Advanced Composite Material Property Data Modeling for Engineering Analysis and Design[1]

by

Lisa K. Spainhour and William J. Rasdorf
North Carolina State University
Raleigh, NC 27695-7908

Jessica M. Alberts
Washington University at St. Louis
St. Louis, MO 63130

Abstract: Awareness of fiber-reinforced plastics is increasing in the domain of civil engineering. However, much of the potential of these new materials is lost because of inefficient data management practices. The main focus of this research is the design of a formal conceptual data model, which encompasses the data needs of civil and structural engineers throughout the life cycle of a composite material component. This data model can be used to support automated data exchange and database development. Other issues addressed in this research include assessing the suitability of the Entity-Relationship model for composite materials data, and modeling special types of data applicable to composite materials.

Keywords: Composite materials, fiber-reinforced plastics, textile composites, database design, conceptual modeling, Entity-Relationship diagram, ASTM test data, product data

1. Introduction

Currently, there are trends in the engineering community that lead to decreased database development, database development without the benefit of formal conceptual modeling methodologies, and subsequently, decreased database usage. However, if these problems can be overcome, there are tremendous opportunities for the use of conceptual data models, materials databases, and integrated systems to address real-world civil engineering applications. In particular, composite materials have potential as structural components in bridges, buildings, and infrastructure rehabilitation because of their high stiffness- and strength-to-weight ratios, resistance to corrosion, and special thermal, electrical, and magnetic properties. Being aware of both the potential problems and opportunities, we have sought to develop a conceptual data model for fiber-reinforced composite materials data using the Entity-Relationship methodology [1].

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1.1. Problems in the Engineering Community

It is well known that there is a lack of analytical tools to support the use of composite materials in civil engineering. There are few integrated systems that support engineering analysis and design; those that exist are underutilized in the field of civil engineering. Although electronic test equipment is common, data is often exchanged in paper form by charts and graphs rather than through computerized files. Because database management systems were developed for business applications, there is a lack of suitable data types for engineering.

Coupled with the above items is a lack of good historical materials data describing fiber-reinforced composites. Characterizing composite materials is very data intensive, much more so than traditional civil engineering materials. In addition, there has been little research into the data needs of thick composite sections required for many civil applications, including pultruded, braided, woven, filament-wound, bulk, and thick laminated composites. Because composites incorporate comparatively new technologies, standardized test methods are still under development for many material properties.

Finally, many databases in use today were developed in an ad hoc manner with no modeling methodology. The structure and contents of these databases are therefore suspect as no formal normalization or verification procedures have been performed. Often the data structure does not account for quality assessments, metadata, or other items that help ensure and maintain data accuracy. Without ready availability of complete, trustworthy properties data, there is an uncertainty on the part of engineering analysts and designers regarding the behavior and performance of composite materials: this uncertainty is unacceptable because civil engineers deal with the public safety, health, and well-being.

1.2. Opportunities

Despite the problems that face developers and users of materials databases, many important contributions can be made through continued research in this area. Formal conceptual data models provide a better understanding of the data in a domain area by distilling the data down to concepts of entities, relationships, and attributes, and are useful as common languages for communication across diverse organizations. As defined in [2], conceptual modeling is the activity of formally describing some aspects of the physical and social world around us for purposes of understanding and communication. Modeling functional application requirements and information system components at a conceptual level is even more important given the growing demand for information systems of ever-increasing size, scope, and complexity.

Many empirical studies have shown that a poor initial understanding of data and functional requirements can result in huge expenses later in correcting errors and making changes to a system during operation [2]. Most graphical conceptual models can be mapped directly into database structures, ensuring well structured, normalized designs, while textual models provide an implementation language for computerized data exchange. Examples of conceptual data models are the textual model provided by the EXPRESS language, which is the implementation language of the STEP product data exchange effort, and Entity-Relationship (ER) and NIAM diagrams, both graphical data modeling tools [1,3,4].

Continued development of materials databases is important for several reasons. Acting in the same way as a materials handbook, a materials database can support general browsing of materials data, searching for the properties of a particular material, and selecting one or more materials that meet specific property constraints. In addition, data from a materials database can be automatically extracted and formatted for input into integrated application programs, and output from analysis and design software can be stored in databases, thereby supporting data exchange. Finally, a material properties database can be joined with an expert system front end to form an Intelligent Knowledge System (IKS), where the database acts as a data archive and the expert system provides heuristic and diagnostic reasoning to solve complex design problems [5].

1.3. Related Work

Standards organizations such as the American Society for Testing and Materials (ASTM), 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 [6,7]. 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.

A data modeling effort relevant to composite materials is the PAS-C program, sponsored by the US. Air Force [8]. SCRA, Inc. is developing a suite of application protocols to support analysis and design information for laminated composites. The resulting product definition model will be sufficient to represent and exchange composite parts information for design, analysis, test, production, quality assurance, and repair of aircraft composite structural components. PDA, Inc. has also developed the Advanced Materials Database System (AMDBS), a material properties database for laminated composites, which maintains test, finite element, and CAD data; a commercial version of this software has since been released [9].

To contrast the research described herein with the efforts enumerated in the previous subsection, it is important to note that we are interested in examining the breadth and depth of data involved in the domain of composite materials. Whereas the two efforts cited above focus exclusively on laminated composites, we are concerned with all types of fiber-reinforced plastics, including pultruded, filament wound, braided, woven, and bulk molded composites. Similarly, both prior efforts focus primarily on the data needed to support computer aided design and finite element analysis, while this research focuses on the entire life cycle of the material component.

However, while both of the above efforts provide a final product, a suite of application protocols and a commercially available database, respectively, our research provides only a conceptual model in the form of Entity-Relationship diagrams. This model can subsequently be mapped directly into a relational database for implementation purposes. Moreover, we suggest that additional work should be undertaken to utilize the extended-relational or object-oriented database model, thus enabling the implementation of the special data types mentioned previously.

2. Conceptual data modeling

To ensure the development of a well structured, normalized database, we have pursued a sequential modeling methodology. However, the primary focus of this research is on developing a formal conceptual model of the data. We have utilized a collection of Entity-Relationship diagrams for the initial conceptual model and are investigating the general constructs provided by the extended ER models, the specific implementations available, and their suitability for composite materials data. The general modeling methodology, as well as some features of the ER model and its extensions are described in more detail in the following subsections.

2.1. Modeling Methodology

The overall modeling methodology utilized during this research is illustrated in Figure 1. First, we attempted to determine the data needs and functional requirements of those who use composite materials data regarding engineering material properties, metadata, special data types, and the associated database functions. Once the required properties and procedures were established, we developed an information model for a generic engineering material. An information model is a high-level model that organizes the data needs of the domain area and illustrates the basic structure of the database that is required to meet those needs. We then developed a conceptual model using the ER modeling methodology and investigated the suitability of both the ER model and its extensions for composite materials data.

Note that Figure 1 indicates the use of both graphical conceptual models and textual specifications. Textual specifications are used most often as data exchange languages to support the exchange of data between unlike software programs. As a future extension of this research, we will consider the development of a formal textual specification using PDES tools and standards and based upon the data needs as defined by the conceptual ER model. The focus of this research, however, is the development of a graphical model, which is more commonly used to support database implementations through direct mapping into computational models.

Computational models are computer sensible; 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 software specific database implementation. While this too is not within the scope of the current research, we suggest the use of either an extended relational or object-oriented database management system, either of which can be used to implement the special types of data modeled during this research. The database implementation can then be used as a component of an integrated system to support a variety of engineering application programs; this stage is shown on the diagram as the computer model.

2.2. Entity-Relationship Diagrams

An Entity-Relationship (ER) diagram distills the information content of a domain area down to the concepts of 1) entities or objects, 2) relationships between those entities, and 3) attributes or properties of the entities and relationships. A simple Entity-Relationship diagram is illustrated in Figure 2. In this diagram, the names enclosed by rectangles represent entities (e.g. yarn, fabric), those enclosed by diamonds represent relationships between entities (e.g. a yarn is part of a fabric).

Those names not enclosed but joined with either an entity or relationship by a straight line represent attributes (e.g. the thickness and aspect ratio of the cross-section are properties of a yarn). Key attributes, which are indicated by boldface type and underlining, serve to uniquely identify each instance of an entity. The data type of each attribute, although not required by the ER methodology, is included in parentheses after the attribute name; the data type "an" indicates an alphanumeric type. The numbers enclosed in parentheses are cardinality numbers and they represent the minimum and maximum number of each entity that can participate in the relationship. For example, a fabric must be made of at least one but perhaps many types of yarn, whereas a yarn can be a component of no fabric or many fabrics.

2.3. Extended Entity-Relationship models

As a group, extended Entity-Relationship (EER) models are similar enough to the classical model to be easily understandable and close to user perception of the domain; however, they provide more expressive power. In general, they extend the traditional ER model by incorporating one or more of the concepts of 1) data abstraction, 2) complex entities and attributes, and 3) time dependency. Data abstraction and complex entities are described in this section because both are relevant to the domain; time dependency is not as we were not interested in modeling temporal database applications.

The most common types of data abstraction are listed below [11].

- **Classification:** The grouping of entities that share common characteristics into a class over which uniform conditions hold.

- **Generalization:** The relationship (IS_A) between a general object and a more specialized object, e.g. a tension test "is a" test.

- **Aggregation:** The relationship (IS_PART_OF) between a component and its subcomponents, e.g. a fiber "is part of" a yarn.

- **Grouping:** The relationship (IS_MEMBER_OF) between a member object and a set object, e.g. an inspector "is a member of" an inspection team.

Classification enables the separation of objects into groups that have common properties and can be placed into the same category. Only very basic classes are usually defined. The remaining three abstraction forms are specific types of relationships. Depending on the EER implementation, they are usually represented with a symbol other than the generic relationship symbol, which is a diamond connected to the entities by solid lines. The addition of complex entities is an extension of the last two abstraction forms, aggregation and grouping.

A complex entity is composed of one or more subentities related by the aggregation and/or generalization abstractions. These entities can in turn be complex, building up a hierarchy. For example, a pultruded component might be composed of resin plus tapes and yarns, each of which is composed of fibers. Complex attributes are aggregations or groupings of other attributes. An example of this is the attribute *Dimensions*, which might be the aggregation of the attributes *Length*, *Width*, and *Thickness*.

Because these abstraction types are specific examples of commonly occurring relationships, they can also be modeled using the original relationship symbols. As a result, they do not actually add any new capabilities or functionality to the ER model. They do, however, enable additional expressiveness by providing unique symbols for these events, simplifying the diagrams and clarifying the concepts.

3. Suitability of ER Method for Composites Data

The initial composite materials conceptual model was developed using the classical Entity-Relationship model. As part of the research we are evaluating the suitability of the ER model and its extensions for composite materials data, and assessing the applicability, strengths, weaknesses, and limitations of the model and its extensions. Several conclusions from this study are presented below.

- It is important for developers of conceptual models and composites databases to understand the abstraction concepts even if the symbols of the extended ER model are not used. That is, even if the classical model is selected instead of an EER model, the concepts of aggregation and generalization and their relevance to composite materials data are important to understand.

- The symbolic representations provided by the EER model clarify the abstraction concepts and can simplify the model diagrams because fewer symbols are often required to present an idea; therefore there is benefit in using an extended model. However, the limited number of symbols in the classical model are much less confusing to interpret, particularly if one is not as familiar with the modeling methodology.

- None of the ER or EER models investigated deals with the concept of data types for attributes. We feel that it is necessary for the diagram to indicate the data type of an attribute if the model is to be mapped directly into a database.

- The complex attributes provided by the EER models are an aggregation of enumerated attributes, either simple or complex; for example, the *Date* attribute might be composed of the *Day*, *Month*, and *Year* attributes. We feel that additional nonatomic attributes, such as attributes with a set, ordered list, or matrix data type, are required to fully model composite materials and other engineering data. The key difference between the set and list types and the aforementioned complex type is that the number of attributes is undetermined prior to instantiation for the former. An attribute of type matrix on the other hand has a given number of subattributes ordered in two or more dimensions.

We are developing an EER that incorporates the concepts listed above and utilizes selected symbolic representations from existing ER models. We anticipate the use of this model for visualization and understanding the domain area instead of direct mapping into a DBMS. Therefore, rather than developing a mapping algorithm from our EER methodology to a relational or other DBMS, we will instead provide mapping from the extended ER diagram to the classical ER diagram for subsequent implementation. Because the model is still under development, the portions of the composites database illustrated below utilize the traditional ER model.

4. Data Models for Composite Materials

It was immediately apparent that no single database design could (or should) encompass the data requirements of all types of fiber-reinforced composites, or the data needs of all engineering application programs and users. What we have provided, therefore, is a modular, extensible ER model, which can be modified to suit any number of purposes. Various entities representing, for example, different types of composites or alternate test methods can be selected or discarded from the model based upon the needs of the end users. In a similar manner, the model is extensible: additional entities and attributes can be added as new materials and manufacturing methods are developed and as different organizational priorities are established.

Finally, we have provided model components which define phenomena and data types pertinent to composite materials, e.g. dimensions, graph data, and bitmap data. These components can be altered to suit the needs of particular purposes and attached to the overall model at various points. For example, bitmap representation of photographs and diagrams might be used to explain test setups, fracture surfaces, and/or component geometries; therefore, the bitmap model component can be modified and attached to the global model at numerous locations. The remainder of the paper suggests the basic structure of a generic materials database and illustrates several components of a conceptual model for composites.

4.1. Information Model

To develop a generic information model for engineering materials in the form of an overall design for an engineering materials database, first we looked at the various stages in the life cycle of a material component. For most components, the life cycle can be broken into four distinct stages:

- Design,
- Manufacturing,

- Use, and
- Salvage or disposal.

At each life cycle stage, we identified the typical applications to be supported by database, and determined the data needed by each application and supplied as a result of the application. Upon gaining an understanding of the life cycle of a component, we divided the resulting data needs into three different categories as defined and illustrated below.

- **Properties data:** Material properties data that describes a material or set of similar materials. This material may or may not be used in components described elsewhere in the database. Types of data included in this category are:

    - ASTM specimen test data
    - Non-standard test data
    - Supplier data, including properties and cost data
    - Catalog data, including toxicity, health, and safety data
    - Design allowables

- **Product data:** Data about a specific material component or product, as opposed to general materials data. Product data would be supported by the properties data provided above. Types of data included in this category are:

    - Subcomponents and constituents which make up component
    - Geometry of component, including features
    - Dimensions and tolerances of components and subcomponents
    - Processing at each stage of product development
    - Expected application, environment, loading on the component

- **Service data:** Data on a product or component under actual service conditions. Actual definition and description of the product are provided in the previous category. Types of data included in this category are:

    - Variations in service environment and loads
    - Performance evaluations
    - Inspection, maintenance, and repair history
    - Failure causes and modes
    - Disposal, salvage, and/or recycling of constituent materials

The three types of data can be separated into three databases that support the various stages of the composite material life cycle, as illustrated in Figure 3. The separation of the databases can be either physical or merely conceptual; in practice, a single database would serve the same purpose. In the scenario presented in this figure, the data in the properties database feeds the design and manufacturing stages by providing the bulk of the data needed by those two processes. The data supplied by these stages, which is basically the final design and expected end use of the component, would be stored in the product database.

The data in the product database, along with the original properties data, would supply the use and salvage stages, and the information gained during those stages, primarily the service history and failure record of the component, would be maintained in the service database. The data in the service database provides a record of the performance of previous designs, and therefore can be used to guide the design stage of future components. Note that the properties database is continually updated through the use of external databases, which can be bibliographic databases, industry databases, and standards organization databases. The entire sequence of databases is expanded as more information is discovered, through experiments, statistical analyses, and the study of components in service.

4.2. Conceptual Model

The information model presented in the previous subsection provides the structure and basic data content of a materials database supporting the entire life cycle of a generic engineering material. The conceptual model, in the form of a set of interconnecting Entity-Relationship diagrams will, when complete, provide a means of creating a database with all of the functionality of the information model, yet particular to fiber-reinforced plastics. To illustrate the conceptual model, we will include portions of the ER diagrams representing properties data, product data, service data, and as an example of a special data type, dimensions data.

4.2.1. Properties Data

We are interested in several aspects of composite materials properties data, including modeling the data content of related ASTM standard tests, incorporating sufficient metadata to document test conditions, extracting a generic set of data requirements for a typical non-standard test, and assessing and maintaining the quality of the test data, particularly as it is reduced and refined. To do this, we first considered the ASTM standard test methods relevant to fiber-reinforced composite materials [11]. We examined each test specification, distilling out the data items required to document the test and record the results. We then compared the specifications, seeking out commonalities in the required data items.

We discovered that certain attributes and entities are common to all tests, others are common to all tests of a specific type, e.g. flexural tests, impact tests, or composite properties tests, and still others are unique to a single test. This enabled us to reduce the size of the ER model by using the concept of the generalization hierarchy. Figure 4 illustrates the top level of the model, which includes data pertaining to all tests, regardless of type, and a portion of the second level, indicating which types of test are covered. The entities on the second level, those enclosed with two rectangles, have additional relationships and attributes that are not indicated on this diagram. Because the IS_A relationship is always a one-to-one relationship, cardinality numbers are omitted from these relationships on this and other diagrams.

Figure 5 shows the remainder of the model for the set of tension tests provided by ASTM. In this and the remaining figures, although all of the entities are included, only a subset of the attributes are included due to space limitations. The existence of the third and final level of detail, that of the individual test specifications, is indicated on this diagram by the entities enclosed by three rectangles. For purposes of user interface, the levels of the model can be compressed, so that the user perceives all information pertaining to a single test as being on the same level.

This initial model is currently being expanded through the incorporation of additional metadata requirements as extracted from [5] and other sources. The recommendations from ASTM Standard Guide for Identification of Composite Materials in Computerized Material Property Databases (E1309) and ASTM Standard Guide for Identification of Fibers, Fillers, and Core Materials in Computerized Material Property Databases (E1471) for identifying and describing composite materials and their components are also being merged with the model. As a final step, a general ER model will be developed for a nonstandard test, drawing on the types of attributes and entities required to describe the standard ASTM tests.

4.2.2. Product Data

Three primary types of data are important in describing a component or material product. Initially, the relationship between components and subcomponents results in an aggregation hierarchy. Traditionally, the aggregation hierarchy can only be a one-to-many relationship, because each component can have many subcomponents and each subcomponent can be part of only one component. However because "bulk" components, such as resins, yarns, and fabrics, can be subcomponents of many different components, additional cardinalities are allowed in this model. Figure 6 depicts a partial Entity-Relationship model for composites reinforced with textile preforms; the aggregation hierarchy is evident in the figure.

Processing information is also included on this model, because the type and nature of the processing procedures at each stage of development determine the attributes that should be recorded. For example, if a component is molded, *Resin_injection_speed* and *Resin_injection_temperature* might be required as attributes. If it is cured, the curing pressure and temperature are also important. Figure 6 illustrates some of the processing entities that are important for textile-reinforced composites.

The final type of information that is important to record is the shape and dimensions of the component and each subcomponent. Each subcomponent and component entity on the diagram is related to an entity containing shape information. For a detailed discussion of modeling shape and dimensionality data, see the subsection entitled *Dimensions Data*.

4.2.3. Service Data

It is important to record data on components in service because it provides valuable insights with which to guide future designs. Service data provides information on the behavior of components under combined loads and actual service conditions. These conditions may exceed those covered by standard test methods; therefore this type of data may not otherwise be readily available. In addition, service data provides information about conditions prior to failure and failure modes, the substitution of an alternate part, and the disposal of the original component. Other types of data which can be maintained during the operation or use of a component include its inspection, maintenance, and repair history. Figure 7 illustrates a partial ER model for service data; the attributes of several entities were omitted due to space limitations.

To record data on service conditions, it is necessary to record the variations in loading, humidity, temperature, and chemical exposure over the service life of the component. This task is becoming easier with the prevalence of data acquisition equipment linked to computer storage facilities. Remote sensors can record external conditions at discrete time intervals, and optical fibers can be embedded with structural fibers in a component to detect variations in load and deflection.

The manner in which this type of data is stored in the database is highly dependent on the data needs of integrated application programs. The raw data that can be recorded is often too large to be included in the database itself, although it should at least be maintained off-line. Data reduction algorithms, joined with the database as integrated application programs, can be used to compress the information into a more usable format. In the model in Figure 7, the raw data values for applied load are averaged over a set time period and the results are stored as attributes. The maximum, minimum, and average values for each entity, as well as the standard deviation and the time period itself, are included.

4.2.4. Dimensions Data

One of the key aspects in describing a test is documenting the size, shape, and dimensions of the test specimens. Dimension data is also important in describing equipment setups and component geometries. The difficulty in storing dimension data is that different parameters, e.g. length, diameter, thickness, are appropriate depending on the general shape of the object. We have developed an ER model component that incorporates a generalization hierarchy to allow dimension data to be stored in a minimal amount of space, while providing the most intuitive set of attributes possible.

Figure 8 illustrates a portion of the ER model for dimension data. The entity entitled *Object* acts as a link to the rest of the ER model; in a full ER model, this attribute would be either *Specimen*, *Component*, or *Equipment*, depending on where the dimension data is applicable. The *Shape_name* attribute indicate which path of the ER model is to be followed for a particular object. For standard-shaped objects, the attributes specify the dimension parameters which are common to that shape.

Complex shapes, whether two- or three-dimensional can be represented by attributes representing parameter names and parameter values. An example application of this method is an I-beam whose top and bottom flanges are not alike. During instantiation of the resulting database, the *Parameter_name* attribute might be instantiated to "top flange width," "bottom flange width," "top flange thickness," and "bottom flange thickness," while the *Parameter_value* attribute is instantiated to the corresponding numeric values.

A figure, either a photograph or diagram on which the dimension parameters are marked, might also be used to clarify the dimensions of an object. The *Image* entity would then contain attributes locating and describing the file containing the bitmap image. If an extended relational or object-oriented database implementation is used, the actual bitmap file can be included as an attribute and accessed within the database management system. A figure might be particularly useful is the object's shape and dimension parameters are exceedingly complex.

To customize the ER diagram component for dimensions to suit a particular application, only the entities representing required shapes and dimensions would be included. As stated above, the *Shape* entity would be related directly to the *Specimen*, *Component*, and/or *Equipment* entity as required. In addition, following the convention established in ASTM 1471, statistical attributes representing a dimension distribution parameter (e.g. tolerance, percent error), dimension distribution parameter value (a numeric value), and dimension distribution sample size (number of samples) can be included to modify any dimension attribute. Attributes representing unit names can also be added if the database does not use a standard convention.

5. Summary

The work described herein is currently in progress at North Carolina State University, and this paper has provided preliminary results, particularly regarding the suitability of the ER model for composite materials data. In addition, it has also illustrated the basic structure of a comprehensive composite materials database and provided ER model diagrams to represent several database components. When the research is complete, we will have provided a thorough evaluation of the data needs of civil engineering users and the data contents of composite materials.

In addition, we will have expanded upon the examples presented here to analyze and present various aspects of developing composite materials data models, including different ways of modeling the special types of data required for composite materials, and components which can be used to maintain the accuracy of the data and reduce the size of large data sets. Finally, this research will establish a modular, extensible Entity-Relationship diagram that manages data from the entire life cycle of fiber-reinforced plastic components created using a variety of common manufacturing procedures.

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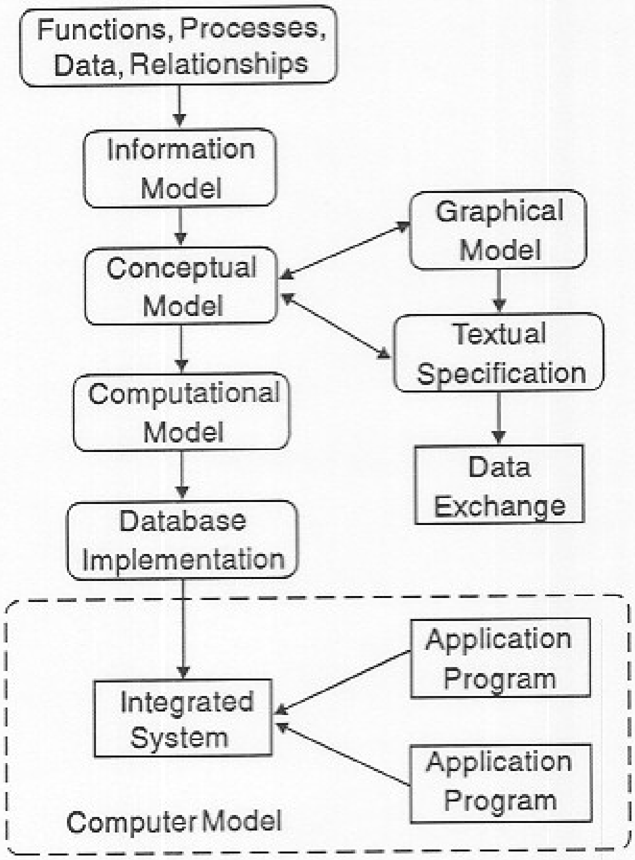

Figure 1: Overall modeling methodology

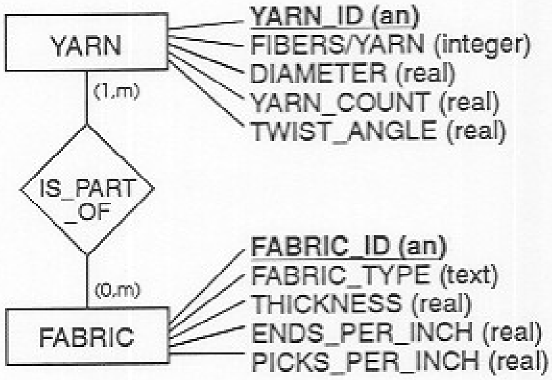

Figure 2: Example Entity-Relationship diagram

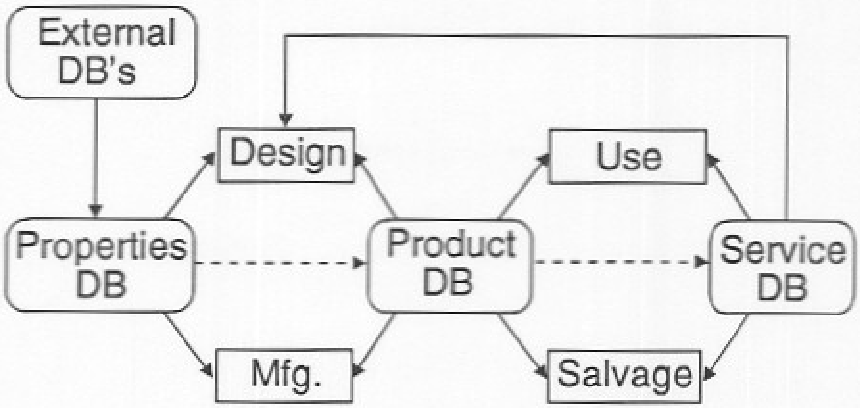

Figure 3: Conceptual materials databases

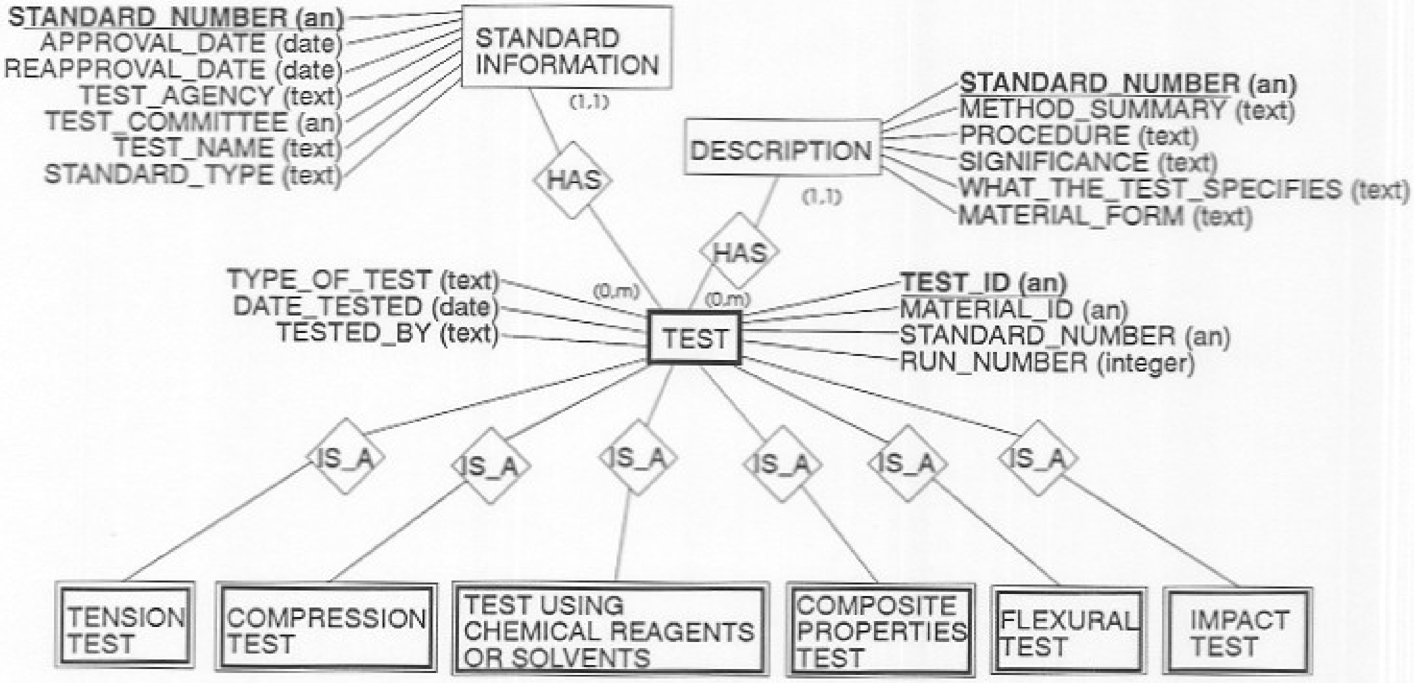

Figure 4: ER model of top level ASTM test data

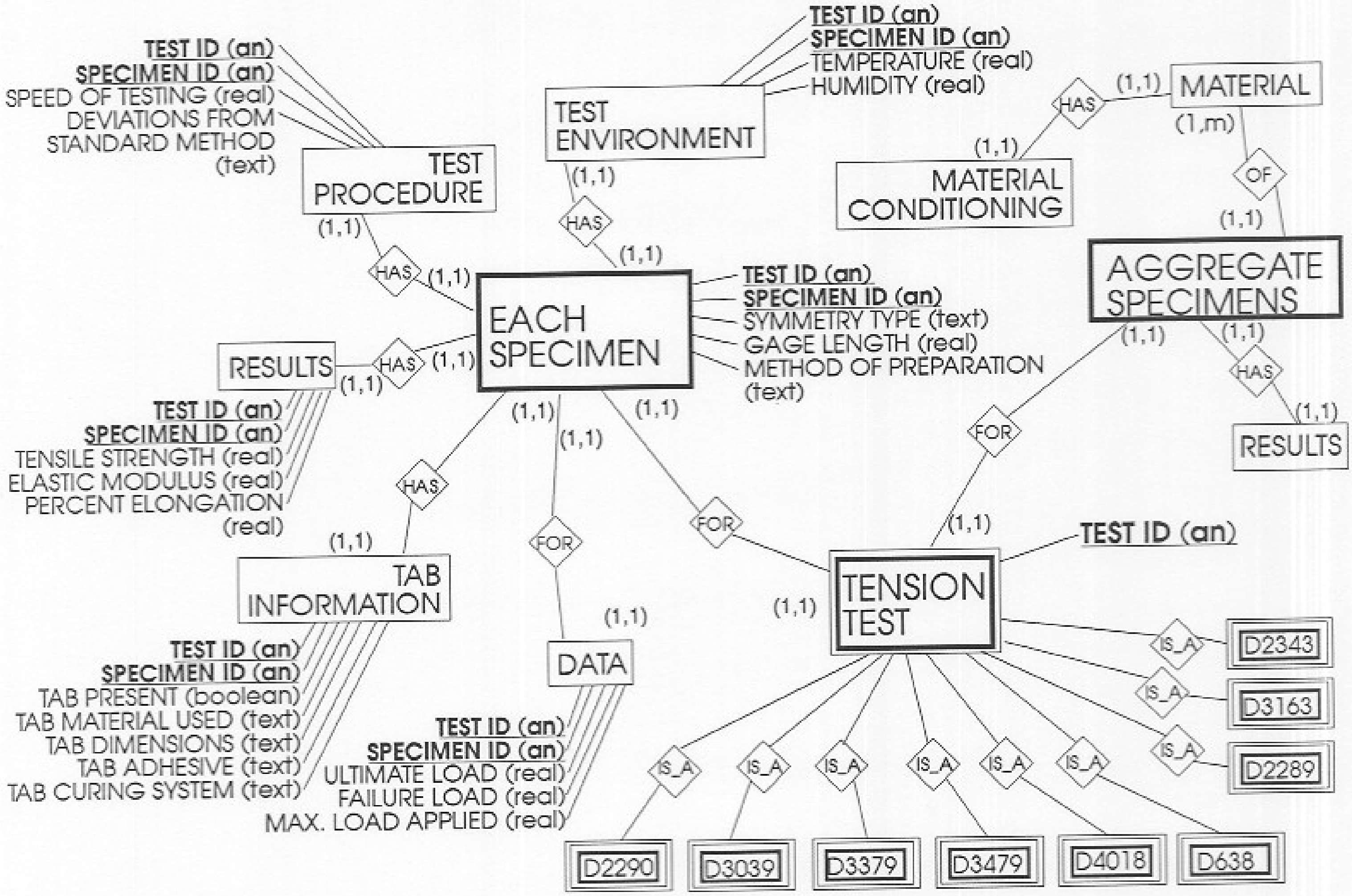

Figure 5: ER model of ASTM tension test data

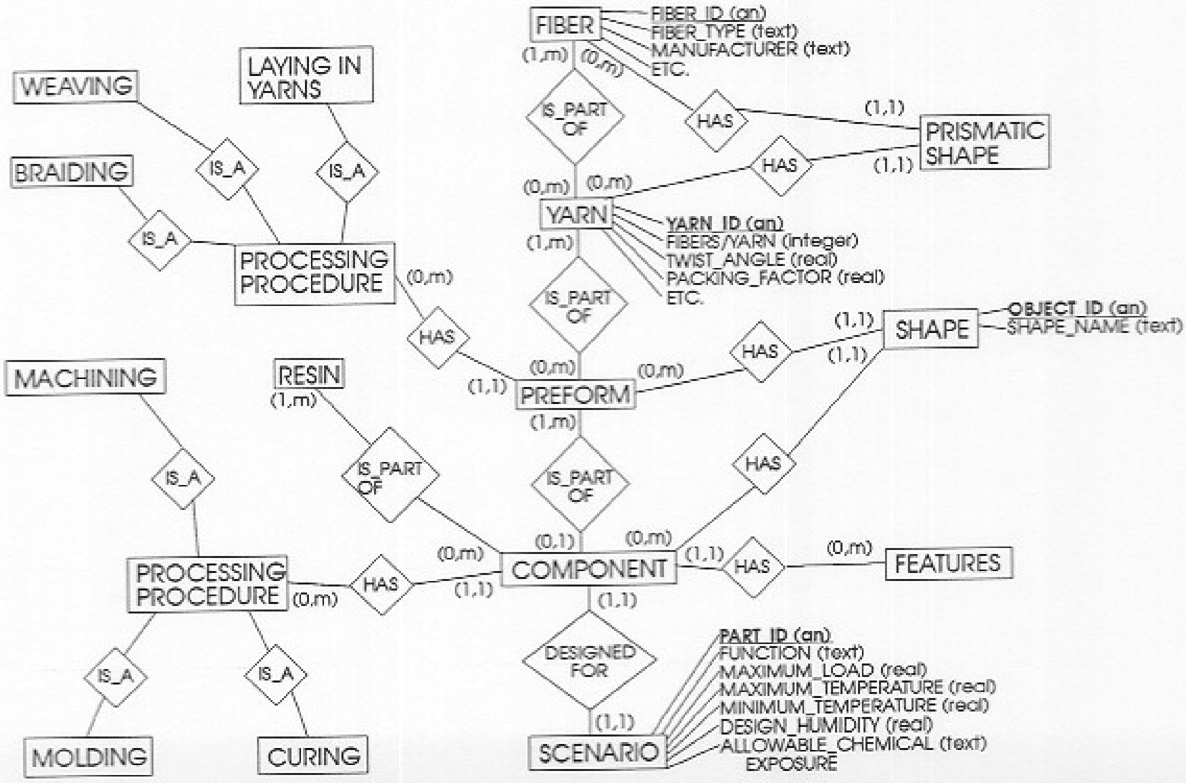

Figure 6: ER model of textile-reinforced composite

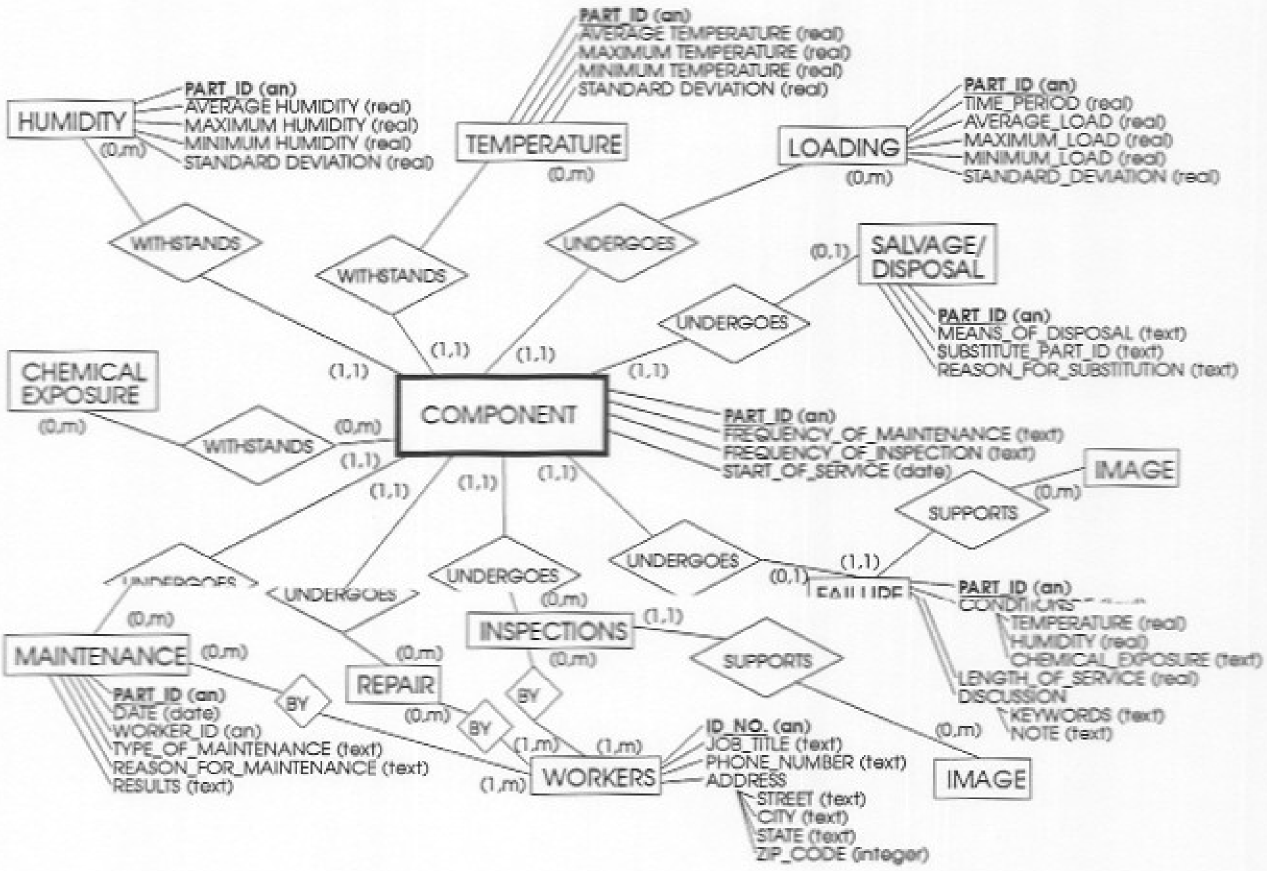

Figure 7: ER model of service data

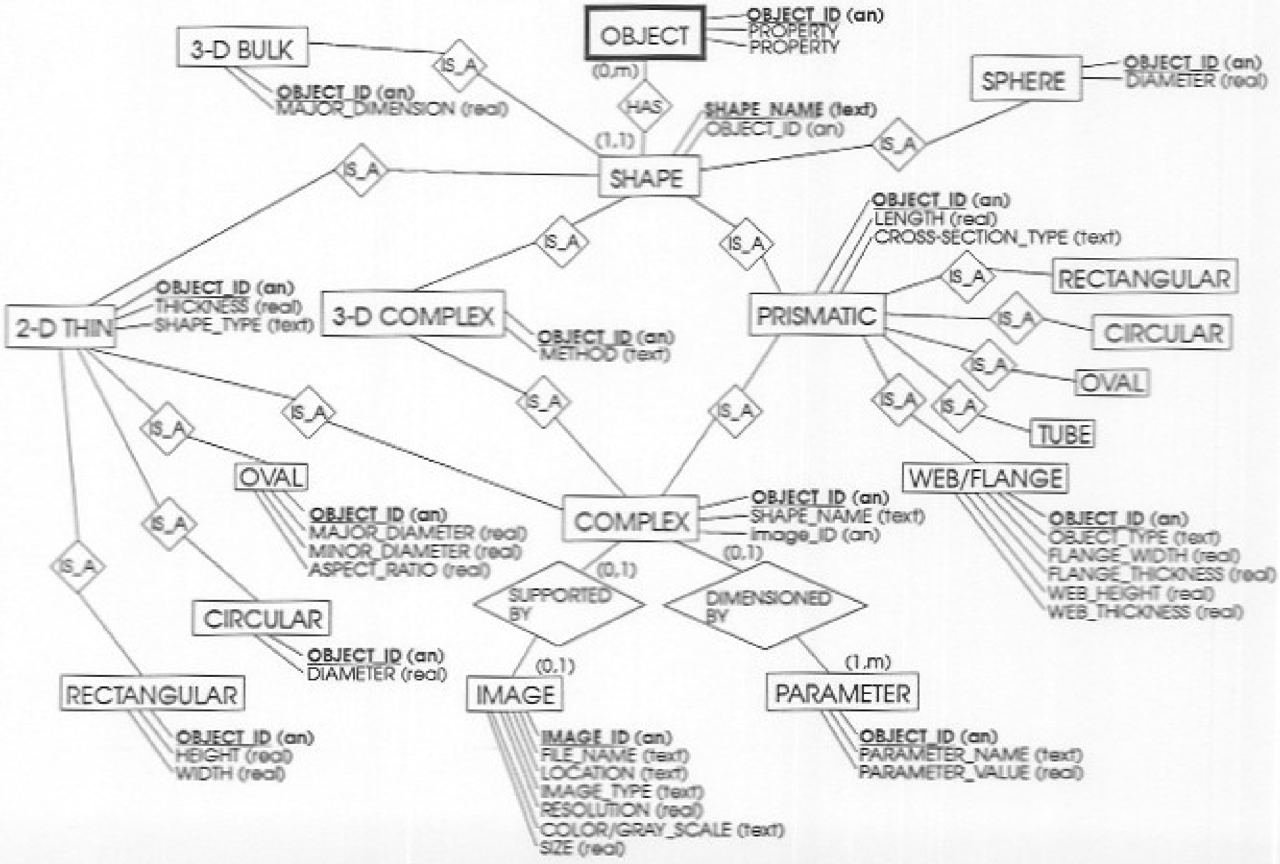

Figure 8: ER model of dimension information