered as some indication of the size of parts possible to fabricate on existing facilities:

Type of Structure	Size
Filament Wound Motor Case (First Stage Minuteman)	$5\frac{1}{2}$' D x 19' long
Deep Submergence Vehicle Outer Hull	8' D x 40' long
Shipboard Deckhouses USS Fechteler	35' long, $4\frac{1}{2}$' wide x $7\frac{1}{2}$' high
USS Atlanta	24' long, 17' wide x 8' high
PCM 84	55' long, $10\frac{1}{2}$' wide x 8' high 27' long, $10\frac{1}{2}$' wide x 8' high
Ship Masts (USS Wright)	83' long
Sonar Domes (Compass Island)	33' long x 7' wide 33' long x 3' wide
Minesweeper Floats (0-Type O)	17' long
Submarine Fairwaters (USS Halfbreak)	- - - - -
Radomes Grumman WF-2	33' long, 20' wide x 5' high
Lockheed WV-2 Rotodome	38' D x 7' high
Lockheed Constellation Lower Radome	30' long, 20' wide x 6' high

Type of Structure	Size
Missile Shipping and Storage Containers (Polaris)	5' D x 26' long
Helicopter Rotor Blades	29½' long x 3' wide
B-52 Wing Tip	8' wide x 4' long

APPENDIX C

Some Aspects of Raw Material Control For Filamentary Composites

Some of the properties and characteristics often specified as required to fall within specific limits are listed below.

Fibers and Filaments

Tensile strength

Tensile modulus

Density

Diameter

Splices

Contamination

Resin Systems (Includes the type of resin, the accelerator, curing agent, etc.)

Viscosity

Epoxide equivalent (in the case of epoxies)

Shelf life

Gel time

Specific gravity

Mechanical properties of a resin casting (in some cases)

Mechanical properties of a specified reinforced composite

Prepreg (Roving, tape or cloth)

Resin content

Volatile content

Resin flow

Viscosity index

Tack and drapability

Weight/yard

Band width consistency

Visual examination--ribbonization, filament breakage, filament spacing, end count or filaments/inch, catenary, carrier, and contamination

Storage and working life

Mechanical properties and measurements on a specified reinforced composite--strength, modulus, resin content, specific gravity, void content, barcol hardness

The current system of raw material quality control based on specifications, inspection, and test is similar to that used for other engineering materials and, in principle, should be adequate, provided that there is sufficient knowledge of what properties and characteristics need to be controlled, and how closely, and what sampling, inspection, and test procedures are necessary to assure compliance. In brief, the system is adequate if one knows what to specify and how to assure that what is specified is, in fact, obtained. The vendor's problems in controlling quality during manufacture constitute another phase of the over-all problem of raw material quality control.

Examples of Problems

One of the major problems in the control of raw material variables is inconsistency within a given roll and between supposedly identical rolls within a given batch. For example, it has been noted in commercial fabric prepreg production that often appreciable differences exist in drapability and tack for a prepreg cloth that presumably has been rigidly quality controlled. In filament winding operations, the band width variation in a prepreg tape has caused gaps and overlaps to occur in the final part. Variations in resin advancement have created conditions whereby the proper flow of resin during cure could not be maintained, resulting in excessive voids or undesirable residual stresses in the end item.

Control During Manufacture

Recently an investigation was conducted to determine the feasibility of dynamically measuring certain properties of a fiberglass roving prepreg during its manufacture. The properties to be monitored nondestructively included band width, glass weight/yard, resin/glass ratio, and state of resin advancement.

A method of measuring band width was developed which involved the measurement of the change of a shadow created by the prepreg passing directly in front of a light beam. The equipment was arranged so that the change in the shadow cast on a light sensing element provided a proportionate change in a recording voltmeter.

The dynamic measurement of glass weight and resin/glass ratio was found to be possible with the use of beta gages. Actual resin contents were measured within $\frac{1}{2}$ of 1 percent of the recorded readings. However, the equipment required is very expensive to purchase and operate and is too bulky to fit into present manufacturing process lines. Precise positioning of the prepreg roving in the beta ray field is very difficult and considerable scatter results when this is not properly performed.

To date, attempts to dynamically measure the state of resin advancement have not been successful.

APPENDIX D

Aspects of In-Process Quality Control

A typical approach to the integration of in-process quality measurement considerations may take the following form:

- Determine inspectability of design and process.
- Compare existing quality measurement and control technology with product requirements.
- Initiate projects to provide advanced quality measurement and control techniques where necessary.
- Identify quality measurement and control limitations and assist in their logical resolution by design changes if required.
- Assure that adequate nondestructive test capability exists to demonstrate hardware integrity.

Normally a plan would be devised initially to include a detail breakdown of the manufacturing sequence of the in-process controls deemed necessary. Examples of the pertinent types of controls are indicated in the following list:

- Control of raw material going into part.
- Inspection of tools and equipment for acceptability.
- Monitoring of the critical positioning and orientation of the material as it is applied to the part.
- Inspection of in-process dimensions as required.
- Monitoring for good workmanship standards.
- Inspection for in-process defects.
- Monitoring of all debulk, cure, and postcure cycles.

- Inspection of in-process machining, trim, bonding, subassembly, and assembly operations.
- Monitoring of production control panel fabrication and testing.
- Monitoring of all in-process rework and repair operations.

All records involved in the materials control, manufacture, monitoring, and inspection of each component to be delivered should be compiled into a documentation package that is presented with the part for customer acceptance.

Production Control Panels and Tag Ends

Production control panels are small flat test panels, fabricated with the part, from the same material, and by the same process as the part in question. They experience the same debulk, cure, and postcure cycles as the part and are, therefore, quite representative of the quality of the part.

Tag ends are also useful in verifying the integrity of a given part. These are small panels, preferably flat, taken from part cutout areas or extensions which are representative of the part fabrication.

Both the production control panels and the tag end panels are subsequently tested for conformance to property requirements listed in a fabrication specification. These tests should include at least the following:

- Tensile or compressive strength
- Tensile or compressive modulus
- Interlaminar shear
- Resin content
- Void content
- Water migration
- Specific gravity
- Barcol hardness
- Vapor porosity

As a control on bonding operations, production control bond panels should be fabricated for each bonding operation incorporating adherents and adhesive identical to those used in the part assembly. These panels should remain with the part through the cure of the adhesive joint. Laboratory tests normally consist of single-lap shear and peel tests for conformance to the requirements of the fabrication specification.

Production control panel and tag end tests cannot only demonstrate part quality when the specimen is properly designed and tested, but may also provide additional property data for the designer to use as a basis for reliable material allowables and in structural analysis, thus improving design reliability.

APPENDIX E

Survey of NDT Methods

Acoustic

Coin tapping has been used in industry for many years as an accepted method for determining voids in bonded structures. In recent years, this method is generally being replaced with other nondestructive test methods which have proven to be more reliable.

Some of the advantages of coin tapping have been:

a) It is a relatively fast method of inspection;
b) Minimum of equipment required for test;
c) Short training period required for personnel;
d) No test couplant (oil, water, etc.) needed to perform the inspection.

However, the higher reliability required of composite structures tends to make this method of bond inspection one of the least desirable. Major disadvantages of coin tapping for present composite structure are:

a) It is dependent on aural interpretation and is subject to sound interference and difference of hearing and judgment by the inspectors.
b) There is no assurance of complete coverage on large surfaces.
c) Voids have to be large for reliable detection.
d) It is generally restricted to structures with relatively thin skins.

Because of its major disadvantages, it appears that coin tapping, in most cases has reached the end of its usefulness for inspection of composite structures, particularly where these structures are critical members of flight hardware and the utmost inspection reliability is required.

"Crackling" Test -- The so-called "stress wave" analysis technique (Ref. 74) has proven to be a useful tool in tests of composite rocket motor cases under the Polaris program. Further development of a capability to monitor acoustic emissions to the point where it would be done during the useful life of a structure might add considerable impetus to the use of composites.

Ultrasonics

Ultrasonic testing has generally become accepted as one of the reliable nondestructive inspection methods for the detection of voids or unbonds and delaminations.

Ultrasonic methods presently being used for inspection of composite structures and some typical applications are described below.

a) The Pulse-Echo method is used primarily for the inspection of metal-to-metal bonds, fiberglass-to-fiberglass bonds, boron-to-metal bonds, fiberglass laminates (up to 3/4" thick). This technique has been successful in reliably detecting defects in these bond lines equivalent to the response from a 1/8" diameter flat bottom hold (FBH). It is also being utilized for the inspection of honeycomb composites when it is necessary to evaluate the unbonds in detail (i.e., outline each cell unbond on a recording). With certain restrictions, this technique has been successful for both metallic and nonmetallic honeycomb cores and skins. Scanning both sides of the honeycomb part is required for honeycomb structures.

b) The pulse-echo reflector plate technique is being successfully used for thin fiberglass and boron laminates. It is reliably detecting defects in these laminates equivalent to the response of a 1/8" diameter FBH. Access to both sides of the part is required.

c) Through-transmission techniques are being used for the inspection of honeycomb core composites, metallic-nonmetallic laminate build-ups and thick fiberglass laminates. Defects equivalent to $\frac{1}{2}$" unbonds are being detected in the honeycomb composite structures and defects equivalent to the response of a $\frac{1}{4}$"

diameter FBH are detected in the laminate composites. Access to both sides of the part is required.

d) The Resonant Frequency method is being used primarily for the detection of unbonds in metal-to-metal and fiberglass-to-metal bonds. It is also being used for inspection of fiberglass-to-fiberglass bonds where the exposed layer is not exceptionally thick. For reliable detection, the unbonds normally have to be as large as the transducer diameter. Some of the advantages of the ultrasonic nondestructive test methods are:

a) High sensitivity, permitting detection of small voids or unbonds.

b) Great penetrating power.

c) Consistency and accuracy in identifying the location and relative size of voids or unbonds.

d) Fast response, permitting rapid and automated inspection.

However, there are also disadvantages associated with this inspection method. These are:

a) High cost of equipment.

b) Contamination of test specimen because of need for a couplant.

c) Requirement for highly-trained personnel.

d) Need for sophisticated tooling and fixtures when part geometry becomes complex.

Areas which should be investigated in the future are:

a) Application of ultrasonic phenomena for determining bond strength in composite structures.

b) Application of computer technology for interpretation of received ultrasonic information. This could relieve present problems of operator skill and interpretation.

Infrared

There is a need for faster inspection methods that can provide accurate, easy-to-interpret test results for void detection and which, in addition, do not introduce external contaminating agents during the operation. In light of these objectives, the infrared method has proven to be very capable under certain conditions. The infrared nondestructive test is based on gauging the rate of heat flow in a structure by remote surface temperature measurements with an infrared radiometer. A source is required to deliver heat in some controlled fashion to the part being inspected. The rate at which the radiant energy from the heat source is diffused or transmitted will reveal any voids within the part. The voids can be identified by the amount of infrared radiation emitted from the surface of the part, as indicated by the infrared radiometer measurements of the surface temperature. Two conditions that limit the sensitivity of infrared, and therefore its usefulness for void inspection, are: 1) excessive thickness of the laminate or facing sheet, and, 2) a very high thermal conductivity of the laminate or facing sheet material. Both conditions affect the infrared method by allowing lateral heat transfer which will prevent small defects from being detected.

At present, an infrared bond inspection system can be utilized for the detection of voids in honeycomb core/fiberglass skin composite structures. The system is essentially a closed-circuit, slow-scan video system which generates a television-like presentation of the normally invisible infrared energy emanating from the honeycomb box assembly being inspected. A thermal or infrared pattern is generated on the front surface of the test specimen by the simultaneous application of heat to its back side and forced air cooling to its front surface. The infrared pattern generated can be analyzed to evaluate the bond integrity of the test specimen. Bondline voids are easily detectable as cool or dark spots on the infrared presentation. Future areas of infrared research will involve investigation of ability to measure certain properties of composite structures such as resin content, degree of cure, glueline thickness, and bond strength.

Penetrating Radiation

Radiographic and fluoroscopic inspection methods have been successfully utilized for inspection of composite structures, primarily in determining fiber orientation of unidirectional layups, honeycomb core damage, intimacy of bonded components, and fit of subassemblies in a major assembly. The inspection can be performed using either one of the penetrating radiation methods; however, both methods have disadvantages. Radiographic inspection necessitates the use and development of film which is time consuming and costly on large composite structures. The fluoroscopic method eliminates the need for film, but has the disadvantage of decreased sensitivity as compared to the radiographic inspection meth and also, provides no permanent record. In the near future, these methods will be replaced by an Automated X-Ray Sensitive Vidicon and Image Intensifier System offering a combination of radiographic sensitivity and fluoroscopic simplicity. In this system, the x-ray vidicon image will be presented on a remote 17" video screen at approximately 30X. The image amplification system will also present a view on the same screen at a 1:1 ratio. The viewing area using the vidicon tube is approximately ½" x ½" with 1% to 2% penetrameter sensitivity. The viewing area of the image intensifier is approximately 8"x 8" with 3% to 4% penetrameter sensitivity. The x-ray generator will have freedom of movement to allow angulation changes to produce the most desirable view. The viewing speed is variable, with the maximum speed being limited by the interpreter's perception. All controls and viewing apparatus on this system are remote.

Neutron Radiography

This innovative method of examining the internal structure of composite structures, now in the exploratory stage, offers the possibility of an important alternative to x radiography. It produces a detailed image of materials combinations that cannot be x rayed effectively, adding a new dimension to the visual test procedures. The technique involves placing an object to be radiographed in a neutron beam emitted from a nuclear reactor. Neutrons pass through the object and, with the aid of an indirect transfer mechanism, create an image on a sheet of x-ray film positioned behind it. Contrasts in the resulting film negative vary according to the rate at which neutrons are absorbed as they pass through the object being radiographed. The primary area of investigation in neutron radiography will be the evaluation of its capability to look directly at the adhesive in a bondline and to determine the structure of the adhesive at cure.

Microwave

Known most familiarly as the radiation emitted by radar equipment, microwaves are electromagnetic energy oscillating at superhigh frequencies (e.g., ten gigahertz). Recent advances make the nondestructive investigation of material possible with microwaves. Microwave testing involves measuring the energy reflected by, scattered by, or transmitted through materials placed in a microwave beam. The microwaves interact with the molecules of the material through which they pass (only nonmetals) and reflect from surfaces and discontinuities. The areas of application that will be investigated with microwaves are:

a) Monitoring of the chemical composition of both liquid and solid materials (except metals) through measurements of dielectric constant and loss factor.

b) Flaw detection in nonmetal structures (i.e., delaminations, voids, inclusions, etc.).

c) Noncontacting profilometer measurements to determine surface smoothness, regularity, out-of-roundness, etc.

Eddy-Sonic

The Eddy-Sonic test method is relatively new in the field of nondestructive testing for composite structures. It utilizes eddy currents to excite a metallic composite acoustically and the resultant acoustical response is analyzed to determine structure quality. It does not require a liquid couplant as in the ultrasonic methods. This elimination of the couplant variations leads to easier signal interpretation and permits high-speed scanning. This nondestructive test method is presently being investigated for application to some of the composite structures where one of the members is metallic.

Optical

Microscopic inspection is a valuable technique in the NDT of composites, particularly in the examination of fibers prior to fabrication. The establishment of rigid defect criteria for fibers would greatly aid in the scanning and evaluation of the large amount of data which is characteristic of a micro inspection system.

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13. ABSTRACT

The problem of designing structures with fibrous composite materials was examined, with the view that constituent materials and the means of forming a composite from them are well-enough established to be assured of repeatable properties. There was no intent to deal with questions of filament or matrix development, or to deal with specific materials; on the other hand, in examining design problems and potentials it was inevitable that the influence of glass, boron, and graphite fibers, and resin matrices would be strong. The advantages which can accrue from the use of filamentary composites were briefly reviewed, and confirmed as outstanding in many cases. The substantial progress made to date in limited applications is recognized, but the report concentrates on what must be done to benefit as fully as possible from these new materials and to minimize need for "cut-and-try" approaches to design objectives. Accordingly, major design difficulties were sought out and defined. Important among these is the current difficulty in standardizing on the tests needed to characterize many of the important composite material properties and in predicting them by theoretical analyses. The load transfer problem was cited as major, with only limited successes to date. Design with composites was recognized as being more intimately bound to fabrication than is design with conventional materials, and the need for design handbooks and specifications was identified as one part of an important communications, education, and acceptance problem. No attempt was made to give priority to the various research efforts cited by the Committee as necessary. Virtually all of them are required and should receive the support necessary to bring structural composites into routine usage.

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Design with composites						
Design concepts and approaches						
Micro-behavior of filamentary composites						
Macro-behavior of filamentary composites						
Structural unit behavior						
Anisotropy of fibrous composites						
Load transfer in composite structure						
Analytic techniques for filamentary composites						
Failure modes in structural composites						
Finite element analysis						
Finite difference analysis						
Bending membrane coupling						
Fabrication of filamentary composites						
Testing structural composites						
Non-destructive testing						
Orthotropic structures						
Anisotropic structures						