A DESIGN ENVIRONMENT FOR LAMINATED FIBER-REINFORCED THICK COMPOSITE MATERIALS

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Abstract

The research described herein concerns the integration of several components of engineering software using a relational database. More specifically, a conceptual finite element material preprocessing system for laminated fiber-reinforced, thick composite materials is studied. In this computer-aided analysis (CAA) system, a materials database is integrated with several software components, including commercially available finite element analysis (FEA) programs and preprocessors, and tools for the design of laminated composite materials. The system focuses on assembling, manipulating, and using composite materials data, resulting in the transfer of two- and three-dimensional composite materials property data into a finite element analysis program.

The system is life-cycle in nature, supporting a composite through testing, analysis, and design. It offers great versatility in its ability to use raw ply data from any source, design layups, generate laminate properties, and generate FEA materials data files. Despite the fact that such integrated systems are not new in many domains, they have not been successfully introduced to the realm of composite materials analysis and design. This outcome is due largely to the nature of the materials themselves and the overhead they bring to the development of a successful life-cycle model.

1 Introduction

Although a vast amount of software is available to solve many complex engineering problems, integration among the programs is often lacking. For example, the required file structure for batch input varies from program to program; therefore, the user must create multiple input files to manipulate the same data with different programs. In addition, there is no archival repository in which to store input information in a generic format. While there has been some focus on integration with respect to CAD/CAM software, relatively few standard programs exist to generate batch input files from a database. The problem is especially apparent in the realm of finite element analysis, where a large volume of input must be provided. In addition, using composite materials data for

the analysis procedure further complicates the data entry task, because it magnifies the amount of input data required.

To address the problems of material data input and archival storage in the context of composite materials analysis, a prototype integrated finite element material property preprocessing system has been developed. The computational system, known as the Composites Database Interface (CDI), is composed of several stand-alone, task-specific computer programs, some of which are commercial and others which were written for this particular application. At the core of the system is a database, which provides an archive for fiber-reinforced composite material property data. The system currently enables the user to generate FEA materials data files for orthotropic materials, in either axisymmetric structures or two-dimensional structures subjected to membrane forces.

2 Applications in Engineering

Fiber-reinforced composite materials possess many attributes which make them outstanding engineering materials and suitable in numerous structural applications. For example, parts can be consolidated together to eliminate joints and fasteners; the geometry, fiber, and matrix can be specified to maximize structural efficiency; and a custom color can be molded into the parts for aesthetic or safety reasons. Useful engineering properties of various composite materials include the following: light weight, resistant to rot and corrosion, high strength-to-weight and stiffness-to-weight ratios, nonmagnetic, nonconductive, and possessing low thermal expansion and conductivity.

In the aerospace industry, fiber-reinforced composites are primarily being used in applications where reduced weight and increased durability are of significant importance. Examples include airplane wings and fuselages, and heat-resistant space shuttle components. However, because composites reinforced with glass fibers are magnetically invisible and electrically nonconductive, they are also ideal for building enclosures around and supporting structures for computer test facilities, radar and radio wave transmitters and antennae, subway and light rail facilities, and magnetic resonance imaging (MRI) equipment in hospitals. Composites are presently being used in each of these applications.

Many composite materials can withstand harsh chemical environments which are highly destructive to traditional engineering materials such as steel and concrete. As a result, composite structures are suitable in chemical plants, factories, and sewage and wastewater treatment facilities, in corrosive applications such as exhaust stacks and scrubbers, walkways and floor systems, platforms, handrails, grating, and filters [Pritchard89]. Composites are fairly common in underground storage tanks, tanker trucks, and piping systems. A highly beneficial use of fiber-reinforced composite materials is in rehabilitating our nation's deteriorating infrastructure and, where necessary, rebuilding with durable, long lasting structures and facilities. The use of composite materials in bridge construction, as rebar, cables, tendons, and deck panels, is being supported by the United States Department of Transportation, the Federal Highway Administration, and several state Departments of Transportation.

3 Background

Advanced composite materials offer potential solutions to numerous engineering problems, due primarily to their high strength-to-weight and stiffness-to-weight ratios and their corrosion resistance. However, none of these potential advances can be achieved without the availability of sufficient

materials testing and design criteria, and integrated analytical tools for the engineer. Composites research is substantially increasing in the engineering community, both in this country and abroad, yet very little of this research is being directed toward materials data gathering, management, and integration. The lack of historical design knowledge on the part of engineers leads to an uncertainty regarding the precise behavior of composite materials, resulting, to some extent, in an unwillingness to use these materials in engineering design [Stanton88]. A key first need exists, therefore, to make information available about composite materials, their derivation, their properties, and their use to researchers, materials scientists, and engineers.

3.1 The Need for Engineering Materials Databases

Several organizations, including the National Academy of Science, have emphasized the critical need for materials data reporting standards [Stockmayer78,Stanton88]. G.E. Hansen states that it is in the best interest of all those involved in composite materials, including industry, universities, and government agencies, to develop and use a standard database of composite materials data [Hansen88].

The need to embark on an activity like that discussed herein is evidenced by a number of related research efforts in the concrete materials area, including projects at Oak Ridge National Laboratory and the Strategic Highway Research Program. These efforts are directed toward obtaining concrete material property and performance information and designing a database to collect data on long term performance of concrete. The issue of an appropriate database design is a key component of these project. Also, the American Concrete Institute has initiated Committee 126 to develop standard formats for building and accessing computerized databases on the properties of concretes and related materials.

All of these efforts are aimed at designing databases and collecting data. Clearly, this research is being done well after a substantial amount of theoretical and experimental research has been done. However, these efforts point to a need to understand the broad range of material properties which may be of interest to engineers on a long term basis and to do so as they are emerging. The use of fiber-reinforced composite materials is now emerging in the civil and mechanical disciplines. This research seeks ways to design the knowledge base for the diverse properties of these robust materials, thereby contributing to the establishment of research agendas and directions in the area.

3.2 The Need for Integrated Analysis Systems

Studies have shown that the transfer of material properties data is a weak link in the overall CAD/CAM/CAE process [Stanton88]. Part of the problem is simply a failure of the engineering community to support materials data exchange in electronic formats. In laboratories, materials data collection and processing has been largely computerized; however, data transfer is still very limited. Furthermore, the technical data exchange standards that are available today do not fully support materials data transfer [Stanton88]. This lack of data reporting standards means that existing materials data must be carefully evaluated to ascertain its completeness, applicability, and integrity. The influence of new materials and the lack of research directed towards specific engineering data needs makes the problem even more acute.

James Turner at the University of Michigan sees data exchange as the most significant challenge facing developers of computer-aided design systems, stating that we should no longer accept "stand-alone" computer programs, focusing instead on "stand-together" programs, which share results

with and accept input data from other programs through common databases [Turner92]. Robert McDonald of Boeing Commercial Airplanes concurs. McDonald not only notes the importance of automating various engineering, design, manufacturing, construction, and support processes using a centralized database, but also states the importance of treating data and information as a corporate resource [McDonald90].

3.3 Contributions of This Research

Because the analysis system described herein addresses only the generation of material data for input to a FEA program, it cannot be considered to comprise a completely integrated finite element analysis system. It does, however, serve a purpose and fulfill a need in the engineering community. Because of analysis and design problems peculiar to the use of composite materials, generating material property values for program input is more difficult than with traditional engineering materials. Some of the very properties which make composite materials useful also make designing with them more difficult. We can make the following observations concerning composite materials:

- Fiber-reinforced composites have complex material properties—orthogonal or anisotropic;
- Each composite layup or laminate has a different set of material properties; and
- More than one layup may be used to design a single composite structure.

For these reasons and others which introduce even further uncertainty, defining material properties for a fiber-reinforced composite is very complex. In addition, designing structures using composite materials is a relatively new discipline for which few analytical tools exist. Strength properties of the material are often determined through experimentation rather than by calculation. For example, a particular layup may be chosen for a structure; then a model is designed and the analysis is performed; using the results of the analysis, a second layup is selected and the process is repeated. As a result, several different material configurations may actually be analyzed for a particular design scenario to determine the best design. We can conclude that designing a composite material structure is a repetitive process, well suited to automation.

It is evident, therefore, that there are numerous data collection and usage issues associated with composite materials. The key to designing with composite materials, however, is obtaining complete and accurate data to predict the performance of the composite in a design scenario. An integrated computer-aided analysis system for fiber-reinforced composite materials can be designed, containing a database to maintain material properties for both plies and laminates, and application programs to provide this data to laminate design programs and finite element analysis programs.

4 A Computer-Aided Analysis System

This section describes the architecture of a prototype integrated computer-aided analysis system for thick fiber-reinforced composites, the Composites Database Interface (CDI). On a physical level, the primary purpose of the CDI analysis system is to automate the process of generating composite materials data and transferring this data to a finite element analysis system. A secondary purpose is to provide an archive to store composite materials data. A third purpose of the research is to gain insight into the nature and organizational issues of the different types of data that are needed to define composite material properties.

To integrate the components of CDI, we use an incrementally expandable (or modular) architecture. Existing technology in finite element analysis and database management is adopted to achieve the required functionality of the integrated system at the physical level. The benefits of the system include the ability to generate a laminate in an ad hoc manner, having the material properties both immediately available for formatted FEA input and archived in a materials database.

4.1 Functional Components

From a functional point of view, the CDI provides the following capabilities:

- Help,
- Data Manipulation,
- Laminate Design,
- Reports/Views, and
- FEA Interface File Generation.

These capabilities are provided by software components which are discussed in the following subsections and are illustrated in Figure 1. Certain components in Figure 1 are enclosed in dashed lines; these are the components illustrated in Section 5 below. Note that the applications support only the data management aspects of the analysis system; the actual finite element analysis capability is not provided in the CDI.

All program code was written using the R:BASE For DOS application programming language [Microrim88]; the CDI, therefore, can be executed only from within the R:BASE DBMS environment. An external FORTRAN program, STIF3D, is embedded within the laminate design component and invoked by R:BASE upon execution of the corresponding lower level system component [Tretheway89]. A top-level, menu-driven user interface allows the user to access the desired component to initiate an appropriate function.

4.1.1 Help Component

The purpose of the CDI Help component, as its name indicates, is to aid the user in executing the remaining CDI components. This functionality is consistent with the objectives of an integrated analysis system, as it reduces the user's dependence upon reference manuals and supplementary texts. The Help component provides the user with a collection of help screens, each describing a specific CDI function. It provides general instructions about how it operates, supplies background information, and discusses possible options or command variations.

4.1.2 Data Manipulation Component

The function of the Data Manipulation component of the CDI is to provide the user with a simple means of entering, editing, and removing the data in the composite materials database, which acts as a data archive for the system. Two different methods for performing these actions are included in the CDI. The user can either manipulate the data by using on-screen data entry forms developed in

R:BASE, or enter the R:BASE Prompt By Example (PBE) mode directly to perform various tasks. In general, the forms and associated menu system guide the user, in a detailed step-by-step manner, through the data manipulation process; the PBE mode allows greater freedom but provides less guidance to the user.

Forms are data entry and modification tools that can be developed in R:BASE as part of a database definition. A form corresponds to a specific database table and contains numerous prompts. The data entered on each form corresponds to a single row in the table; each prompt, in turn, corresponds to a particular field of that row. When used for data entry, the fields of a form are initially empty. Data is entered into the form by typing a response to each prompt; a null value is entered by leaving the field empty. Once the data has been completely entered into a form and has been determined to be accurate, the user may enter it into the database as a new row in the corresponding table.

Forms can be used in a similar manner to modify data. The user first specifies which form and row (or rows) of data are to be modified. When the form appears on the screen, each field automatically contains the database values for the specified row. To change the values shown, the user simply types over the current data values, then selects the *Save* action from a menu. The user may also delete database rows by using similar menu options.

An alternate means of data entry and modification provided within the Data Manipulation component of the CDI is the Prompt By Example (PBE) mode of R:BASE. PBE allows the user to execute R:BASE commands directly, with the aid of screen prompts and context-sensitive informational messages. Possible PBE actions of interest are quite broad in their overall functionality and include modifying data, querying the database, using SQL (Structured Query Language) commands, and accessing operating system utilities. Additionally, PBE commands may be used to read in data from flat ASCII files. This functionality is useful when a large volume of materials data is already on computer media; the DBMS has the capability to load the data directly into the appropriate database tables.

4.1.3 Laminate Design Component

The Laminate Design component of the CDI allows the user to design both quasi-isotropic and general laminates from the unidirectional ply data stored in the database. A laminate consists of layers of a single composite ply, oriented at appropriate angles to satisfy the expected loading configuration. A quasi-isotropic laminate is distinguished by equal elastic moduli in the major and minor directions; an example is a laminate having equal ply portions at 0, 45, 90, and -45 degree angles. The general laminate may have plies oriented in any direction. The distinction between the two types of laminates is made because a simpler analysis technique is used in the CDI program for designing quasi-isotropic laminates.

As input to the Laminate Design component, the user provides the name of the unidirectional ply and the laminate code or stacking sequence for the layup to be designed. The laminate code indicates the orientation of each ply in the laminate. The material properties for the plies are obtained from the database. The laminate data, which includes average stiffness properties and thermal expansion coefficients, is then generated and stored in the materials database. The process of designing laminates, therefore, can be separated conceptually into two phases. First the user designs the laminate by selecting the ply and stacking sequence, then the system analyzes the laminate and generates its material properties.

Two different models are available for generating stiffness data for thick laminates. Laminates

may be analyzed using classical laminated plate theory, which is the current industry standard, as documented by Tsai in [Tsai87], by Halpin in [Halpin84], and by numerous other composite materials texts. Alternatively, a modified version of the STIF3D code, developed at the University of Delaware, may be used for laminate design. Thermal expansion coefficients can be generated only by using the classical laminated plate model.

Briefly, laminated plate theory, the most common design model, assumes a state of plane stress in the plane of the laminate. For each ply layer, a matrix of stiffness coefficients is computed from the elastic constants of the ply, its thickness, and its orientation with respect to an arbitrary in-plane axis. A matrix of normal stiffness properties, $[A]$, is generated for the laminate by taking the weighted averages of each set of ply properties. Effective elastic constants (E_x , E_y , ν_{xy} , etc.) are then computed from the normal stiffness coefficients and stored in the database.

Had the codes required normal and bending stiffness coefficients, $[A]$ and $[D]$ matrices, these values would have been stored instead. Because of the repetitive stacking sequences used for thick composite laminates, the secondary coupling effects usually observed between the normal and bending stiffness coefficients of nonsymmetric laminates are minimized, and the normal and bending stiffness may be considered separately with a high degree of accuracy [Hoskin86].

The classical laminate model only generates two-dimensional stiffness data, however, and three dimensions of data are required for certain finite element analysis procedures. The third dimension properties must be approximated from the available ply and laminate data. A set of approximations that are based upon the assumptions of transversely isotropic plies and interpolation between known values are suggested to the user by the CDI program; the user may either accept these recommendations or modify the values as necessary. Note fields are provided in the database to document various assumptions made by the user.

STIF3D is based upon classical plate theory; however, it involves a more complex three-dimensional analysis theory which includes $[B]$ and $[D]$ terms. As a result it generates an entire set of three-dimensional laminate stiffness properties (stiffness matrix coefficients and effective elastic constants), and is exact for any laminated composite.

4.1.4 Reports/Views Component

The Reports/Views component of the CDI provides the user with the capacity to observe the data stored in the database. Data may be viewed on the monitor or hard-copy reports may be generated. By means of menu selections, the user may specify the type and amount of data to be generated, thereby creating custom views and reports. In general, reports may be separated into two categories: identification reports and material property reports. Either category may be generated for either unidirectional plies or laminates. The user may also elect to report on a single class of composites or to report on all available materials.

An identification report provides general descriptive data about a composite, such as the identification code; the composite, fiber, and matrix names (e.g. T300/5208, T300, and N5208, respectively); and the laminate code (e.g. [0(2)/45/-45]4T). Material property reports are more detailed including, in addition to the above information, the values of various material properties for the selected plies or laminates, such as elastic and shear moduli, thermal expansion coefficients, Poisson's ratio(s), and density.

4.1.5 Interface File Generation Component

The Interface File Generation component allows the user to create files of material data suitable for use with either the ANSYS finite element analysis program [Swanson89] or with the MAZE preprocessor for the NIKE2D and DYNA2D analysis codes [Hallquist83]. ANSYS is a widely used commercial FEA code with a variety of general-purpose elements and functionalities. NIKE2D and DYNA2D are primarily used for dynamic analyses and specialty applications.

Input Requirements of FEA Codes

Both ANSYS and MAZE encompass three types of finite element analysis: two-dimensional, three-dimensional, and axisymmetric. As noted in the previous section, the CDI system currently enables the user to generate materials data for 1) orthotropic materials, and 2) either axisymmetric structures or two-dimensional structures subjected to plane stress or strain. In ANSYS, the STIF42 element, a two-dimensional orthotropic isoparametric solid with two degrees of freedom per node, is used to model such structures. In MAZE, no specific element is required but the material definition must correspond to material type 2, orthotropic elastic. The two types of axisymmetric structures considered are hoop-wound, in which the composite fibers are wrapped circumferentially around the structure at some angle to the hoop axis, and radial composites, in which the fibers are aligned radially out from the center axis at some angle to the radial axis. All of these element models require elastic constants as input, e.g. E_x , ν_{xy} , etc., rather than stiffness coefficients ($[A]$, $[B]$, and $[D]$ coefficients).

The current scope of the materials database includes two-dimensional ply data (in the plane of the ply) and three-dimensional laminate properties. When three dimensions of ply properties are required by the FEA program, the plies are assumed to be transversely isotropic; that is, material properties in all planes perpendicular to the composite fiber are assumed equivalent. This data is not stored in the database to reduce redundancy.

Recall that, since the interface file generated by the CDI system only contains materials data, a separate file with the remaining FEA input data must also be developed using a text editor. This file, known as the batch input file, contains the finite element mesh, loading information, and the applicable constitutive relationships for the structure to be analyzed. These two files, the batch input file and the materials data file, must be integrated together and used as batch input for the finite element program of choice. The integration of the materials data file and the batch input file with the analysis code is handled differently for each FEA program.

Integration with ANSYS

First, consider integrating a set of data into the ANSYS FEA code. Figure 2 schematically represents the data flow for this integration method. When the ANSYS Interface File Generation component of the CDI is executed, the materials data for one or more composites is placed into the materials data file shown in Figure 2, in a format appropriate for ANSYS execution. Meanwhile, the batch file is created separately and, along with the mesh and loading data, several commands for directly accessing the materials data file are included.

As a result, the batch input file is processed in ANSYS until a command is executed transferring control to a specific line in the materials data file. The materials data file is then executed until a command returning control to the batch input file is encountered. This method of integration is possible because the materials data file is formatted by the CDI program as a User file, a special type of ANSYS input file. The User file acts as a library file to the batch input file, which means that, once created, it can be used with multiple batch input files.

To execute the ANSYS Interface File Generation component of the CDI, the user must provide the name of the materials data file, and for each material definition to be extracted from the database, the following must be provided: an ANSYS data block name, the material name or identification code, and its orientation with respect to the ANSYS global coordinate axes. The material properties are then transformed from the orthotropic material axes to the ANSYS coordinate axes.

Integration with MAZE

Integration with MAZE is somewhat different because MAZE does not have the ability to reference library files. All of the required data, including materials data, must be contained in one file. Therefore, after the materials data file is created by running the MAZE Interface File Generation component of the CDI, it must be appended onto an existing MAZE batch input file using a text editor. Figure 3 schematically represents the data flow for integration with MAZE. Materials are defined within the CDI by a material number, which must correspond to the material numbering scheme used elsewhere in the batch input file.

To create interface files suitable for use with MAZE, one must use a procedure similar to that described above for ANSYS. The single difference is that because material definitions are not placed in data blocks, the user does not need to provide a data block name. Instead the materials are numbered consecutively from 1 to n in the order that the material properties are extracted from the database.

4.2 System Integration

The functional components of the CDI are integrated via the R:BASE For DOS relational database management system and an R:BASE relational database. R:BASE For DOS, generally referred to as R:BASE, was developed by Microrim, Inc., and is a multi-user relational database management system that was designed for use on a microcomputer [Microrim88]. R:BASE enables the user to interactively define database schemas, create custom data entry forms, and generate advanced output reports. The DBMS also provides an advanced SQL-based command language and an application programming language.

The relational data model was chosen for the prototype database design because it allows sufficient flexibility in data representation while permitting different applications to use the same data in a program-independent fashion. We certainly recognize the large body of research directed at the use of other data models in engineering such as the object-oriented model. However, studies indicate that there is no consensus regarding the future of database systems with respect to either the object-oriented or extended relational model [Cattell91,French90]. Furthermore, because our focus is on understanding the broad array of data that is necessary to describe these materials rather than on breaking new ground in engineering data models, we believe that the needs of the prototype are best served by using a well understood and well formed model such as the relational model.

However, it is also recognized that the relational model alone is insufficient to accommodate the needs of a scientific database. We will therefore research the potential uses of an extended relational model. Refer to Section 6 for additional information.

4.2.1 Component Integration

The role of R:BASE and the database in the CDI is two-fold. First, R:BASE is used as a data transfer mechanism. This capability facilitates the transfer of data between the user and the system components, and it also allows data transfer among the set of heterogeneous application programs with a minimum of user interaction. R:BASE assumes a dynamic role in the evolving analysis process and provides the required data to each application program throughout the process. Second, the R:BASE database is used as a passive data repository. This capability provides the overall system with a centralized and manageable storage area for capturing the information obtained throughout the composite material life cycle. The data integrity of the process can thus more easily be monitored because the information is maintained in one centralized location [Rasdorf87].

To create an integrated software system, such as the CDI, all components in the system must be interfaced with one another. We elected to interface each of the application programs with the materials database, thus effectively interfacing all of the components together. A benefit of this integration scheme is the ease with which interface programs can be developed for an R:BASE database. The integration procedure is simplified through using the DBMS Application Programming Language (APL), which provides commands allowing direct communication and interaction with the database. Because it is built into the database management system, the APL provides for fast and efficient data transfer between the database and the applications.

To provide the necessary composite materials data in R:BASE to support the prototype, five initial relations have been developed. Sufficient relations have been defined to represent the data needed by the FEA programs as described in Subsection 4.1.5. Additionally, these relations are designed to support identification and material property data for unidirectional plies and laminated composites. A system of identification codes ties the data in the various relations together. The appendix includes a detailed description of the database schema, including table and column descriptions.

5 CDI System Demonstration

This section includes a detailed transcript of a sample execution of the various components of the CDI system. For clarity, the following typographical conventions are employed in this section. Typewriter font (*typewriter*) is used to designate screen prompts and sans serif font (*sans serif*) represents text that is entered by the user. An italics font (*italics*) is used to represent any CDI menu name or menu item. The example assumes that the user has initiated R:BASE and is currently in the R:BASE command mode, signified by an *R>* prompt on the screen.

5.1 Problem Statement

To illustrate the functionality of the CDI system, the design of the cylindrical sides of a large tank, illustrated in Figure 4 is considered. The tank is to be used as a pressure vessel; accordingly, the loading on the tank consists of an internal pressure, which induces membrane forces such that the stress in the hoop direction is twice that in the axial direction. Because of the potential weight savings and a concern about thermally induced stresses, the tank is to be constructed of a thick graphite fiber-reinforced composite, which has a relatively small coefficient of thermal expansion. To best resist the pressure loading, the material will be hoop-wound about a form, creating a laminate which has twice the strength in the hoop direction as in the axial direction.

The tank designer wishes to perform finite element analysis, using ANSYS, on this fiber-reinforced tank. The first laminate configuration to be tested is a [30/-30/0/45/-45]5S layup. Because the tank only undergoes membrane forces, the ANSYS STIF42 element is an acceptable element with which to analyze the finite element model. The composite material to be used in this design, identified as IM7/8551-7, is made from the 8551-7 epoxy matrix and the IM7 graphite fiber, and has the following unidirectional properties:

Elastic modulus in fiber direction (E_1): 23.0×10^6 psi
Elastic modulus in transverse direction (E_2): 1.21×10^6 psi
Shear modulus of elasticity (G_{12}): 0.83×10^6 psi
Major Poisson's ratio (ν_{12}): 0.34
Density (ρ): 148×10^{-6} lbf-s²/in
Major thermal expansion coef. (α_x): 0.24×10^{-6} in/in-°F
Minor thermal expansion coef. (α_y): 14.0×10^{-6} in/in-°F
Ply thickness: .0052 inches

These ply properties must be stored in the database using the Data Manipulation component of the CDI. The tank is composed of a laminate, however; as a result, the laminate property data must be generated and stored in the database using one of the models in the Laminate Design component. Finally, using the Interface File Generation component, the user must create materials data files suitable for use with ANSYS. This entire procedure is illustrated in the subsections which follow. The user may also edit or delete any database data with the Data Manipulation component, access Help, or print reports using the Report/Views component. Additional laminate design models exist, and interface files can also be generated for use with MAZE. Because of space considerations, these and other actions are not illustrated in this sample transcript.

5.2 Entry of Ply Data into Database

To initiate the Composites Database Interface, the user types the following command at the R> prompt: RUN COMP.CMD. An introductory screen first appears; the main menu, shown in Figure 5, appears after any key is pressed. From this menu, the user may access any available program action by selecting the appropriate option. To enter the requisite ply data, the user selects the *Database* option from the main menu, and then selects the *Enter Database Data* from the subsequent menu, *Database Actions*, illustrated in Figure 6. From a final menu listing data categories, the user selects the option to enter data on unidirectional composites. Subsequently, several prompts appear.

Upon properly entering both the composite name and an arbitrary identification code, a data entry form appears on the screen. This form corresponds to the UNICOMP table, and contains ply identification data. The user then fills in the empty fields with the appropriate data. After all data items have been entered, the form is saved, thus entering this row of data into the database table. A short pause will follow, then a second data entry form appears, corresponding to the UNIPROP table. The property data values given previously should be typed into the corresponding empty fields on this form. When complete, the form should resemble the illustration in Figure 7. The ply identification and property data is now stored in the database.

5.3 Design of Composite Laminate Using Ply Data

To design a laminate and generate its material properties from the corresponding unidirectional composite, the *Laminate* option is selected from the CDI main menu shown in Figure 5. The

Laminate Design menu is then displayed. From this menu, the option, *Three-dimensional stiffness theory (STIF3D)* is selected to develop a full set of three-dimensional stiffness properties. Recall that we wish to design a laminate from the previously entered ply data with the stacking sequence [30/-30/0/45/-45]5S.

Figure 8 contains a transcript depicting the required interaction in designing this laminate. After prompting the user for appropriate input, control is transferred to the STIF3D program and a header of information appears on the screen; this header contains standard information and is not shown in the figure for space considerations. The system then suggests approximate three-dimensional ply data by assuming that the ply is transversely isotropic. The transverse Poisson's ratio is assumed to be 0.45, the value suggested in [Thompson89]. Note that the transverse shear modulus suggested by STIF3D is not mathematically consistent with the standard mechanics of orthotropic materials model; the user modifies G_{23} to correct this error.

Control is then transferred back to the CDI system and program execution continues. The newly created data is displayed to the user, who is then given the opportunity to repeat the procedure. After this process is complete, the material property data for the laminate is permanently available in the database and may be edited, deleted, viewed, or used to create materials data files.

5.4 Generating Material Property Files for ANSYS

To create a data file for transferring material property data to a FEA program, the user selects the *Files* option of the CDI main menu. The *Generate Interface Files* menu then appears, enumerating the types of data file which can be generated. The ANSYS model is demonstrated in this example. Similar steps are involved in creating files suitable for use with MAZE. Sample materials data files in the format appropriate for both ANSYS and MAZE input are illustrated in Figures 10 and 11, respectively.

Figure 9 contains a sample transcript of the user interaction involved in creating the material property data file. Recall that the structure we are modeling is an axisymmetric cylinder, that the composite is hoop-wound, and that the major laminate axis exactly corresponds to the ANSYS Z-axis (hoop). All of this information will be used in creating the materials data file.

Initially, the user is prompted for the name of the file to be created and the laminate to be used. Then, a list of all stiffness runs associated with this composite is printed. Recall that because there is more than one laminate design model and because each model may be run with different assumptions, more than one set of stiffness data may be defined for a single laminate. To complete the interface file generation, the user must select the appropriate data set; in this case, the user selects the first run to use the STIF3D data generated previously. A name is given for the data block (the part of the material data file containing data on one specific composite) and information is provided to describe the orientation of the laminate on the finite element structure. Finally, the user is allowed to enter a comment line in the data block describing the particular laminate defined within.

Figure 10 illustrates the contents of the resulting ANSYS interface file. Note the control commands at the beginning and end of the file; these commands allow the materials data file to be used as an ANSYS User file. This file would be used independently but in conjunction with a batch input file containing the finite element mesh data, loading data, and commands referencing the materials data file. In ANSYS, the X-axis corresponds to axial direction, the Y-axis corresponds to the radial direction, and the Z-axis is equivalent to the hoop or circumferential direction.

Figure 11 contains a data file compatible with MAZE which was generated for the same laminate illustrated in the above example. Note that the MAZE data file has a simpler structure than the ANSYS data file, with fewer control commands. This structure is possible because, unlike the ANSYS file, the MAZE data file cannot be used independently from the batch input file. Instead, the materials data file illustrated in Figure 11 must be appended onto the end of the batch input file, so that the finite element mesh data, loading data, and material property data are all in the same file.

6 Current Status and Future Work

The computer-aided analysis system described in this paper, the CDI, is currently operational at the level of functionality described above. The system has been tested and documented [Spainhour90]. To achieve full functionality, the Laminate Design component must be expanded to include a fully three-dimensional classical laminate design model. Further system enhancements will include adding other laminate design models reflecting the particular characteristics and behaviors of thick composite laminates and the ability to generate interface files for general three-dimensional (non-axisymmetric) structures. The modularity currently inherent in the CDI system will effectively support such enhancement and expansion.

Additional system enhancements will focus on the composite materials database. First, the composite material property data needs and requirements of engineers and materials scientists will be investigated. This process will provide a more thorough understand of the nature and types of data which need to be stored and processed. Then an extended relational model will be developed to support these needs using an extension of the relational model such as the nested relational model (NRM).

This model relaxes the first normal form restriction of the traditional relational DBMS, thus allowing attributes of a relation to be a set of values, another relation, an image, etc. The NRM provides an intuitive mapping of complex physical systems into the model, allowing data to remain in hierarchical form within the database schema. The model may thus actually be an excellent underlying data model for mapping complex objects to an object-oriented database while retaining the theoretical and mathematical benefits of the relational model [Harvey91].

A formal methodology such as the NIAM model or extended entity-relationship diagrams will be used to develop the data model. Using a formal methodology indicates that the database is designed in a systematic fashion, ensuring a quality data model and a database design which accurately and completely models the data involved. The target database will incorporate many types of composite materials data, such as strength, hardness, and fatigue properties, and will support extended data types such as pictures, graphs, constraints, and text, to the extent possible.

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Appendix: Database Schema

The appendix contains the database schema for the experimental prototype of the Composites Database, as implemented in the R:BASE database management system. Each table is documented and the associated columns are enumerated. A brief description is provided for each table and column.

- **UNICOMP** (Unid, Uniname, Class, Fiber, Matrix, Prodform, Process)

The UNICOMP relation contains identification and descriptive information concerning unidirectional ply composites.

- UNID: Unique database identifier of a unidirectional composite
- UNINAME: Commonly used composite name or identification
- CLASS: Composite class, typically same as fiber type
- FIBER: Name of fiber used in the composite
- MATRIX: Name of matrix used in the composite
- VOLFRAC: Volume fraction of fiber in the composite
- PRODFORM: Form in which the composite product is available
- PROCESS: Processing which the composite has undergone

- **UNIPROP** (Unid, E1, E2, Alp1, Alp2, Nu12, G12, Dens, Plythick)

The UNIPROP relation contains material property data about unidirectional ply composites, specifically that which is relevant to finite element analysis.

- UNID: Unique database identifier of a unidirectional composite
- E1: Modulus of elasticity in fiber direction, in psi
- E2: Modulus of elasticity transverse to fiber, in psi
- ALP1: Coefficient of thermal expansion in fiber direction, in in/in-°F
- ALP2: Coefficient of thermal expansion transverse to fiber, in in/in-°F
- NU12: Major Poisson's ratio, unitless quantity
- G12: Shear modulus of elasticity, in psi
- DENS: Composite density, in lbf-s²/in
- PLYTHICK: Thickness of a unidirectional ply, in inches

- **LAMINATE** (Lamid, Unid, Lamcode, Lamthick)

The LAMINATE relation contains the information necessary for complete identification of a laminated composite.

- LAMID: Unique database identifier of a laminated composite
- UNID: Unidirectional composite used in the laminate
- LAMCODE: Laminate code indicating ply orientations and thicknesses
- LAMTHICK: Thickness of the laminated composite, in inches

- **LAMSTIFF** (Lamid, Runid, Method, Assump, Ex, Ey, Ez, ExBend, EyBend, Nuxy, Nuyz, Nuxz, Gxy, Gyz, Gxz)

The LAMSTIFF relation contains material stiffness data about thick laminated composites necessary to perform axisymmetric finite element analysis. In addition, it contains the data required to uniquely identify a stiffness analysis run.

- LAMID: Unique database identifier of a laminated composite

- RUNID: Identifier of stiffness analysis run number
 - METHOD: Method used for generating stiffness properties
 - ASSUMP: Three-dimensional ply/laminate assumptions used in generating laminate stiffness properties (note field)
 - EX: Major elastic modulus in X direction (at zero degrees rotation), in psi
 - EY: Minor elastic modulus in Y direction (at ninety degrees rotation), in psi
 - EZ: Elastic modulus in Z direction (through thickness), in psi
 - EXBEND: Bending stiffness around X axis, in psi
 - EYBEND: Bending stiffness around Y axis, in psi
 - NUXY: Major Poisson's ratio for the laminate in X-Y plane, unitless quantity
 - NUYZ: Poisson's ratio for the laminate in Y-Z plane, unitless quantity
 - NUXZ: Poisson's ratio for the laminate in X-Z plane, unitless quantity
 - GXY: Shear modulus of elasticity in X-Y plane, in psi
 - GYZ: Shear modulus of elasticity in Y-Z plane, in psi
 - GXZ: Shear modulus of elasticity in X-Z plane, in psi
- LAMTHERM (Lamid, Alpx, Alpy, Alpxy, Alpz)

The LAMTHERM relation contains thermal expansion data about laminated composites necessary to perform finite element analysis.

 - LAMID: Unique database identifier of a laminated composite
 - ALPX: Major coefficient of thermal expansion in X direction, in in/in-°F
 - ALPY: Minor coefficient of thermal expansion in Y direction, in in/in-°F
 - ALPXY: Coefficient of thermal expansion at forty-five degrees in X-Y plane, in in/in-°F
 - ALPZ: Coefficient of thermal expansion in Z direction, in in/in-°F

Figure 1: Composites Database Interface System Architecture

Figure 2: Data Flow for Data Integration With ANSYS

Figure 3: Data Flow for Data Integration With MAZE

Figure 4: Large Tank to be Constructed of Thick Laminated Composites

Figure 5: CDI Main Menu

Figure 6: Database Actions Menu

UNIDIRECTIONAL COMPOSITE MATERIALS	
IDENTIFICATION CODE: U1 COMPOSITE NAME: IM7/8551-7 CLASS: CFRP	FIBER: IM7 MATRIX: 8551-7
ELASTIC MODULI: E1: <input type="text" value="23.0E6"/> (psi) E2: <input type="text" value="1.21E6"/> (psi)	THERMAL EXPANSION COEF: ALP1: <input type="text" value=".24E-6"/> (in/in-°F) ALP2: <input type="text" value="14E-6"/> (in/in-°F)
POISSON'S RATIOS: NU12(MAJOR): <input type="text" value="0.34"/> NU21(MINOR): <input type="text" value="0.018"/>	SHEAR MODULUS OF ELASTICITY: G12: <input type="text" value="0.83E6"/> (psi)
DENSITY: <input type="text" value="148E-6"/> (lbf-s ² /in ⁴ = lbf/in ³ / 386.4 in/s ²)	

Figure 7: Data Entry Form for Ply Material Property Data

ENTER THE NAME OF THE UNIDIRECTIONAL COMPOSITE IN THIS LAMINATE.
 (TYPE [ENTER] TO LIST ALL UNIDIRECTIONAL COMPOSITES): IM7/8551-7
 DO YOU WISH TO DESIGN A QUASI-ISOTROPIC LAMINATE? (Y/N) N

ENTER THE LAMINATE CODE (STACKING SEQUENCE) IN THIS FORM:
 [dir(layers)/dir(layers)...]XX,
 WHERE (layers) IS OPTIONAL FOR ANY DIRECTION AND "XX" MAY BE
 #T, FOR REPEAT SUBLAMINATE # TIMES,
 #S, FOR REPEAT # TIMES THEN MAKE SYMMETRIC,
 S#, FOR MAKE SYMMETRIC THEN REPEAT # TIMES.
 [30/-30/0/45/-45]5S

ENTER AN ID CODE FOR THE LAMINATE IN THIS FORM: L1, L2.
 (TYPE [ENTER] TO LIST ALL CURRENTLY USED ID CODES): L1

(STIF3D HEADER)

THE IN-PLANE PROPERTIES ARE AS FOLLOWS: IM7/8551-7
 E1 = 2.3E7 E2 = 1.21E6 NU12 = 3.4E-1 G12 = 8.3E5
 THE OUT-OF-PLANE PROPERTIES ARE APPROXIMATED
 USING THE IN-PLANE PROPERTIES. HENCE:
 E3 = 1.21E6 NU13 = 3.4E-1 NU23 = 4.5E-1 G13 = 8.3E5 G23 = 8.3E5

ARE THESE VALUES ACCEPTABLE? (Y OR N) N
 E3 = ? 1.21E6 NU13 = ? 3.4E-1
 NU23 = ? 4.5E-1 G13 = ? 8.3E5
 G23 = ? .42E6

THE COEFFICIENTS OF HYGROSCOPIC EXPANSION ARE SET EQUAL TO ZERO.
 DO YOU WANT TO CHANGE THESE VALUES? (Y OR N) N
 Stop - Program Terminated

RECORD ANY NECESSARY DATA PERTAINING TO THE THREE-DIMENSIONAL
 ASSUMPTIONS OR TYPE [ENTER] TO INDICATE THAT THE DEFAULTS WERE USED.
 G23 corrected to .42E6; otherwise standard assumptions were used.

MATERIAL STIFFNESS PROPERTIES ARE AS FOLLOWS:
 Ex = 9400000. Ey = 3100000. Ez = 1400000.
 ExBend = 9700000. EyBend = 2800000.
 Gxy = 4400000. Gyz = 490000. Gxz = 640000.
 NUxy = .93 NUyz = .32 NUxz = .049
 WHERE "X" IS THE MAJOR AXIS (0 ROTATION) AND "Y" IS THE MINOR.
 DATA FOR THIS LAMINATE IS NOW LOADED INTO THE DATABASE.
 REPEAT USING ANOTHER STACKING SEQUENCE WITH THIS PLY? (Y/N) N
 REPEAT USING ANOTHER UNIDIRECTIONAL PLY? (Y/N) N

Figure 8: Designing a Composite Laminate

ENTER A NAME FOR THE ANSYS USER FILE: ANSYS.SPL

HOW MANY UNIDIRECTIONALS TO BE DEFINED? 0

HOW MANY LAMINATES TO BE DEFINED? 1

ENTER THE ID CODE OF LAMINATED COMPOSITE NUMBER 1 OF 1.

(TYPE [ENTER] TO LIST THOSE CURRENTLY DEFINED): L1

LAMINATED COMPOSITE MATERIALS

=====

LAM ID	LAMINATE CODE	UNI. COMPOSITE	METHOD	RUN ID
=====	=====	=====	=====	=====
			(STIFFNESS DATA ONLY)	
L1	[30/-30/0/45/-45]5S	IM7/8551-7	STIF3D	1
			CLASSIC	2

ENTER THE DESIRED RUN ID NUMBER: 1

ENTER A DATA BLOCK NAME FOR THIS MATERIAL (UP TO EIGHT CHARACTERS): TANK1

TYPE [P] IF DEFINING A 2-DIMENSIONAL PLANE SOLID IN THE X-Y PLANE; TYPE [A] IF DEFINING AN AXISYMMETRIC CYLINDER WITH SYMMETRY AROUND THE Y-AXIS IN THE Z-DIRECTION. A

TYPE [H] IF THE COMPOSITE IS HOOP-WOUND; TYPE [R] FOR RADIAL. H

ENTER ANGLE BETWEEN COMPOSITE'S MAJOR DIRECTION AND ANSYS Z-AXIS: 0

CREATING ANSYS DATA BLOCK...

IF DESIRED, ENTER A COMMENT LINE TO BE ADDED TO THE DATA BLOCK DESCRIBING THE MATERIAL; TYPE [ENTER] FOR NONE.
[30/-30/0/45/-45]5S from IM7/8551-7 hoop-wound at 0 deg from Z-axis.

DATA BLOCK COMPLETE. PRESS ANY KEY TO CONTINUE. [ENTER]
FILE GENERATION COMPLETE. PRESS ANY KEY TO CONTINUE. [ENTER]

Figure 9: Generating an ANSYS Material Data File

```

TANK1
C*** [30/-30/0/45/-45]5S from IM7/8551-7 hoop-wound at 0 deg from Z-axis
*SET,AR10,ARG1
*IF,ARG2,GT,0,:LB1
*SET,ARG2,ARG1
:LB1
*IF,ARG3,GT,0,:LB2
*SET,ARG3,1
:LB2
MP,EX,AR10,1400000.
MP,EY,AR10,3100000.
MP,EZ,AR10,9400000.
MP,ALPX,AR10,0.000014
MP,ALPY,AR10,0.000009
MP,ALPZ,AR10,0.000004
MP,NUXY,AR10,0.319999
MP,NUYZ,AR10,0.930000
MP,NUXZ,AR10,0.048999
MP,DENS,AR10,0.000148
MP,GXY,AR10,4400000.
*IF,AR10,GE,ARG2,:LB3
*SET,AR10,AR10+ARG3
*GO,:LB2
:LB3
/EOF

```

Figure 10: ANSYS Material Data File for [30/-30/0/45/-45]5S Laminate and Axisymmetric Cylinder

MAT 3 2 HEAD
[30/-30/0/45/-45]5S from IM7/8551-7 hoop-wound at 0 deg from Z-axis.
EA 1400000.
EB 3100000.
EC 9400000.
PRBA 0.319999
PRCB 0.930000
PRCA 0.048999
RO 0.000148
GAB 4400000.
AOPT 2.0
RP
ZP
PSIG 0.0
HGQ 0.059999
ENDMAT

Figure 11: MAZE Material Data File for [30/-30/0/45/-45]5S Laminate and Axisymmetric Cylinder