Development of an Information Model for Composites Design Data¹

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Abstract: Material properties data, particularly that of advanced composite materials such as fiber-reinforced plastics, provides a very complex domain which is difficult to computerize. As a foundational activity supporting the development of material property databases, we have examined and modeled the data contained within this large, diverse, and intricate domain. Our primary objective was to gain a better understanding of the data involved in this system and its transformation and use. We examined the life cycle of a fiber-reinforced composite material, from a raw material to a manufactured product, focusing on the various applications which require and/or supply materials data and the types of materials data which must be included. A high-level information model was created to illustrate the overall picture of composite materials data which emerged from this analysis. This model provides a global view of the data encompassed in the domain of composite materials, and forms the basis of a formal conceptual model from which databases may be developed.

1. Introduction

Composite materials are increasingly being viewed as a potential solution to many structural and infrastructure problems facing civil engineers today [Ballinger90, Tarricone93]. A key need exists, therefore, to make information about composite materials, their derivation, their properties, and their use available to researchers, materials scientists, and engineers. In response to this need, the engineering community is beginning to develop material properties databases to support the use of composite materials for engineering applications. However, many of these databases suffer from design flaws because they were developed in an "ad hoc" manner, without the use of formal modeling techniques.

1.1. Modeling

A good database implementation depends upon how accurately and completely the data involved in the domain can be modeled. One way to ensure a good data model is by using a formal

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modeling methodology which enables a database schema to be designed in a systematic fashion. Using such an approach improves both the quality and timeliness of the database design procedure. A sequential modeling methodology can be used to thoroughly examine the data within the domain of composite materials. The steps in the sequential modeling methodology are as follows.

First, the data needs and functional requirements of those who use composite materials data should be established with respect to the engineering material properties, metadata, special data types, and functions that are required. Once the required properties and procedures are determined, an information model can be developed to describe a generic engineering material and, more specifically, a composite material. An information model is a high-level model that defines and organizes the data needs of the domain area. It also illustrates the basic structure of the data and relationships among data items. A data flow diagram or a state space diagram can be considered information models [Chadha91].

A conceptual model can then be developed using a formal modeling methodology, such as the Entity-Relationship method or NIAM [Chen76, Nijssen89]. A conceptual model provides a more formal, detailed look at the domain, by distilling the information content down to the concepts of entities, attributes, and relationships. Conceptual models are generally paper models, although newer Computer-Aided Software Engineering (CASE) tools allow computerized development of conceptual models.

The next step in the methodology is to convert the conceptual model into a computational model. Computational models are computer-sensible, which means that the model can be directly read and interpreted by appropriate computer software. A well-known example is SQL, which includes a data definition language for relational database management systems.

The final step in the modeling methodology is to translate the computer-sensible computational model into a computer model, which is a software specific database implementation. The database implementation can then be used as a component of an integrated system to support a variety of engineering application programs.

1.2. Focus

In research conducted at North Carolina State University, a collection of Entity-Relationship diagrams was developed which provide a conceptual model of the data within the domain of composite materials over its entire life cycle. The purpose of developing this conceptual model is to enable the eventual development of composite material property databases. But as a foundational activity to create the conceptual model, a detailed examination was performed on the data contained within this large, diverse, and intricate domain and a high level information model needed to be created first. This paper summarizes the work done to create that information model and makes a presentation of the information model itself. For additional details on the Entity-Relationship conceptual model that was subsequently derived from the information model, see [Spainhour94] and [Spainhour95].

This paper focuses on the importance of developing an accurate, complete, and non-redundant information model prior to developing conceptual models and subsequently computational models. It describes the development of an information model for composite materials as a demonstration of the types of activities which must be involved at this level. An information model helps the data modeler understand the data involved in a domain and its transformation and use. By developing an information model, we have a better understanding of the scope of data and metadata required to support the needs of civil, structural, and mechanical engineering applications and a variety of users, including decision makers, technical users, and clerical users.

It is our hope that research in the areas of data modeling, data standards, and integrated computer-aided analysis and design systems, including that described herein, will help overcome the difficulties in developing historical composite materials databases. In short, we hope to provide the foundational tools and capabilities that engineers need to begin solving traditional problems using advanced composite materials. With such a research knowledge base established, composite materials can continue to gain a prominent role as engineering materials, suitable for both government and commercial applications.

2. Composites Data and Standards Activities

Standards organizations such as the American Society for Testing and Materials (ASTM), the International Organization for Standardization (ISO), and the Committee on Data for Science and Technology (CODATA) have various efforts focused on modeling and computerizing materials data. The STandard for the Exchange of Product data (STEP) effort is key in the development of a data exchange language for engineering product data, including material properties. The American Concrete Institute (ACI) and the American Society of Mechanical Engineers (ASME) are attempting, respectively, to gather archival material properties data on concrete that has been in service for up to fifty years, and to build a database to maintain characteristics of the 20,000 types of steel available internationally [Oland90, ASME93]. Key aspects of these efforts include developing data formats for structuring materials data, and gathering properties on materials that have been in service for many years. We hope to avoid the latter scenario by recognizing the data needs of composite materials and developing data structures to support those while the materials technology is still emerging.

The work which is most relevant to that described herein is the work by ASTM Committee E-49 on Computerization of Material Property Data in developing standard data formats [ASTM93]. These ASTM standards, enumerated below, recommend required and optional fields for identifying composite materials and recording test data.

- **E1434:** Standard Guide for Development of Standard Data Records for Computerization of Mechanical Test Data for High-Modulus Fiber-Reinforced Composite Materials
- **E1309:** Standard Guide for Identification of Composite Materials in Computerized Material Property Databases
- **E1471:** Standard Guide for Identification of Fibers, Fillers, and Core Materials in Computerized Material Property Databases

Each standard provides a generic format for computerizing the data within its domain. The standards provide fields which are likely to be valuable to certain engineers and material specialists and therefore should be recorded and included when a set of identification or test data is transferred to another organization or entity. These standards provide the beginning of a data model definition for composite materials. While the standards are recommendations for what data should be included in computerizing data, they do not provide guidelines for structuring the data within a database. Furthermore, the standards are generic, attempting to be as concise as possible, while accounting for the data needs of many tests and types of composites.

Because of their generality, the data fields are often not as precise as possible. For example, ASTM E1309 attempts to address the features of all types of composites, including particulate, short fiber, metal matrix, and ceramic matrix composites, in a useful manner within one format. However, the standard leans toward the needs of laminated composites. In doing so, it tends to leave out information pertinent to other types of composites or use generic note fields where specific parameters might be more appropriate. For example, the field *structural detail* is very generic, and might be replaced with the field *winding angle* if a standard format were developed specifically for filament wound composites. The fields *ply count* and *lay-up code* are relevant only to laminates.

To contrast the research described herein with the efforts described in the previous paragraphs, it is important to note that we are interested in examining the breadth and depth of data involved in the domain of composite materials. The ASTM data formats focus on identification and test data, while we are interested in modeling the entire life cycle of a material, from selection and design to disposal. Whereas the ASTM effort focuses primarily on laminated composites, we are concerned with all types of fiber-reinforced plastics, including pultruded, filament wound, braided, woven, and bulk molded composites. In addition, the data formats provide a relatively small number of attributes, with a limited number of generic data fields for metadata storage.

3. Life Cycle of Composite Materials

Before examining fiber-reinforced composite materials data in particular, it is important to first look at the data needs and functional requirements of engineering materials in general. First, this process provides a sound basis for the eventual development of a specific composites model by ensuring that it will be broadly reflective of the needs of the engineering community. It provides an overview of the nature and types of data that are important for any engineering material, knowledge which can then be applied to the domain of composites, perhaps leading to a discovery which would not have been made otherwise. Second, a generic model of materials data can be modified to suit different material classes and/or application areas; therefore the work becomes extensible and more generically applicable to many different types of materials beyond fiber-reinforced composites.

3.1. Forms of Materials Data

Materials data takes many forms. Engineers are generally concerned with test data. Properties such as strength, stiffness, and creep are available in many materials handbooks and property databases. However, many other types of materials data are often overlooked, including:

- Identification and description of materials,
- Source of material, test specimen, or data set,
- Composition of material,
- Substructure of composite material or component,
- Performance of material or component,
- Availability of constituents or materials,
- Safety and health information (e.g. toxicity),
- Environmental interaction information,
- Processing and manufacturing parameters,
- Geometry and shape of constituents and components,
- Tolerances on materials and components, and
- Costs of constituents, components, etc.

Data of these types provide supporting information for the material properties test data. For example, this information documents who developed a material and performed specific tests, what is its underlying composition and shape, how it should be used, when the given properties data is applicable, and why it behaves in a certain manner. In looking at the engineering environment to evaluate data needs and data sources, it is important to consider data pertaining to each of these types.

3.2. Materials Hierarchy

It is also important to note that the definition of what constitutes a material is constantly evolving. While a polymer is a material with a distinct set of properties, it can also be a constituent of a fiber or matrix, which has additional properties. In the same way, a fiber is a component of a prepreg tape, and its properties become properties of the prepreg. Many engineering components are made up of subcomponents which have been joined together in some manner. The hierarchical nature of materials data must be incorporated into a conceptual model to support engineering materials.

A general materials hierarchy is presented in Figure 1. At the top level is a generic material, also known as a material class or material category. A generic material encompasses several commercially available materials and has properties which generally describe all materials in that class. Examples include structural steel and graphite/epoxy prepreg. Generic materials may be instances of other generic materials; for example, high-strength concrete is an instance of concrete.

Following the left branch of the hierarchy, available materials are those which are obtainable from a specific manufacturer, which have specific properties that supersede those of the related

generic material. For example, A*370-8H/3501-5A is a graphite/epoxy prepreg manufactured by Hercules. It has specific properties; however, it is available in several sheet widths with various tracer threads. On-site materials are those which are available on-site for manufacturing; one of the available forms has been selected from the manufacturer, yet the material is usually supplied in bulk form. Thus, while it is immediately available, it is not an actual component until some shape, form, or dimensions have been applied to the material through machining, cutting, or other processing. Finally, the components can be combined into structures, which can further be combined into more complex structures.

On the right branch of the hierarchy are designed components and designed structures. They are identical to those on the left branch, except that their existence is conceptual. That is, components may be dimensioned, designed, and analyzed in a theoretical framework. Because designed structures do not physically exist, they may be based on properties of either generic materials or available materials. Even further complexity is introduced when we realize that actual structures may or may not be based on the designs in the theoretical hierarchy.

3.3. Material Life Cycle Stages

To develop a comprehensive conceptual model and subsequently a materials database, data should be included from the entire life cycle of the material, from the inception of design concept through the failure and disposal of the component. There are four sequential stages in the life cycle of an engineering material: design, manufacturing, use, and disposal. Each stage encompasses numerous potential activities or applications. Each application potentially needs and/or supplies materials data. It is important to recall the hierarchical nature of materials data. Each of these stages, particularly design and manufacturing, can apply to numerous subcomponents, which can then be combined recursively to make increasingly complex structures.

The types of data needed and/or supplied by each application are enumerated in Tables 1 through 4, categorized according to the life cycle stages. The data items in these tables are not necessarily atomic; that is, they often refer to a collection of information of a specific type which is either required to complete an activity or supplied by the completion of the activity. In addition, all of the fields or data categories will not necessarily be applicable to each material component.

It is also important to distinguish exactly what the data items are referring to. Some items refer to one component; others to an entire batch. It is important to understand that, at this stage, it is impossible to completely describe the data required. That will be further defined by many factors, including the specific material being documented (e.g. identifying an aluminum alloy will require different data than identifying a composite laminate), the performance characteristics desired (e.g. if a particular chemical exposure must be withstood, data which might otherwise be irrelevant is important), and the organization maintaining the data (e.g. procurement, quality assurance, and inspection procedures can vary greatly among different organizations). This illustrates why it is so hard to develop universal material property models and databases.

In addition to documenting the design, manufacturing, use, and disposal of the component in question, this data also ties together information about previous and subsequent components which served the same purpose. Much of the information is needed to store and maintain the knowledge that went into decisions regarding the component, e.g. why a particular design was selected and why it failed. The collection of this information is known as design knowledge capture, and is important to provide a historical record which is useful in later stages of the component life cycle and which can be used to guide future designs. To further the idea of knowledge capture, note fields should be included at every stage to document all of the design decisions and record discussions, justifications, and cautions that cannot be anticipated prior to initiating the component life cycle.

3.3.1. Design Stage

Design is an iterative procedure that begins with an initial or preliminary design, on which some type of functional and cost analyses are performed. The design is iteratively varied and the analyses repeated until certain performance criteria are met. At that point a detailed design is completed [Charles89]. The applications within the design stage are illustrated in Figure 2, which is adapted from an illustration in reference [Charles89]. In this figure, rectangular boxes refer to design stages and rounded rectangles refer the input and outputs from each of these stages. The "Y" and "N" branches indicate the success or failure of a particular design stage.

In the context of Figure 2, preliminary design refers to the initial specification of shape and topology of a component. Detailed design refers to the final, complete specification of a design, including the design scenario, material specification, design tolerances, and final geometry. The "performance analysis" application refers to the analysis of the design for additional factors beyond structural performance. Designs are driven by three factors:

- Component loading needs (internal pressure, gravity, etc.),
- Material performance issues (high temperature, impact resistance, non-toxicity), and
- Component manufacturing issues (long shelf life, easy to mold, etc.) [Johnson89].

Loading needs are evaluated using structural analysis programs; however, the specific data required to complete a "performance analysis" depends upon the desired performance, e.g. resistance to ultraviolet light, fracture toughness, etc. Aesthetic issues such as color and surface finish could also be considered performance criteria. By necessity, therefore, the data required for the performance analysis of a component is discussed in very general terms. As stated previously, this information could be defined in more detail once a specific desired performance is identified. Manufacturing issues will be considered in the context of the manufacturing stage of the material life cycle.

Taking into account the types of materials data mentioned previously, Table 1 enumerates the data required and/or supplied by application programs during each stage in the design process. It is assumed that identification information is required in each application in this and other stages of the life cycle. Within the specific context of the design stage, the identification of the

component would include a version number to distinguish between preliminary design alternatives.

Furthermore, as indicated previously, the following information is required for each subcomponent in a design. This is indicated in the final design application by the "Final component substructure" field, which provides a mechanism for identifying all of the subcomponents used in a particular component. By referring back to this information in the record for each subcomponent, the entire component hierarchy and all of the supporting data can be found.

Table 1: Data required and supplied by applications during design stage

Preliminary Design (Component Design)	
Data Needed:	Data Supplied:
Identification of component being replaced	Preliminary or revised component specification
Purpose/application of component	
Desired functionality of component, including material performance issues*	
Expected environment (temperature range, humidity, chemical exposure)*	
Expected loads*	
Failure analysis of previous designs	
Previous design version (material, cost, structural and performance analysis results)	
Availability and cost of materials	
Expected final cost of component	
Service history of previous designs	
Codes, standards, and specifications	
Suggested alterations of previous design versions	
Material Testing	
Data Needed:	Data Supplied:
Identification of material specimen to be tested	Identification of test organization and administrator
Specification of test to be performed	Time and date of test
Standard test specifications	Test metadata
	Material property test results

* This combination of items is referred to elsewhere as the expected service history of the component.

Table 1, continued: Data required and supplied by applications during design stage

Material Selection	
Data Needed:	Data Supplied:
Expected service history of component	Preliminary material composition
Material property test results	
Material Design	
Data Needed:	Data Supplied:
Expected service history of component	Material composition
Composition of suggested constituents	Material properties
Properties of suggested constituents	
Cost Analysis	
Data Needed:	Data Supplied:
Preliminary material composition	Cost of preliminary component as specified
Preliminary design geometry	Suggested design alterations
Costs of materials	
Structural Analysis	
Data Needed:	Data Supplied:
Expected service history of component	Forces, moments, deflections of component
Preliminary material composition	Sufficiency of preliminary design
Preliminary design geometry	Suggested design alterations
Codes and standards	
Performance Analysis	
Data Needed:	Data Supplied:
Desired functionality of component	Sufficiency of preliminary design
Expected environment (temperature range, humidity, chemical exposure)	Suggested design alterations
Behavior of preliminary material as specified	
Codes and standards	

Table 1, continued: Data required and supplied by applications during design stage

Component Testing	
Data Needed:	Data Supplied:
Expected service history of component	For each test performed, identification of test organization and administrator
Standard test specifications	For each test performed, time and date of test
	For each test performed, test metadata
	For each test performed, test results
	Sufficiency of preliminary design
	Suggested design alterations
Detailed Design	
Data Needed:	Data Supplied:
Expected service history of component	Final design geometry**
	Final component substructure**
	Final material composition**
	Component functionality/strength/suitability**
	Discussion/justification of selected design
	Required manufacturing tolerances
	Suggested/required manufacturing methods

The entire concept of test documentation, that is, the description of the test equipment, environment, procedure, etc. is identified here only as a need for test metadata. For a more complete discussion of what data is required to document a test, refer to the next section.

3.3.2. Manufacturing Stage

The manufacturing stage encompasses all activities from the selection of a manufacturing process based on material properties and desired characteristics through the production of the completed product. Applications identified in the manufacturing stage of the material life cycle are itemized in Table 2 below; for each application, the types of data needed and supplied by the application are listed. In the manufacturing stage, identifying the component includes documenting the lot number of the batch being produced.

** The combination of these items is referred to elsewhere as the component specification.

Table 2: Data required and supplied by applications during manufacturing stage

Process Selection	
Data Needed:	Data Supplied:
Component specification	Selected process
Expected service history	Discussion/justification of selected process
Required manufacturing tolerances	Processing parameters
Suggested/required manufacturing methods	
Availability of processes	
Suitability of processes	
Health and safety information	
Procurement	
Data Needed:	Data Supplied:
Availability of constituent materials from manufacturers	Selected supplier
Cost of constituent materials	Cost per component
Supplier information (name, address, service record, etc.)	Supply schedule
Assembly/Processing	
Data Needed:	Data Supplied:
On-site availability of constituent materials	Personnel involved in each stage
Production sequence	Date and time of stage initiation
Processing required at each stage	Date and time of stage completion
Required manufacturing tolerances	Actual processing applied at each stage
Safety and health information	End condition at each stage
Material Inspection/Quality Assurance	
Data Needed:	Data Supplied:
Component specification	Name(s) of inspector
Regularity of inspections	Date of inspection
Features/defects to be monitored	Type of inspection (visual, NDE, etc.)
Required manufacturing tolerances	Description of inspection
	Results of inspection
	Actual manufacturing tolerances
	Action to be taken
	Percent defective parts for each type of defect
	Percent parts outside of tolerance range

3.3.3. Use Stage

The use stage encompasses the entire operation and use portion of a material component or product. Components are subjected to service loads and operating conditions, and may be inspected, repaired, or altered. Applications included in this stage of the material life cycle are itemized below. In table 3, the types of data needed and supplied by the application are listed for each application.

Table 3: Data required and supplied by applications during use stage

Operation	
Data Needed:	Data Supplied:
Component specification	Variation in service load ^{***}
Expected service history	Variation in service temperature ^{***}
Environmental interaction	Variation in humidity ^{***}
Safety and health information	Chemical exposure ^{***}
Corrosion, wear properties	
Inspection	
Data Needed:	Data Supplied:
Component specification	Name(s) of inspector
Service history	Date of inspection
Regularity of inspections	Type of inspection (visual, NDE, etc.)
Reason for inspection	Description of inspection
	Results of inspection
	Action to be taken
Maintenance	
Data Needed:	Data Supplied:
Component specification	Name(s) of maintenance personnel
Service history	Date of maintenance
Regularity of maintenance	Description of maintenance procedure
Reason for maintenance	Results of maintenance
	Action to be taken next

^{***} The combination of these items is referred to elsewhere as the service history of the component.

Table 3, continued: Data required and supplied by applications during use stage

Repair	
Data Needed:	Data Supplied:
Component specification	Name(s) of repair personnel
Service history	Date of repair
Reason for repair	Description of repair
	Results of repair
	Action to be taken

3.3.4. Disposal Stage

The final stage in the life of a composite material component is the disposal stage. This stage includes all activities from the failure of a component to the disposal and/or recycling of the constituents, including the substitution of a replacement. Applications identified in the disposal stage of the material life cycle are itemized below along with the types of data needed and supplied by the application.

Table 4: Data required and supplied by applications during disposal stage

Failure Analysis	
Data Needed:	Data Supplied:
Source of material	Type/mode of failure
Conditions under which failure occurred (environment, load)	Reason for failure
Expected service history	Suggested design variations
Service history	
Substitution	
Data Needed:	Data Supplied:
Design specification	Identification of replacement component
Expected service history	Description of replacement component
Service history	Discussion/justification of selected replacement component
Reason for substitution	Variation in functionality
Availability of potential replacement components	
Cost of potential replacement components	

Table 4, continued: Data required and supplied by applications during disposal stage

Recycling	
Data Needed:	Data Supplied:
Material composition	Recycling action taken
Environmental interaction	
Safety and health (toxicity)	
Disposal	
Data Needed:	Data Supplied:
Material composition	Disposal method
Environmental interaction	Disposal location
Safety and health (toxicity)	

If, upon failure, the component is replaced by a substitute part, we identify the replacement component as part of the disposal data. In the context of database implementation, the identification of the substituted component would tie into another data record with life cycle data for the new component. In this way, we have life cycle data for the entire project, while still maintaining the component life cycle as the primary frame of reference in the data model.

4. The Role of Metadata

Because of the importance of metadata in the domain of materials data, particularly for composite materials, we consider it separately. Metadata, or data about the data, is the term used to refer to data describing a specific material component or specimen, its origin, and the tests performed on it. There is much disagreement among developers and users of engineering materials regarding the type and amount of test data which should be recorded. Metadata into can be separated into two categories, objective and interpretive. Objective metadata answers the questions "who," "where," and "how," indicating, for example, who generated a data set and how a test was performed. Interpretive metadata, on the other hand, indicates the quality of a data set, including the accuracy and completeness of the data set, its significance, and its expected purpose.

4.1. The Importance of Maintaining Metadata

A significant proliferation of new test methods, along with a proliferation of new materials, complicates the data interpretation problem. Many standard test methods exist and notable efforts are being made to establish standard methods for emerging engineering materials, especially by professional societies such as the American Society for Testing and Materials (ASTM). However, these efforts often lag the development of new materials, and composites are no exception. Often, standards that exist are not followed because an organization lacks suitable equipment or chooses to test under specific conditions more relevant to the end use of the material.

Documenting test parameters through metadata is most important in the absence of standardized test specifications. However, it is important to maintain metadata even when standards are followed, as there is still an amount of uncertainty regarding procedures and methodologies followed. In most test specifications, the parameters are variable within specified ranges or for a certain specimen type or size. Recording this metadata in a data model is necessary both to record nonstandard test conditions and to account for the variability allowed by the test specification.

In conclusion, metadata serves two purposes in a material properties database. First, data documenting a material test is very useful to compare test results, particularly in the absence of standard test methods. Second, when standard test methods are available, the storage of metadata indicates to what degree a specific test adopts the standard methodology. Thus, metadata can be used to validate the accuracy of a single test against a standard, and it can be used to evaluate the consistency of two or more nonstandard test methods. In addition, a full complement of metadata documents variations in material processing, which plays a significant role in the final character of many materials, including composites.

4.2. Recommendations Regarding Metadata

To completely characterize a material and a particular test, the Mechanical Properties Data Center (MPDC) [Mindlin86] suggests that the data items in the following categories be recorded for each test:

- Data source (reference, laboratory, traceability),
- Material description (source, lot number, composition, heat-treatment, etc.)
- Test description (standard methods, details of non-standard procedures, equipment, loading procedures, etc.),
- Test environment (temperature, chamber, corrosive chemistry, etc.), and
- Raw data (test values, etc.).

While raw data does not technically qualify as metadata, it is important to maintain in a materials database to the extent that space allows. First, raw data might be necessary to validate derived data at a later date: points on a load-elongation curve, along with proper sample dimensions, can be used to verify the elastic modulus of a material. Secondly, raw data can be used to derive new data that was not originally conceived of when the test was performed. The raw load-elongation data, for example, might be used to examine strain at breakage or ultimate strength, whereas this information would have been lost if the only data stored in the database were the elastic modulus. Note also that MPDC suggests that details of non-standard test procedures should be stored. Efforts to achieve standardization of test methods are critical, but non-standard situations must be expected and properly handled, particularly while standards are under development.

Committee E-49 on Computerization of Material Property Data, whose mission is to develop standard classifications, guides, practices, and terminology for building and accessing material property databases is developing similar guidelines to aid organizations and individuals that are involved in building databases or intelligent knowledge systems [Kaufman88]. E-49 guidelines

suggest that the following types of information will be useful for test data sources: general test type; specific test method; specific dimensions, location, and orientation; test independent variables; property descriptors; specific test results (including raw data); and all validity requirements and any individual data or assessments needed to establish validity.

We have examined the general metadata recommendations of ASTM, MPDC, and other organizations, evaluating them in the context of the complex nature of composite materials data. In particular, several standards developed by ASTM Committee E-49 include metadata requirements for composite materials. From this information, coupled with the above-mentioned recommendations and [Rencker89], we have extracted a set of general metadata requirements, which are listed and categorized in Table 5 below. The metadata recommendations provided below focus primarily on objective metadata; the quality of a data set is not discussed within because of space limitations, although it is considered in [Spainhour94]. As with the types of data required to document a material life cycle, the items in the list are not strictly atomic, and often refer to a group or collection of data.

Table 5: General metadata requirements

Data Source (if extracted from printed material)	
Reference name	Citation information
Pages referenced	Section referenced (figure, table, etc.)
Date accessed	
Data Source (if extracted from database)	
Database name	Date accessed
Time accessed	Description of search procedure
Data Source (if laboratory test)	
Test laboratory	Contact person
Address	Telephone number
Date received	
Data Description	
Type of property, e.g. theoretical, tested, statistical, design allowable	Theoretical basis, if theoretical property
Statistical basis, if statistical property	Governing agency, if design allowable
Test Description, if Tested	
Test administrator	Test date
Test location	Test specification or method used
Specification agency	Type of test

Table 5, continued: General metadata requirements

Material Description	
Specification	Commercial designation
Source, supplier, and/or manufacturer	Manufacturer's code number
Date of manufacture	Lot number
Chemical composition	Substructure
Shape, dimensions	Manufacture, assembly
Curing, heat treating	Preprocessing
Service history	Physical properties (density, moisture content)
Test Specimen	
Type or shape	Dimensions
Location within sample	Orientation within sample
Method of removing sample	Tab information (if applicable): material, adhesive, length, thickness, angle, fillet radius
Gage length	Preprocessing
Preparation	
Specimen Preconditioning	
Time(s)	Temperature(s)
Humidity(s)	Chemical exposures
Test Environment	
Temperature(s)	Humidity(s)
Chemical exposures	Exposure times
Test Procedure	
Equipment identification	Equipment control mode
Grip type and torque-up conditions (if applicable)	Test parameters, e.g. loading rate, stress level
Procedure steps	Deviations from standard procedure
Test Results	
Number of specimens	Raw data
Property for each specimen	Type of failure, if specimen failed
Average property	Standard deviation
Observations, notes, particularly of unusual occurrences	

5. Life Cycle Data Flow

In the previous sections, we presented the applications supported over the life cycle of an engineering material and the data needed and supplied by those applications. This section groups the data into categories or domains, and discusses the data flow between those domains over the life cycle of the material. To satisfy the data needs over the life cycle of an engineering material, we envision the collection of materials data separated conceptually into three domains as listed below.

- **Properties data:** Generic materials data describing materials which may or may not have been built.
- **Product data:** The specification of an actual component or product.
- **Service data:** Data on the service life of a component.

Figure 3 depicts the data flow between the applications in the four life cycle stages and the three conceptual domains. A collection of properties data describing the structural, performance, and manufacturing characteristics of one or more materials is usually available prior to initiating a component design. The properties data, therefore, supplies information to both the design and manufacturing stages of the life cycle. After completion of the design and manufacturing stages, a final component design is available, as well as a history of the design and manufacturing processes. This information makes up the product data.

As the component is used and finally disposed of, the material properties and design/manufacturing information are often important. For example, before changing the loading or environment for a particular component, the engineer would need to know the conditions for which the component was originally designed. As a result, the information in both the product domain, and the properties domain, to a lesser extent, supplies these two life cycle stages. Finally, service information should be recorded as the component is used, and the disposal, salvage, or recycling of the component should be documented. This information from the use and disposal stages constitutes the service domain.

Design is often adaptive or variational, taking a previous design and modifying it to suit different conditions or a new purpose. Therefore, having information about previous designs available is important during the design stage of a component. For this reason, Figure 3 includes an arrow from the service domain to the design stage, depicting the need for information on the performance of previous component when performing the design for another. Note that the data in the properties domain is continually updated through the flow of information from external databases, including handbooks and other reference sources, into the properties domain for the material at hand. External databases can be bibliographic, providing citations and abstracts to relevant literature, or numeric, containing actual property values. External databases are often provided by government agencies, standards organizations, or private industry, either through the public domain or as a fee-based service. The entire set of data is expanded as more information is discovered, through experiments, statistical analyses, and the study of components in service.

The following sections enumerate in more detail the potential contents of the three conceptual domains and relationships among them. There are similarities in the lists below, which indicate the types of data in each of the three domains, and those in the previous sections, which describe the data supplied by and or needed by various applications in the material life cycle. This is because the categories listed below describe in general terms the contents of the final conceptual model, which must encompass all of the data items supplied to and generated by the applications in the material life cycle.

5.1. Properties Domain

The properties domain contains generic materials data, which is data about material forms and components available from suppliers and data which applies general categories of materials, e.g. structural steel, graphite/epoxy prepregs, etc. This data is gathered from specimen material property tests, and from external databases and handbooks. Types of data which are in the properties domain include:

- ASTM standard test data
- Non-standard test data
- Test metadata
- Supplier data (costs and availability)
- Design allowables
- Catalog data

The properties data is self-sustaining and can be entered at will. There is no need for instances of the material to be in use, as indicated by corresponding data records in the product and service domains, for records to exist in the properties domain. The opposite statement is not true, however; for a material component to exist in the product domain, a corresponding set of properties must be present in the properties domain.

5.2. Product Domain

The product domain contains information on specific design components. This information constitutes the complete specification of the collection of material products. The first level at which product data may be obtained is from bulk, on-site materials. These materials, such as potted core, rolls of prepreg, and standard lengths of pultruded sections, are physically on-site, yet they have not yet been used in any structures. Product data is also maintained on components, which are on-site materials to which size, shape, and dimensions have been applied through machining and processing, and on structures made from one or more components. Types of data which are in the product domain include:

- Design history
- Expected loading and service environment
- Subcomponents and constituents
- Final shape, geometry, and features
- Required and actual processing

5.3. Service Domain

The service domain contains all of the information generated by the actual use of the component. In addition, information documenting the failure and disposal of the component is included in this conceptual domain. Types of data which are in the service domain include:

- Service environment
- Service loads
- Maintenance and repair history
- Performance evaluations
- Failure conditions and mode
- Disposal method

6. Information Model for a Composite Material

In keeping with the sequential modeling methodology presented previously, we first considered the data content of materials data by looking at the life cycle of a generic engineering material component and by focusing on materials metadata. We then considered the data flow throughout the life cycle of a material. Now, by developing an information model for an engineering material, we begin to understand some of the relationships among data items. This, in turn, begins to indicate how a conceptual model should be structured.

We have identified three interrelated parameters which define a materials data set and describe its function and its information content. The three parameters are as follows:

- **Property:** The property or type of data being described in the data set, e.g. electrical properties, thermal properties.
- **Time/stage of development:** The moment in time or stage of product development for which the data set is applicable, e.g. data about a constituent, data about a subcomponent.
- **Refinement/reduction of data:** The stage of refinement or amount of data reduction which has been applied to the data, e.g. raw data, certified data.

The combination of the three parameters defines a particular materials data set. That is, for each point in the development of a material product, a data set with a particular amount of reduction or refinement can be created to describe each relevant material property. Figure 4 depicts each of the parameters as a dimension in a three-dimensional matrix. The "stage of development" dimension extends from constituent data at one end to final product data at the opposite end. The "refinement/reduction" dimension extends from raw data to application data, which is distilled, verified, and formatted for input to an application program. The "property" dimension consists of distinct points, one for each property being described.

The entire matrix provides a complete description of the material product. Each (x, y, z) point in the three-dimensional coordinate space is defined by its position with respect to the three parameters. Because this is a high level model, each cell in the three-dimensional matrix is a data set rather than an atomic data value; the cells can also be empty. The shape of the matrix

coordinate space is arbitrary. It depends upon many factors, including the specific domain of interest, the type of materials being characterized, and the amount of data gathered.

6.1. Type of Property

The property dimension is a one-dimensional array consisting of distinct points for each type of property being defined. The points are distinct because the data sets for each type of property are generally not related. A potential property array is illustrated in Figure 5. In this and the following figures, the circles represent collections of data joined by a unifying factor, also referred to as data sets. The exact content of the array would be determined from the needs of the end users of the database, including component loading needs and material performance issues as discussed in Section 3.3.1.

6.2. Stage of Development

Documenting the stage of development requires a two-dimensional tree structure with inter-related data sets. The leaves of the tree (nodes with no children) define the different constituent materials which are combined during the development of the final material product. Parent nodes are created with the addition of processing to the material constituents. The data sets are inter-related because each data set builds upon the information provided by the previous set. In the context of Section 3.3, the data concerning the use and disposal stages would occur at the level of the final product, which is the root node of the tree. A possible stage of development tree for a laminated composite is illustrated in Figure 6.

6.3. Refinement/Reduction of Data

The third dimension of the matrix describes the refinement and reduction of a data set as it progresses from raw data to application data. Figure 7 illustrates the reduction and refinement of data as a tree structure, in which the leaves of the tree are individual data sets, and parents are created due to the reduction and aggregation of the data. This figure expands upon concepts presented in [French90] and [Westbrook86]. This model represents all of the stages through which a data set can pass. It is unlikely, however, that every stage of reduction will be present for a given data set.

In the figure, the lowest level of reduction is that of raw data, the actual measurements read from the testing apparatuses; it is modeled as a leaf, with no children. Physical data is described in terms of the actual properties being investigated, e.g. strains, stresses, etc. Data might be calibrated to a particular value, and/or reduced by eliminating unnecessary or erroneous values. Finally, the data set can be validated through either a comparison of the test conditions and procedures with accepted standards and/or a comparison of the data to certified results for similar test conditions.

Each of the above actions is performed at the level of the individual test. Results from more than one test can be grouped together (aggregated) and evaluated against one another using techniques such as the least squares regression analysis. The evaluation procedure might result in the

elimination of one or more individual data sets. Thus far, we only discussed the data resulting from experimental tests. Theoretical data, which is the results of computer modeling and other theoretical analyses, can also be incorporated into the collection of data.

In addition, catalog data can be used to enhance or augment data from tests and computer analyses. Catalog data implies any data that is extracted from external sources, including databases, handbooks, and reference materials. Catalog data may already have been evaluated and/or processed. A great deal of catalog data is available commercially and through the public domain; where private use and further reduction are permissible, proper credit must always be given to the owner of proprietary data.

Like the aggregated experimental data, catalog data and theoretical data may also be evaluated using comparison techniques. The evaluated data can be further manipulated and processed, resulting in derived data. This category includes average, typical, and maximum values, etc. After a great deal of validation, evaluation, and often external certification procedures, design data can be generated.

Design data, as discussed in Section 3.3.1, includes design allowables and other parameters which directly govern design procedures. For most materials, design data is primarily catalog data; however, for advanced materials where few specifications exist, design data is often generated from experimental and theoretical data. Finally, application data is data which has been distilled, verified, and formatted for input to an application program.

As each progressive step in the refinement or reduction of a data set occurs, additional data is generated. For example, if a data set is calibrated, the calibration factor, reason for calibration, and results of the procedure are important. It is also necessary to record validation techniques, mark rejected data sets, and indicate which individual tests were included in aggregated data sets. Generally speaking, it is important to store the relationships between data sets and the information gained at each stage of data reduction.

6.4. Usefulness and Limitations

While the information model is useful for understanding the relationships between various parameters required to describe materials data, it cannot be used directly as a conceptual database model. Firstly, it lacks the level of detail required to efficiently model materials data. The intersection of the three component dimensions of the matrix results in a data set containing a large amount of disparate data. To support efficient computerization, this model must be further subdivided such that each data set is distilled down to the level of objects and relationships.

Secondly, the overall shape of model results in the possibility of unused space and therefore is inefficient for large scale data storage. The final size of the matrix model is arbitrary, depending upon the size of each dimension, which in turn depends upon the material being described and the parameters about which information is desired. However, within those constraints, the three-dimensional shape of the matrix space requires that there be data cells available for the intersection of all (x, y, z) points on the matrix. Depending upon the exact requirements placed

on the information model, this could result in a large amount of unused storage space. An example would be if ductility information were only required for one stage in the development of a material product; the data cell corresponding to ductility properties would be empty for the remainder of the life cycle of the material.

7. Conclusions

This paper discusses the life cycle stages of an engineering material and the data needed and supplied by various applications throughout that life cycle. It describes how a materials database can transfer data in and out of the application programs, and provides an information model which defines a materials data set by the intersection of three parameters: property, stage of development, and refinement/reduction of the data. Much of this information is presented in a generic manner, so that it is applicable to all types of engineering materials. The special data needs of composite materials are also discussed.

As stated in the introduction, this research into the data needs of composite materials, in support of the development of an accurate, complete, and non-redundant information model, was a foundational activity preceding the development of the formal model to support the life cycle of a composite material [Spainhour94]. This requires a detailed and rigorous analysis as described herein. We found that the conceptual model, which consisted of a collection of Entity-Relationship diagrams, was able to incorporate most of the themes and concepts developed in the information model. We recognize that establishing the data needs of the database end users and developing a rigorous high-level information model, prior to developing a conceptual model, is an essential step to support effective computer models and computational analysis systems.

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Figure 1: General materials hierarchy

Figure 2: Design stage of material life cycle

Figure 3: Life cycle data flow between three domains of conceptual materials data

Figure 4: Three-dimensional matrix model of materials data

Figure 5: Property data array

Figure 6: Stage of development tree

Figure 7: Refinement/reduction of data tree