Composite analysis and design system

ESAComp

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ABSTRACT

A computer software ESAComp is under development for the analysis and design of composites. It is aimed at mechanical analyses of composite material systems and at the design and analysis of laminated structural elements. Versatility, efficiency, and expandability are the key requirements set for the system. The objectives of the development work and the development process are introduced. The system description is given.

INTRODUCTION

The unique characteristics of composites cannot be utilized to their full extent without extensive computing. Finite element (FE) programs are available for global analyses of structures, but they do not provide efficient tools for design and analysis of laminates and laminated structural elements. Several programs have been developed for these purposes, but they are typically laborious to use, they do not include all the capabilities a designer needs, and they cannot be extended by the user. Most of the programs are analysis programs, i.e. they solve direct problems. Design programs are typically based on general optimization techniques or on exact solutions of inverse problems. Some attempts have been made to develop expert systems for composite design. A review of the composite analysis and design programs is given by Saarela. 1

Due to the shortcomings of existing programs the European Space Agency (ESA) has launched a project for the development of a new software called ESAComp. 2 The first phase of this project will produce a limited analysis system. Currently it is being coded and will be available in early 1995. More analysis capabilities and tools for design and optimization will be integrated into the system during the second phase that is expected to be completed in 1996. The open nature of the software will enable further extensions.
OBJECTIVES

The design process and analysis/design tools of composite structures were reviewed to set objectives for the development work. It was concluded that initial studies on the mechanical behavior of composites, the preliminary and detailed design of structural elements, and the verification of elements are the tasks for which there is no integrated tool available. It was further found out that the existing programs do not provide means for the organization of the work. In addition, they do not enable efficient handling of practical industrial aspects such as, for example, factors of safety and loads consisting of a constant and variable part. The system should eliminate the shortcoming.

The development of an analysis system was set as the first objective since each task can be performed by solving direct problems, i.e. by running necessary analyses and by comparing results. In addition, analyses form the basis for inverse problem solvers. The development and implementation of these solvers, i.e. design and optimization tools, was specified to be the second objective. The system then becomes a design and analysis system (Figure 1).

Data exchange capabilities with external databases were seen necessary for the import of initial material and design data. Interfaces with FE programs were also specified to the system since global structural analyses are essential subprocesses in design. Finally, it was defined that the system should be easily expandable because all the desired capabilities cannot be implemented during the development work. Moreover, enhanced theories are continuously introduced in the field of composite structures.

Figure 1. System to be developed.
DEVELOPMENT PROCESS

The ESA software engineering standards\(^3\) define the general approach for the development process. The software lifecycle was started with the user requirements definition for the limited analysis system to be developed in the first phase. A total of 130 detailed capability requirements was set. Preliminary requirements for the extensions planned to be developed in the second phase were also defined to guarantee that they can be implemented in the system. A theoretical background document for the analyses was prepared since no consistent theoretical document was available.

The detailed user requirements were further transformed into software requirements. Functional and operational requirements were the most important results of this task. The components of the software were identified during the architectural design. Data structures, data file formats, and data exchange and expandability aspects were also defined.

SYSTEM DESCRIPTION

Operating system and programming language

Computers and operating systems were considered during the software requirements definition phase. UNIX workstations with the X Window/Motif environment were selected because they are most commonly used in structural analysis and design. C, C++ and FORTRAN were the candidate programming languages. FORTRAN was ruled out because it was seen inefficient in the programming of the extensive support system. C was preferred to C++ to guarantee easy portability of the system.

Analysis/design environment

Requirements for the analysis/design environment were outlined by detailing typical design processes (Figure 2). It was concluded that (1) fibers, (2) matrix materials, (3) plies, (4) laminates, (5) geometries of structural elements, and (6) loading conditions are the objects related to a design study. Besides objects, a study includes (7) results that are achieved with defined (8) analysis option settings and specified further by (9) unit and output format settings.

To allow the user to work with design studies, the "case" concept was introduced as a top level entity. It was specified that a case shall accept specifications of all the identified objects and results related to the objects. The system was further structured by providing the user with a working area where he/she is able to work with an active case. The working area allows the user to specify objects to the active case, to select specified objects for analysis/design tasks, and to include in the case the results of tasks with specified option settings. The user is further able to save the active case to the database, and to activate any case of the database, i.e. to retrieve it to the working area.
Objects of a case
A classification based on the constitutive behavior was established for fibers, matrix materials, and plies. Plies are also classified on the basis of their physical nature as reinforced plies, homogeneous plies, honeycomb core plies, or homogeneous core plies. Comprehensive data sheets were specified for the objects to enable versatile analyses. Mechanical data may include engineering constants and hygrothermal expansion coefficients, the first failure (yield) and final failure (ultimate) stresses and strains, and several sets of limit stresses and strains. With the limit sets the user can specify, for instance, failure stresses and strains corresponding to the fatigue failure for different load spectra. The reliability of each data item can be described with parameters of the statistical distribution. The user is further able to specify the product and the most important processing characteristics of the product.

Plies, their stacking sequence, and ply orientations define a laminate. The stress-free environment, temperature and moisture content profiles through the thickness of the laminate, and initial strains of plies may be included in the specification. The system complements the specification by classifying the laminate based on its physical nature and constitutive behavior.

A loading condition may be given either by a stress or strain state. It may include internal loads such as temperature and moisture loads, and initial strains of plies. It may further consist of a constant load and a variable load since structures are often loaded in that way. A spacecraft structure, for instance, can be subjected to a constant thrust load and to dynamic loads resulting from wind gusts and propulsion shutdown effects.
The simplest structural element is a continuous laminate fully defined by the laminate specification. The other structural elements included in the limited analysis system are notched laminates (laminate with a circular hole), bars with circular and rectangular cross-sections, and flat plates. The dimensions and, if applicable, boundary conditions are included in the geometry specification of the structural elements.

**Analysis capabilities**

The following analyses were specified to the phase one analysis system:
- micromechanical analyses (rule-of-mixtures relations)
- stiffness, load response, and failure analyses of plies and laminates
- creation of failure and design envelopes for plies and laminates
- load response and failure analyses of notched laminates
- stability, free vibration, and failure analyses of bars
- stability, free vibration, and failure analyses of rectangular plates.

Both solid laminates and sandwiches can be analyzed. Analyses are generally based on the Classical Lamination Theory. In the analyses of sandwich plates the user is able to include the effects of out-of-plane shear deformations with the first-order theory. Local instability of sandwiches is also considered.

A choice of several failure criteria and of three different approaches were introduced for failure analyses of laminates. The simplest approach is the first ply failure (FPF) analysis that is used to evaluate the reserve factor and margin of safety against the first failure of an intact laminate. The so-called last ply failure (LPF) analyses evaluate reserve factors and margins of safety against the final failure of a laminate. The simpler model uses degraded ply data for all the plies of a laminate. The more complicated progressing failure model is based on consecutive linear analyses where the intact ply data is replaced with the degraded ply data as the first failure occurs in a ply. After final ply failure the ply is assumed to carry no loads.

When a loading condition consists of a constant and variable part, results of a failure analysis are available for all the loading combinations. Figure 3 illustrates how a reserve factor is computed for the constant load, resultant load, and for the combination of the constant and variable load. Since constant loads are typically quite well known and variable loads may exhibit a wide scatter, separate factors of safety can be associated for the constant and variable load. The concept is further discussed by Palanterä and Klein.

Comparative analyses were seen to be important. Thus, it was specified that the system shall enable multiple selection of objects and parameters included in an analysis. For instance, several loading conditions and failure criteria may be specified for a failure analysis. The user is also able to analyze plies and laminates with varying ply orientations and ply proportions. Sensitivity analyses are available for studying the performance of structural elements within a specified tolerance for a ply property, ply orientation, or fiber fraction.
The second phase of the development work will extend the analysis capabilities. At least failure analyses including material non-linearity, free-edge analyses of laminates, and analyses of common mechanical and adhesively bonded joints will be introduced. A possibility to specify temperature/moisture dependent material and ply data will also be included.

![failure envelope](image)

- $c$ = constant
- $v$ = variable
- $r$ = resultant
- $RF$ = Reserve Factor

Figure 3. An example of reserve factors related to a loading condition. The value 1 is assumed for the factors of safety.

**Design capabilities**

The major effort in the second phase will be put in the development of design and optimization tools. Design tools will select plies and laminates that meet a design specification set by the user for a structural element. Design tools that create laminates for structural elements will also be developed. The design tools will thus produce feasible solutions for a design problem.

Design procedures will be based on analysis algorithms and on a rule-based inference process. Heuristic rules are an essential part of these procedures. An explanation of the reasoning process will be available. Companies will be able to feed their experience into the system since the user has a possibility to edit facts and rules related to the process with (close to) natural language. Because these functionalities are difficult to develop using C language, the shell of an expert system tool will most probably be embedded in the system.

Optimization tools will be introduced for the constrained optimization of structural elements. These tools will allow the user to improve the design achieved with the design tools.

**Database**

Since ESAComp is designed for companies and institutions, a database with three levels was introduced for storing cases (Figure 4). The so-called general level is for storing typical data, and the company level for company qualified
data. These levels are normally write protected. The user level enables the user to store own data. A possibility to create directories and subdirectories allows the user to organize the work. For example, a directory can be created for a project and subdirectories for subsystems related to the project.

Each database level, directory and subdirectory accepts an unlimited number of cases. Since the same materials, plies, and laminates are often used in several design studies, a library is available in each level for storing relatively stable data. A library is structured just like a case, i.e. it accepts all types of objects and results with related option settings. Thus, results of general interest can be stored in libraries.

The support system of the database allows the user to activate any case to which he/she has read access. The user is further able to search objects and results from libraries and cases and to copy them to the active case. Objects and results can also be copied from the active case to the user library. The specifications of related objects are copied with the results to the target case or library if not already present in it.

![Database of the ESAComp system.](image)

**User interface**

Besides commands in standard pull-down menus, the ESAComp user interface provides lists for objects and results of the active case. The user is able to view and edit objects of the active case, to view results, and to perform analysis/design tasks by selecting objects from the lists and an appropriate tool from the menu. After the tool selection, a window for the further specification
of the task is displayed as required. From the results available, the user may view and print any combination in numeric form and, when applicable, as line and column charts.

**Help facility**
The help facility provides both system and design help related to the context. The user is further able to call a system manual, design manual, and glossary. Indexes are available for the search of information. The system will provide two levels, the general and user level, for the information. The user is thus able to add information to the system and design help, to the manuals, and to the glossary. The help facility is planned to be extended with the aid of the shell of the expert system tool to provide information related to the objects and results of the active case.

**External interfaces**
Interfaces for importing material, ply, and load data from ASCII files, and interfaces for creating element data for three finite element programs (NASTRAN, ASKA, LARSTRAN) will be included in the system in the first phase. The second phase will introduce interfaces for importing load data from these finite element programs.

**SUMMARY**

A composite analysis and design software ESAComp has been described. An efficient and user-friendly analysis/design environment was developed for the system. The anticipated use in companies and institutions lead to the development of a multilevel database. Versatile analysis capabilities were specified already for a limited analysis system that is currently being coded as a first phase of the development process. The second phase will introduce more analysis tools and design tools that enable the user to find feasible solutions for a design problem. Optimization tools will also be developed to enable the user to improve the design. Easy expandability is the key requirement for the system since all the desired capabilities cannot be implemented during the development work. Moreover, it is realized that a design/analysis software never covers all the needs of designers.

**REFERENCES**