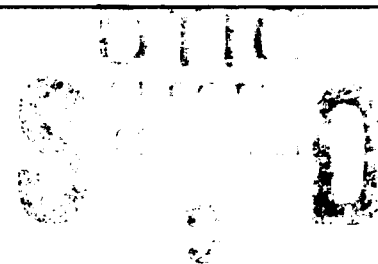


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COMPOSITE MATERIALS DESIGN DATABASE
AND DATA RETRIEVAL SYSTEM REQUIREMENTS

WILLIAM J. RASDORF
NORTH CAROLINA STATE UNIVERSITY

AUGUST 1991

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TABLE OF CONTENTS

	<u>Page</u>
ACKNOWLEDGMENT	v
1. INTRODUCTION	1
1.1 Background	1
1.2 Objectives	1
1.3 Inhibiting Factors	1
1.4 Scope	2
2. COMPOSITE MATERIAL PROPERTY DATA	2
2.1 Composite Material Data Description	3
2.2 Determination and Use of Material Properties	5
3. A CONCEPTUAL COMPOSITE MATERIAL DATA MODEL	6
3.1 Classifier Hierarchies	7
3.2 Data Value Density	9
3.2.1 Interpolation	9
3.2.2 Reduction	10
3.2.3 Incompleteness	10
3.3 Data Value Modifiers	10
3.3.1 Measurement Quality	10
3.3.2 Trustworthiness	10
3.4 Textual References	11
3.5 Materials Database Model Components	11
3.6 Significant Aspects of Materials Databases	12
4. APPLICATION SOFTWARE INTERFACES	13
5. DATA RETRIEVAL APPLICATIONS	14
6. THE ROLE OF EXPERT SYSTEMS	15
7. CONCLUSIONS	15
8. REFERENCES	17
BIBLIOGRAPHY	19
GLOSSARY	25
DISTRIBUTION LIST	35

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1. INTRODUCTION

1.1 Background. The emergence and use of composite materials in engineering applications have increased considerably. A need, therefore, exists to make information available about composite materials, their derivation, their properties, and their use, to researchers and material engineers. To do so requires a greater understanding of the problems and solutions that emerge when integrating composite materials data with computer database technology. Gaining such an understanding will facilitate the eventual development and operation of utilitarian composite materials databases (CMDB) designed to support a collection of analysis and design software.

1.2 Objectives. The objective of this report is to establish the requirements for creating a composite materials design database and data retrieval system for use in ballistic applications. The target database is fundamentally an engineering properties database that is designed to support the needs of analysis, design, and data retrieval software. Of particular concern are the representation of material property data in terms of a data model, interfaces to application software, data retrieval applications, and the role of expert systems in composite material design. Each of these needs is discussed in this report. The eventual objective is to develop a prototype database environment to support these needs. To do so requires a combination of the fields of materials engineering and computer science.

1.3 Inhibiting Factors. A number of factors significantly inhibit the development of a database environment to meet the objective stated earlier. These include, but are not limited to, the following:

- (1) limited access to existing data resources;
- (2) searching for data that satisfies constraints on its properties;
- (3) diversity of material property descriptions;
- (4) lack of suitable data types for engineering data;
- (5) broad range of data needs from processing to design;
- (6) lack of user-friendly standard interfaces to engineering applications software; and
- (7) diversity in levels of quality assurance for data.

Clearly, the data are hard to come by. The key data resources are government documents, research reports, private industry, and laboratory test results. Most representative of government documents are the U.S. Air Force Composites Design Manual and the U.S. Army Military Handbook. The University of Delaware Composites Design Manuals and the Design Data Manual for Composite Materials (Hahn, Hwang, and Cheng 1981) are examples of university research efforts aimed at compiling composites design information. A number of industry representatives also provide a limited amount of data. Last, and particularly relative to the Ballistic Research Laboratory (BRL) initiative, are the test results reported by Swanson (1988) from the University of Utah and by Tsai and Kim (1988) from the Air Force Wright Aeronautical Laboratory.

Despite such sources as these, however, precautions must be observed. Published articles in the open literature seldom contain a complete enumeration of relevant data item values. Proprietary data have to be treated confidentially and may not, therefore, be generally available. Research reports are not subject to regulation regarding their development or presentation, and they, too, are often incomplete with respect to data item values (Dathe 1985). In short, the collection of data resources that is available must be carefully evaluated to ascertain its integrity.

1.4 Scope. This report focuses on the description of material property data, including material and composite properties, geometries, topologies, test methods and procedures, processing methods and procedures, and loadings and conditions of use. Designed components themselves will not be addressed.

The report first discusses composite material property data, then generally discusses the components and structure of a composite materials database and suggests a conceptual data model. Although these items are the focus of the report, consideration is also given to application software interfaces, data retrieval applications, and the role of expert systems.

2. COMPOSITE MATERIAL PROPERTY DATA

The study and use of composite materials have grown dramatically over the last twenty years. Composites are mechanical mixtures of distinctive constituents that can be combined in order to achieve a synergistic blend of properties that cannot be obtained through the use of any of the constituents alone. Composite materials possess highly specific characteristics that make them

uniquely suited to special engineering applications, such as high-speed vehicles, high-performance engines, and other applications requiring materials that can sustain severe mechanical, chemical, and thermal conditions.

Composite materials present a very special challenge to efforts to computerize their properties and performance specifications, because they are uniquely "designed" for specific applications (i.e., they are difficult to classify since they are as various as the engineering circumstances they serve). Their general features, which are particularly important in establishing proper computer representations of such materials, include:

- (1) dependence of properties and performance upon microstructural configuration, shape, and direction;
- (2) environment in which they will be used;
- (3) property definitions of the constituent materials;
- (4) dependence on fabrication and synthesis techniques;
- (5) lack of standardized test methods and characterization schemes for the determination of properties and performance; and,
- (6) an uncommon need to represent the combined response of such materials to multiple excitations and circumstances, such as mechanical, thermal, and chemical loadings.

2.1 Composite Material Data Description. Composite materials constitute a representational challenge, both because of the properties of their microconstituents and because of their arrangement. The global properties of composites, for example, are generally anisotropic, meaning that their response depends on the direction of loading relative to certain special directions defined by the composition. The immediate consequence of this situation, from the standpoint of representation, is that a single property, such as stiffness or strength, becomes an array of properties that requires multiple entries to provide a complete description of the material characteristic. Moreover, when individual plies differ in orientation and combine to form a laminate, yet another set of specific properties and performance characteristics emerges. From the standpoint of database representations, this set of multiple levels is in stark contrast to the material properties and characteristics that are

commonly associated with "traditional materials." Such properties and characteristics provide a unique and permanent definition of the engineering utility of those materials and are obviously much easier to represent in a database. However, it is worth noting that the relational database model is well suited to representing such hierarchies of tabular data.

Another unique feature of composite materials is the need to characterize the properties and response of these materials under unusual conditions. Such conditions frequently involve combinations of severe environments such as cyclic or dynamic mechanical loading, extremely high or low temperature, and severely aggressive chemical exposure. The arrays of properties and performance characteristics mentioned above must be determined as a function of various combinations of these influences that are of interest to specific applications. It is very difficult to find a general representation of these highly variable circumstances and combinations of constituent properties and their configurations. Yet, consideration of such a general representation will result in a better understanding of representations that will, in turn, lead to improvements in database design for specific applications.

Finally, the challenge is further heightened by the necessity to characterize changes in properties and performance as a function of the history of application of the influences commonly applied to these materials. For example, the most important information for materials to be used at very high temperatures is their rate of degradation under a specific set of service and loading conditions, since the utility of the materials is limited by those rates. Moreover, these service-related characteristics depend on the manner in which material properties and performance change during service. The quantification and description of these changes are essential to a complete description of composite materials.

Thus, to develop an appropriate database representation for composite materials, a number of unique circumstances must be considered. In summary, these include:

- (1) arrays of data items may be required to represent a composite material property;
- (2) changes in the structure of the composite material, in its environment of use, and in its loadings may result in different array values; and
- (3) array values may be dependent, as well.

The key challenge from a database design perspective is, therefore, the representation of appropriately connected arrays of data item values.

2.2 Determination and Use of Material Properties. Beyond the complexity and sophistication of the descriptive representations suggested above, efforts to establish databases for composite materials are further frustrated by the fact that test methods to determine material properties and characteristics are still under development and, thus, are not all firmly standardized or accepted as consensus methods for property and performance determinations. Largely because of the complexity of the situation, test methods are commonly developed for circumstances of particular interest to various applications, and variations in those test methods are frequently made, as variations in the applications suggest. A significant proliferation of new test methods, along with a proliferation of new materials, thus complicates the data interpretation problem.

Although notable efforts are being made to establish test methods, especially by professional societies such as the American Society for Testing and Materials (ASTM), these efforts seriously lag the development of composite materials. Consequently, the data arrays mentioned above frequently suffer from absent entries, and suffer even more greatly from multiple entries that differ because of the differences in methods of determination rather than because of differences associated with the material system or performance. Properties such as stiffness and strength suffer less from this malady than do performance characteristic definitions for phenomena such as creep rupture, static and dynamic fatigue, and damage accumulation.

Another important feature related to the determination of properties and performance is the importance of statistical variations of these characteristics in composite materials. It was mentioned earlier that processing plays a significant role in the final character of such materials. In general, not only is processing difficult to control and difficult to repeat, but it presents many difficulties in and of itself. Consequently, variations in properties are surprisingly large from "batch to batch," or even within a given batch, or in some cases with a specific specimen or component. It is impossible to properly discuss the properties and performance of these materials without taking a rigorous quantitative approach to such statistical variations. Indeed, the design of structures with composite materials, and their subsequent certification for service, is frequently based on allowable levels of applied loading determined from a statistical analysis of an allowable rate of failure determined from these statistical variations in material properties and performance.

The concerns about test methods and statistical variations indicate that information regarding the manner in which data are obtained and the manner in which materials are prepared is essential. Efforts to achieve standardization are critical, but nonstandard situations must be expected and properly handled.

Careful consideration of the likely user of material property descriptions must be given for decisions regarding the need to evaluate data and the methods of formatting the data for presentation. Because of the volume and variability of material data that must be handled, search schemes are critical. In addition, representation of dynamic data must be considered.

The complexity and sophistication of computerized descriptions of composite materials may exact somewhat peculiar requirements on such databases. Since these materials are so strongly driven by applications, it may be that databases will be driven by groups of applications, as well. Some of the databases that have currently been established are tailored to groups of users who have peculiar applications or classes of applications that are best served by the structure of the databases involved. Since the cost of these databases is substantial, and cost recovery is a persistent and potentially disabling problem associated with these databases, it may be that tailoring databases to a specific market is a viable development route. However, in order to achieve generality, gateway arrangements are necessary to combine specific databases developed for specific purposes.

Thus, two additional considerations emerge relative to the development of an appropriate database representation for composite materials:

- (1) the lack of standardization and quality control in test methods means that some data item array values are unreliable and that some are missing; and
- (2) the use of data may be application-dependent, and a centralized general data representation may not be achievable, cost effective, or necessary.

3. A CONCEPTUAL COMPOSITE MATERIAL DATA MODEL

The purpose of this section is to consider the conceptual requirements of a composite materials database. To do so requires an exploration of the structure of materials information.

3.1 Classifier Hierarchies. One of the most outstanding features of composite materials data is the large number of classifiers that are necessary to precisely identify observed objects (components), performance (limit states), and function (stress states). In this context, we define: an object as the physical entity being addressed and a component as a constituent part of an object; a limit state as a state of incipient, unsatisfactory behavior in a specific mode (such as limiting loads at which failure occurs) and a performance as a quality that a component must provide for its users; a function as the action for which a component is specially fitted or used and a stress state as a type of induced force per unit area on a component.

Using these categories of classification, one can begin the following hierarchy:

- Components
 - Members
 - Thin wall shape
 - Solid shape
 - Thick wall shape
 - Element of a member
 - Plate
 - Connectors
- Limit states
 - Yield
 - Excessive slenderness
 - Ultimate capacity
 - Instability
 - Local buckling
 - Overall buckling
 - Lateral torsional buckling
- Stress states
 - Axial force
 - Tension
 - Compression
 - Shear
 - Bending
 - Compressive stress due to
 - Tensile stress due to
 - Torsion
 - Combined stress
 - Bending, shear, torsion, axial

This hierarchy, however, is not complete; it does not categorize attributes of objects either in terms of qualities and properties or in terms of processes and behavior; it does not categorize relations and interactions between objects; it does not categorize operations on objects; and it does not categorize location, condition, or time. The intent of the hierarchy is merely to demonstrate the large number of data items of interest in the composite materials area and to show some of the hierarchical relationships between those data items. The physical manifestation of the hierarchy will be the schema of the database itself. A preliminary schema will be offered in the follow-up report.

Another important category of descriptive information that is vital to the interpretation of data item values is textual notes. These, too, are best modeled by a classifier category. For search purposes, it is best to enter textual notes as specific attributes, if possible. Particularly for the newest and most specialized materials, for which experience and understanding have not reached a point of convenient and complete classification, there may be many such descriptive attributes. As a domain unto itself, the collection of textual notes may be modeled as a 2-D vector. This vector establishes an open-ended list with the text of the notes and the number of notes both varying. Whenever the comments for a particular material are identical, it is desirable to reference the same note. Distinct vectors may be appropriate for different material categories.

Two additional categories of descriptive information are particularly noteworthy and important: graphs and equations. A graph represents a collection of data points and can, in fact, be represented as such. Appropriate applications are necessary, then, to generate a graphic representation of the data that has automatic and manual scaling and axis labeling. Curve fitting and generation applications are also necessary.

It is also, at times, necessary to store equations. In one form, equations can be stored in a text field. Such a representation, however, is useful for reference only and is completely nonexecutable. The alternative is to embed equations in application programs that draw their constants, coefficients, and variable values from the database. A database design is required, therefore, that will minimize the number of accesses to different database tables and that will provide values for all of the constants and variables necessary for the execution of the equation.

In summary, the schema can contain at least four types of variables, V, or data:

- (1) identifiers (e.g., graphite/epoxy, T300/5208);
- (2) descriptive characteristics (e.g., suitable for horizontal tail skin);
- (3) independent variables (e.g., cure, test methods, environment); and
- (4) dependent variables (e.g., ultimate tensile strength, strain).

In this example, identifiers determine descriptive characteristics, and both the identifiers and the independent variables determine the dependent variables.

3.2 Data Value Density. We now describe the elements of a data model. While the concept of a relational data schema is intuitively simple, it still lends itself to a significant degree of complexity because of the diversity and complexity of material hierarchies. For any realistic set of attributes, the schema is infeasible and large. The schema characteristics of Interpolation and Reduction can be used to reduce the size of the content of the schema, but they also introduce complexity.

3.2.1 Interpolation. Because of large volumes, some type of condensation of data must occur for the effective use of a database. Associating an interpolation function with an attribute can greatly reduce the number of entries in its domain; only critical points may need to be explicitly represented. However, more than one function may be needed for distinct ranges, as determined by phase changes and the like.

Using the same function for extrapolation may also cause a reduction in the number of explicit data items, and these may be directly proportional to the number and naturalness of the parameters used to describe the function. Naturalness means a function that mimics the physical behavior of the materials system, rather than a general polynomial function that is adequate by numeric measures but that requires ever-increasing terms to span wider ranges of values.

Extrapolation is quite a different matter than interpolation in that the bounds of uncertainty can usually be precisely stated for the latter but are large and frequently indeterminate for the former. Furthermore, the appropriate interpolation or extrapolation function and its adequacy (both in the mathematical and natural senses) varies from property to property.

3.2.2 Reduction. Reduction means the reduction in data content when one or more independent attributes are not recorded. Reduction may occur because the underlying information may not exist or because it may exist sparsely. There may not always be data on heat treatment or test-sample-configuration, for example. Furthermore, when considering the identification of a composite, it may not always be possible to have information about the specific batch number. The problem with data reduction is the loss of information for those variables that depend on all of the missing attribute values.

Note that reduction is an example of vertical data reduction and may be contrasted with the horizontal data reduction provided by interpolation. That is, interpolation causes a sparsity of data at one level in the data hierarchy, whereas reduction causes a sparsity of data that propagates through multiple levels of the hierarchy.

3.2.3 Incompleteness. The conceptual database schema has tables of fixed size with fixed cardinalities. Unfortunately, especially when one considers the actual data subsets, as defined via reduction, the overall domains of the data may be incompletely represented in the database. For example, temperature range is likely to be incomplete for many of the test-sample configurations. Thus, a substantial portion of the theoretically available data might be missing.

3.3 Data Value Modifiers. The set of data is rarely absolute. There will be variation in the material, variation in the measurements, questions of trustworthiness of the measurements, as well as outright errors. We cannot currently deal well with errors using existing database management systems (DMBSs), except by setting error bounds, which will cause erroneous data to be rejected upon input.

3.3.1 Measurement Quality. Most data are obtained by measurements. Associated with specific sets of measurements, there may be degrees of tolerance and uncertainty.

3.3.2 Trustworthiness. There are also, of course, the user's interpretation and belief in the validity of the data. While a specific user may place a belief assessment into the set of modifiers, a more general model would associate the belief with the Source, or rather with a crossproduct of independent attributes such as Source X Material. Auxiliary tables, keyed to these attributes, might represent this level of the user's interpretation.

3.4 Textual References. Textual references are not constrained to be literal strings. They may also be indirect, namely references to published literature. Of course, if the reference is to a large object—for example, a reference to a textbook—only a small portion of the referenced information will be relevant. For an actual implementation, direct and indirect information may be combined: the abstract, itself, will be directly available; for more detail, further data may be indirectly accessed via the author's name and publication information. In either case, keyword(s) play a major role in the access process. Thus, the system can not only process attribute/value pairs but also locate documents and descriptive text based on keyword(s) from which the user can further extract values.

3.5 Materials Database Model Components. The components that might be included in a materials database model are shown below. The relative importance of these components can differ greatly; some may not exist at all in some materials databases. If an existing database system approach is imposed on the materials database, then it is likely that some components will be missing or underemphasized.

<i>D</i>	Base matrix of data values.
<i>V</i>	Set of values within a data cell of <i>D</i> .
<i>Ij</i>	Independent variables identifying the data values.
<i>d</i>	Domain values for the identifying data values.
<i>D^j</i>	Data values at higher levels of abstraction, omitting one or more identifiers (<i>j</i>).
<i>F</i>	Interpolation/extrapolation functions to permit computation of domain values.
<i>M</i>	Modifiers for data values.
<i>I_t</i>	Textual identifiers.
<i>R</i>	References cited by textual identifiers.

The following relationships connecting the components can be identified:

- (1) the data values are determined by the set of their identifiers;
- (2) each data cell is composed of a "small" set of data values, where 1...i could be either different properties or different measurements of the same property;
- (3) some data descriptors are textual;
- (4) some data descriptors are graphical;

- (5) some data descriptors are functions or equations;
- (6) there is a set of textual descriptors from which zero or more may be selected;
- (7) some textual descriptors reference documentation;
- (8) data may be reduced;
- (9) domains may have interpolation functions for values.

3.6 Significant Aspects of Materials Databases. While the components of a CMDB can be mapped to components of other types of databases, some differences stand out and make it difficult to implement an effective CMDB on current Commercial, Off-The-Shelf (COTS) systems, or general DBMSs. These are summarized below, where materials database system (MDBS) terms are related to DBMS terms (in parentheses):

- (1) the number of identifying (key) attributes is much greater than those seen in current commercial applications. A MDBS requires a large number of keys, where a commercial DBMS normally requires only 1, 2, or 3;
- (2) much of the actual data do not exist at the base levels but only at higher levels of abstraction;
- (3) textual notes, descriptors, graphs, and equations are all important for understanding the applicability of the data;
- (4) interpolation functions may be attached to the domains;
- (5) the number of dependent attributes per cell (tuple) is small, but the specific attributes vary from material to material.

Broadly speaking, one consults a computerized materials database or system of databases for one of three purposes:

- (1) to retrieve the properties data for a particular material;
- (2) to find a short list of candidate materials with a specified set of properties; or

- (3) to sort particular materials into groups serving some functional purpose or application area.

For these purposes, a designation or identification scheme that will define and differentiate materials with significantly different properties is required. Each of the unique aspects of a MDBS complicates this need significantly. There is also, of course, the practical consideration of special features or special properties unique to small groups of materials and the consideration of new, specialized materials. The classification of these groups may yet be inadequate or incomplete for translation into existing and general databases.

4. APPLICATION SOFTWARE INTERFACES

It must be recognized that a comprehensive set of materials software is a system involving extensive integration and coordination between its various application programs. Integrations issues, which are so crucial for the implementation of such new technologies, have not yet been addressed. However, these issues do need to be considered, and the problems associated with them must be solved, in order to obtain higher precision, greater reliability, and lower costs.

Although an overall goal must be a long-term, strategically focused, cross-disciplinary approach that accelerates the integration of design, analysis, materials, information processing, and manufacturing into a system, this initiative focuses on the information processing aspects. In particular, it is concerned with the integration of a set of applications that play a role in the composite materials design and manufacturing process. Such integration requires a broadly focused, systems approach rather than an emphasis on the more traditional, discrete efforts. Furthermore, it requires the participation of investigators with complementary skills from a number of disciplines and orientations.

It may be stated that, ultimately, integration may be obtained through:

- (1) object-based tools, languages, and environments;
- (2) nondeterministic approaches to computation, taking into account tolerancing, error propagation, and material and geometric uncertainty; and
- (3) information technologies such as parallel task decomposition, database management, communications, and a man-machine interface.

Using these emerging technologies at the state of development in which they now stand will support a modular, possibly distributed, and cohesive test bed system. With respect to the database and application program/database interaction, a number of objectives emerge:

- (1) separation of the physical details of data storage from the application programs, affording the application developer complete insulation from data structure details;
- (2) modularization to support the development of standardized interfaces and to support wider application program distribution;
- (3) increased application programmer productivity; and
- (4) direct access to all data in a logically centralized location.

5. DATA RETRIEVAL APPLICATIONS

Two broad categories of data users exist in the context of a composite materials information system; designers and analysts, on one hand, and application programs, on the other.

Scheduled operation of a DBMS usually refers to batch processing of application programs using sequentially organized files. Batch processing is a common mode of operation for engineering software. Engineering design systems, however, are not well suited to batch processing. Transaction-oriented processing, in which each application program transaction is processed completely and all files are updated at once, is somewhat of an improvement. A further improvement is on-demand processing, in which data files are organized so that records can be obtained in any sequence as soon as they are required. Relative to application programs in a composite materials design system, this is the recommended approach. Issues related to the appropriate application system organization were discussed in the last section.

Relative to user interaction with a database, interactive, real-time processing is the mode of choice. It is highly desirable to enable users to directly query the database and extract the information that they need. Although general database browsing is not as common in engineering as in other disciplines, it is necessary and must be supported. Data query languages and forms, as well as report generators and interrogation languages, are provided by all commercially available DMBSs for this

purpose and are generally sufficient for composite materials information needs. These increase interactive processing and direct user involvement, thereby increasing the value of stored data. Specific recommendations, however, will be made for customizing a set of standard query action plans to support commonly accessed data.

6. THE ROLE OF EXPERT SYSTEMS

With respect both to material property data and to composite material processing, analysis, and design, it is necessary to integrate expert systems with the overall CMDB environment. Unfortunately, at the present time, the majority of expert systems are stand-alone systems, and environments for effectively coupling heuristic data management with nonheuristic data management remain to be developed. The only available recourse is to resort to traditional DBMS development and use, and to service application-specific expert systems via the DBMS program interface. This approach is entirely satisfactory and supports the current development of software in the composite materials area.

7. CONCLUSIONS

It is clear that existing database technology is not robust enough in its capabilities to fully accommodate the needs of composite materials data representation and use. Three approaches may viably address this issue. The first is the development of new technology. Work is being done in this area in the computer science community, where object-oriented data representations are emerging. Additional work is proceeding on database and expert system coupling techniques and on the representation of the heuristic aspects of knowledge and data. As more robust, general systems emerge for storing and processing data, the capabilities of these systems must be evaluated and compared to the needs of composite materials data processing systems. The natural evolution of such systems will provide incremental improvements that warrant consideration for adoption. It is not suggested, however, that such new technology development be undertaken by the BRL.

The second approach to achieving a technology suited to the needs of composite materials data representation and use is to modify or extend the capabilities of existing technology. This approach has been suggested in Rasdorf (1987), which offers a solution for at least one of the problems enumerated herein. Other researchers have also suggested modifications and extensions to treat the special needs of engineering databases.

The adaptation of existing database technology or the development of new database technology provides data representation and use solutions that will emerge over time. Satisfying immediate needs, however, requires the direct use of existing technology. This approach is recommended for the development of CMDBs so that immediate prototyping can begin. This will facilitate the acquisition of experience and understanding and also facilitate the dissemination and use of CMDBs. Specific recommendations for creating a successful MDBS include:

- (1) clearly define compatibility and integration needs between the data and its users and applications;
- (2) standardize, to the extent possible, testing and data generation procedures;
- (3) standardize, to the extent possible, the database schema;
- (4) develop trial database schemas;
- (5) populate and test databases for trial applications to determine their robustness and flexibility;
and
- (6) monitor the development of database technology and identify alternative technologies as they emerge and mature.

8. REFERENCES

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GLOSSARY

The merger of the materials engineering and computer science fields may result in a degree of ambiguity for some regarding terminology. In the interest of clarification, this section presents a glossary of commonly used terms in these two specialized areas. The primary source for the definitions presented in the Computer Science section is Wiederhold et al. (1987), and the primary source for the definitions presented in the Materials Science and Engineering section is Tsai (1986).

Computer Science

abstraction - The process of providing information at a higher level (e.g., ignoring some of the variables that can affect data values). Abstraction may involve a computational summarization or just a selection of certain parts of the original information.

access - Entering a computerized data system to read, write, search, or edit data.

aggregation - An operation in which data are summarized to a higher level, and a key attribute controlling the aggregation is deleted. For instance, a computation to compute the MEAN density of a set of poly-vinyl is an aggregation. Aggregation functions, such as COUNT, SUM, MAX, MIN, and Standard Deviation, may be part of an aggregation.

association - Indicates a relationship among entities or a connection among database relations.

attribute - The attribute of a data value is its name, and such a name is commonly associated with a column in a table of records; a field containing information about an entity.

characteristics - Used to describe properties, independent variables, etc., pertaining to a material. For example, characteristics might include color, ultimate tensile strength, form, etc.

codasyl model - A framework proposed by a committee of the Conference on Data Systems Languages for describing the logical structure of databases in terms of record and set types.

constraint - A formalization of relationships to describe data semantics and interrelationships among data items and relations.

data - A set of technical information represented by tables, graphs, models, numbers, equations, expressions, or symbols. Note that data differ from information.

data abstraction - Providing the user with an abstract view of the data so that details of how the data are stored and maintained are hidden. Data abstraction must often be weighed against the ability to retrieve information efficiently.

data capture - Collecting data and storing it in a database in such a way that the data in the database approximates or models the object being represented.

data constraints - See **constraint**.

data evaluation - The examination and validation of data by experts to assure that data conform with phenomenological or theoretical models.

data independence - A characteristic of most DBMSs wherein the data in the computer system is independent of the ways in which users view that data.

data item - The smallest unit of data that has meaning in describing information; the smallest unit of named data.

data model - A collection of conceptual tools for describing data, data relationships, data semantics, and data constraints.

data reliability - See **reliability**.

data security - See **security**.

data semantics - The meaning of data, primarily established through the relationship of a data element to other elements and descriptive information.

data structure - How data are organized and placed into memory. The data structure in a database should reflect data semantics and is referred to as the database schema.

database - A collection of related data. A comprehensive database contains all of the information necessary to manage an enterprise. Less comprehensive data collections that support some part of an enterprise are also commonly called databases. A data collection managed by a single-application program is best not considered to be a database.

database management system (DBMS) - The collection of software required for using a database, which handles the definition, storage allocation, retrieval, and update of records by presenting multiple views of the data to the users and programmers. A DBMS controls redundancy of records and provides security and data independent of a database. DBMSs allow the user to sort through large volumes of files and display relationships that would be too time consuming and sometimes virtually impossible to generate in the manual system.

dependent - Data values that depend on other, key values for their meaning.

domain - The collection of data items of the same type in a relation entity. Something about which data are recorded.

engineering information system (EIS) - A computer system that combines databases and data processing programs to aid in the analysis, design, processing, and assembly of engineered systems.

entity - Something about which data are recorded.

entity-relationship model - A framework for describing the logical structure of databases in terms of entities, relationships, and attributes.

expert system - A computer-based system that emulates the performance of a personal expert or consultant. A computer system design based on logic or artificial intelligence.

fields - Contain the basic values that comprise a record. The content of a field is provided to users or their programs on request. Computational processes can manipulate such values. The values are associated with a type and a domain.

file - A collection of logically related record occurrences that is treated as a unit; a file is commonly stored on a secondary storage device.

functional dependence - Attribute B of a relation R is functionally dependent on attribute A of R if, at any instant in time, each value of A has no more than one value of B associated with it in relation R.

graphical database - A data file that includes capabilities for representation of pictorial information in the file.

incompleteness - Having only sparse information, i.e., only measurements for some of the combinations of key parameters.

information - Knowledge acquired or derived; knowledge that can be collected, stored or filed, retrieved, and used to create other knowledge. To be useful, information must be pertinent, communicable, comprehensive, dependable, and convenient.

information hiding - Withholding information, such as processing rules, from the database user to keep him or her from using such information and bypassing formal interfaces.

information management system (IMS) - An organized body of knowledge, provided with appropriate interlinkages between its subparts, a variety of access mechanisms, and user assistance.

integrity - The avoidance of loss of consistency in a database.

knowledge base - The component of a knowledge-based system that contains the system's knowledge. It is generally regarded as the most important component.

knowledge-based system (KBS) - A computer program containing knowledge about objects, events, situations, and courses of action, which emulates the reasoning processes of human experts in a particular domain. The components of a knowledge-based system are the knowledge base, inference engine, and user interface. It may also contain a Truth Maintenance System separate from the inference engine. Types of knowledge-based systems include rule-based systems and model-based systems.

knowledge manipulation - Processing of the rules or semantics that describe the data, rather than the data itself.

knowledge representation - The techniques used to store information in a knowledge base. Knowledge representation techniques include logic (also called formal methods), semantic networks, production rules, frames, and scripts. It is also common to see systems classified as storing Attribute-Value pairs, Object-Attribute-Value triplets, or Frames.

model - A framework used to formally describe something.

normalization - The decomposition of more complex data structures into relational database tables.

object - A collection of data to describe a single entity or event. The description of a single materials instance, including data for a set of temperature conditions, may be organized into an object type. An object may also include procedures for retrieving, manipulating, or updating data within that object. Object data are typically not normalized.

object class or type - Prototype for an object.

object-oriented paradigm - Computing methods based on the concept of objects.

object-oriented programming - Programming methods based on the use of items called objects that communicate with each other via messages. In terms of Knowledge-Based Systems, the main difference of Object-Oriented Programming from Frames is the communication between objects by the sending and receiving of messages. It is important to note that Object-Oriented Programming exists as a programming methodology separate from Knowledge-Based Systems. Object-Oriented Programming provides an ideal framework for the concept of concurrent, asynchronous operations.

persistence - Essential attribute of a database for which information is retained independently of program termination.

prototype - An initial model created for and used to simulate a small-scale version of the larger, actual thing. Prototypes are generally used in research to test the functionality of an idea.

quality assurance - A planned and systematic pattern of all actions necessary to provide adequate confidence that the item or product conforms to established technical requirements.

query - A statement requesting the retrieval of information from a database.

query language - A language especially designed to aid the user in accessing a database.

range constraint - A rule that limits the range of data values.

records - A collection of related fields containing elemental data items. Fields may be related to each other because they describe some specific instance, such as a person, an object, or a property.

relation - A two-dimensional array of nonhomogeneous data elements.

relational database - A database in which the conceptual files are all relations. Related data items of single-valued, simple attributes constitute tuples.

reliability - The ability of an item to perform a required function under stated conditions for a stated period of time. With respect to data, reliability indicates the dependability of the information in terms of accuracy and precision.

SQL - A standard for a relational database language.

schema - The overall logical structure of a database.

security - The process of protecting data against unauthorized access.

semantics - The meaning of data. The semantics of individual data elements are expressed by linking them into objects, and the semantics of objects are expressed by having them participate in relationships with other objects. The linkages and relationships are described by constraints.

structural information - Formal description of relationships among data, which can affect the structure of the database.

table - See **relation**.

thesaurus - The vocabulary and associated terms used in indexing to ensure retrieval. Tight vocabulary control with continual updating is essential to the retrieval of pertinent information.

uncertainty - The concept in a knowledge-based system of a piece of information or a conclusion having a likelihood somewhere between True and False. Some systems have built-in mechanisms for handling uncertainty. The definitions used and the mechanisms employed differ considerably between systems.

user interface - The virtual boundary between the user and the computer system. Its main components are the command language, formats for data representation, input and output devices, sequencing and timing representation, etc.

view - A subset of a database appropriate for a particular user or application. It is obtained by selecting, projecting, joining, and aggregating data from base relations in the database.

Materials Science and Engineering

adhesive - Substance capable of holding two surfaces together.

advanced materials - Materials engineered to have specifications that exceed those of commonly available materials.

anisotropy - A material that has different physical, thermal, and/or electrical properties, depending on its orientation.

angle-ply laminate - A laminate possessing equal plies with positive and negative angles. This bidirectional laminate is simple because it is orthotropic, not anisotropic. A $[\pm 45]$ is a very common angle-ply laminate. A cross-ply laminate is another simple laminate.

autoclave - Pressure vessel that can maintain temperature and pressure of a desired gas (including air) for the curing of organic-matrix composite materials.

bending moment - Stress couple that changes curvature of a beam or plate.

boundary conditions - Load and environmental conditions that exist at the boundaries of a component.

buckling - Unstable, lateral displacement of a structural part, such as a panel, caused by excessive compression and shear. Microbuckling of fibers in a composite material can also occur under axial compression.

combined stresses - State of stress with multiple components active. In the case of plane stress, all three components are present.

compliance - Measurement of softness, as opposed to stiffness, of a material. It is a reciprocal of the Young's modulus, or an inverse of the stiffness matrix.

composite or composite material - Material that is made by combining two or more constituent materials to produce a multiphase system with different physical properties from the starting materials. Fiber-reinforced materials are uni- and multidirectional filamentary composites in woven and nonwoven forms.

constituent materials - Individual materials that make up the composite material.

cross-ply laminate - Special laminate that contains only 0- and 90-degree plies. This bidirectional laminate is orthotropic and has nearly zero Poisson's ratio. The other simple, bidirectional laminate is the angle-ply, which possesses one pair of balanced, off-axis plies.

curing - A reaction in which the molecules of the fiber and matrix of a composite are cross-linked to form a strong, three-dimensional network.

deformation - Changes in size and shape of a body resulting from externally applied stresses, temperature change, and moisture absorption. Deformation in size is measured by the normal strain components; deformation in shape is measured by shear components.

deflection - Displacement of a structure such as a beam.

delamination - Debonding process primarily resulting from unfavorable interlaminar stresses.

design - To select optimum ply number and orientations for a given composite laminate subjected to one or more sets of applied stresses.

displacement - Measure of the movement of a point on the surface and in the interior of a body.

elastic - Fully reversible, single-valued stress-strain. Loading and unloading follow the same path. Although nonlinear relation is admissible, the relation for composite materials is essentially linear.

engineering constants - Measured directly from uniaxial tensile and compressive, and pure shear tests applied to unidirectional as well as laminated composites. Typical constants are the effective Young's modulus, Poisson's ratio, and shear modulus. Each constant is accompanied by letter or numeric subscripts designating the direction associated with the property.

epoxy - Thermosetting resin made by polymerization of an epoxide.

failure criterion - Empirical description of the failure of composite materials subjected to complex state of stresses or strains. The most commonly used are the maximum stress, the maximum strain, and the quadratic criteria.

failure envelope - Ultimate limit in combined stress or strain state defined by a failure criterion.

fiber - Single filament, rolled or formed in one direction, and used as the principal constituent of woven and nonwoven composite materials. Most common fibers are glass, boron, graphite, and aramid.

fiber content - Percent volume of fiber in a composite material. Most common composites in use today have fiber content between 45 and 70 percent.

filament - A single, continuous fiber with exceptionally high specific stiffness and strength, which is the principal constituent of composite materials.

first-ply failure - First-ply or ply group that fails in a multidirectional laminate. The load corresponding to this failure can be the design-limit load.

heterogeneity - On the micro level, local variation of constituent materials. On the macro level, ply-by-ply variation of materials or orientations.

homogeneity - Material uniformity within a body.

interface - Boundary or transition zone between constituent materials, such as the fiber/matrix interface, or the boundary between plies of a laminate. Debonding at the microscopic or fiber/matrix interface can lead to fiber breakage and matrix crackling. Debonding at the macroscopic or interlaminar interface can lead to delamination.

interlaminar stresses - Three stress components associated with the thickness direction of a plate. The remaining three are the in-plane components of the plate. Interlaminar stresses are significant only if the thickness is greater than 10 percent of the length or width of the plate. The effects of these stresses are not easy to assess because three-dimensional stress analysis and failure criterion are not well understood.

isotropy - Property that is not directionally dependent, i.e., remains the same for all orientations of the coordinate axes. Composite laminates can be made isotropic in their in-plane stiffness, e.g., any $[\pi/n]$ laminate with n greater than 2, which is referred to as a quasi-isotropic.

lamina - Ply or layer of unidirectional composite or fabric.

laminate - Plate consisting of layers of uni- or multidirectional plies of one or more composite materials. A laminate is usually thin.

laminated plate theory - The most common method for the analysis and design of composite laminates. Each ply or ply group is treated as a quasi-homogeneous material. Linear strain across the thickness is assumed. This is also called the lamination theory.

layup - Ply stacking sequence or ply orientations of a laminate.

macromechanics - Structural behavior of composite laminates using the laminated plate theory. The fiber and matrix within each ply are smeared and no longer identifiable.

material designation cross-reference - A table of synonyms for specification of a material. It can contain trade names, common names, and chemical names.

material identification - The data necessary to specify a material. For composite materials, this includes structural, mechanical, chemical, and geometric data, etc.

material performance - Mechanical and physical properties of a material that help determine the service life of a product.

material properties - The results of groups of analyses of individual, experimental, property data leading to single values or relationships indicative of the performance of a material. The basis may be typical or nominal values based upon averages of individual test results, minimum values based upon some statistical analysis, or representative curves deduced by materials experts. See **property data**.

material profile - A listing of the desired properties for a particular material with quantitative values specified whenever possible in terms of allowed range, minimum, maximum, etc.

matrix - Material that binds the filaments or fabric to form a composite material. The most common matrices for organic composites are polyester and epoxy.

mic-mac - The integration of micromechanics and macromechanics in the design of composites.

micromechanics - Calculation of the effective ply properties as functions of the fiber and matrix properties. Some numerical approaches also provide the stress and strain within each constituent and those at the interface.

modulus - Elastic constants such as the Young's modulus, shear modulus, or stiffness moduli in general.

moment - Stress couple that causes a plate to bend or twist.

multidirectional - Having multiple ply orientations in a laminate.

orthotropy - Having three mutually perpendicular planes of symmetry. Unidirectional plies, fabric, cross-ply, and angle-ply laminates are all orthotropic.

ply - See **lamina**.

ply group - Group formed by continuous plies with the same angle.

principal direction - Specific coordinate axes orientation when stress and strain components reach maximum and minimum, for the normal components, and zero, for the shear.

property data - The calculated results of individual, experimental, property tests, a description of materials behavior under a stated condition or process. See **material properties**.

resin - Organic material that has high molecular weight, is insoluble in water, and has no definite melting point and no tendency to crystallize. See **epoxy**.

shear stress - Component that results in distortion; different from normal components that result in extension or contraction.

sizing - To select by design the ply number and angles of a laminate subjected to one or more sets of applied stresses. Sizing of isotropic materials is easy, because there is one thickness required for each load. Sizing of composite laminates is fundamentally different, because both ply number and angles must be considered. It is a nonlinear process; i.e., 10 percent ply addition does not mean 10 percent increase in strength. See **design**.

stiffness - Ratio between the applied stress and the resulting strain. Young's modulus is the stiffness of a material subjected to uniaxial stress; shear modulus is the stiffness of a material subjected to shear stress.

strain - Geometric measurement of deformation.

strength - Maximum stress that a material can sustain.

stress - Intensity of forces within a body. The normal component induces length or volume change; the shear component induces shape change.

symmetry in material - Repeating material property; four common symmetries for composite materials are orthotropy, transverse isotropy, square symmetry, and ultimately isotropy. For these cases, the functional relations between stress and strain remain the same; only the independent material constants decrease from 9, 5, 3, to 2, respectively.

transverse isotropy - Material symmetry that possesses an isotropic plane, e.g., a unidirectional composite.

unidirectional - Having parallel fibers in a laminate.

volume fraction - Fraction of a constituent material based on its volume.

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