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Probabilistic Analysis of Large-Scale Composite Structures Using the IPACS Code

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PROBABILISTIC ANALYSIS of LARGE-SCALE COMPOSITE STRUCTURES USING the IPACS CODE

by

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1 INTRODUCTION

Recent emphasis in the design and development of many critical components in the aircraft and aerospace industries has been not only on achieving superior engineering performance, but also on obtaining simultaneous weight and cost reductions. The materials involved in these designs are being pushed into regimes where their mechanical behavior is not well understood, or is based upon simple interpolation and extrapolation methods. Designs have become more complex than ever before, and new materials such as ceramics and high–performance composites are being utilized without complete understanding of material behavior or characterizations. In many cases, information related to the product geometry, loads, boundary conditions, and the defect population is not available in a precise manner. The mechanics and analytical techniques used in the design process usually involve many idealizations and assumptions which may not be valid under realistic operating conditions. As a result, the reliability, quality, safety, and life estimates of such designs raise serious concerns, resulting in a need to develop a systematic engineering analysis and design methodology with a firm scientific basis for addressing these issues.

The traditional deterministic approach to engineering design may not be acceptable or sufficient because of the inherent uncertainties involved at various stages of the modeling, analysis, and design process. A more rational engineering approach would employ nondeterministic, or probabilistic models which are based on statistical models and methodologies. The probabilistic analysis and design methodology offers several advantages over conventional deterministic approaches. The deterministic methods are usually based upon worst–case scenarios, and realistic uncertainties are accounted for through the use of a factor of safety. Such safety factors do not account for uncertainties in a systematic, quantitative manner, thereby leading to inefficient designs. The safety factor approach can be justified to some extent when adequate engineering experience and databases exist, but this requires years of product development information gathering and testing. This is not the case when a new product must be designed in a relatively short period, and may utilize new materials and analysis techniques. The probabilistic approach offers an analytical framework for including most uncertainties and their effects on structural performance. As a result, the reliability and safety of such products can be estimated to the desired level of confidence.

The issue of uncertainties becomes more pronounced when designing with composite materials as compared to metals. Composite structures involve highly complex interactions between constituent fibers and matrix material. Uncertainties in the design of composite structures naturally arise in regard to fiber alignment and ply thickness, and also manifest themselves in the large number of elastic constants required to characterize the material behavior, and in the the strength allowables associated with the myriad of composite failure mechanisms (e.g. fiber buckling, delamination, and matrix cracking). These parts usually must undergo complex manufacturing processes which can introduce additional uncertainties (e.g. porosity or additional fiber misalignment).

The purpose of the work described herein is to evaluate the NASA–Lewis code IPACS (Integrated Probabilistic Assessment of Composite Structures) as a practical tool for the probabilistic analysis of composite structures. The IPACS code allows for a quantitative treatment of uncertainties at various stages of the composite structural analysis and design process, both at the micromechanics level involving fiber and matrix properties, and at higher levels which involve loads and boundary conditions. IPACS can be used for probabilistic static, dynamic, and buckling analysis of composite structures using shell elements. Although IPACS has been successfully applied to the design of a variety of "thin" airframe–type structures, its applicability to "thick" composite structures comprised of hundreds of plies has yet to be established.

The objective of the present investigation is to ascertain the feasibility of using IPACS for probabilistic analysis of a composite fan blade, the development of which is being pursued by various industries for the next generation of aircraft engines. A model representative of the class of fan blades used in the GE90 engine has been chosen as the structural component to be analyzed with IPACS. In this study, typical uncertainties are assumed in the form of probability density functions at the micromechanics level, and structural responses for ply stresses and frequencies are evaluated in the form of cumulative probability density functions. Because of the geometric complexity of the blade, the number of plies varies from several hundred at the root to about a hundred at the tip. This represents an extremely complex composites application for the IPACS code. A sensitivity study with respect to various random variables is also performed.

The report is divided into five sections. Section 2 provides an overview of the IPACS code. The major modules which make up the code, and their functions, are discussed in that section. In Section 3, the IPACS model of a composite fan blade which is similar to the GE90 blade is presented. The problems encountered with the modeling of the blade, and the effort involved in getting an IPACS to run to completion are discussed. Results for the probabilistic stress and frequency analyses are presented in Section 4. Our assessment of the code is stated in Section 5, along with a list of suggested modifications to improve code performance.

2 OVERVIEW of the IPACS CODE

The IPACS (Integrated Probabilistic Assessment of Composite Structures) computer code is specifically designed to numerically simulate the probabilistic analysis of composite structures. To achieve this end, the code integrates the probabilistic analysis of both composite mechanics and structural analysis. Probabilistic analysis of composite mechanics deals with the computation of uncertainties in the composite material properties at the ply and laminate levels, given the uncertainties in material properties at the fiber and matrix levels. These uncertainties in the material properties are subsequently used in the probabilistic structural analysis, along with uncertainties in the geometry of the structure, the applied loads, and the boundary conditions, to compute uncertainties in structural responses.

The IPACS code is constructed in a highly modular fashion, with an executive module controlling the constituent modules which perform specific tasks related to the overall probabilistic analysis of composite structures. Input for the code logically follows the modular construction, with each module having its own block of relevant input. If the execution of a module is not needed in an analysis, then the associated input block is not required. The code capabilities and input format are discussed in Ref. 1.

The major modules in IPACS for the probabilistic analysis of composite structures are PICAN, NESSUS, and FPI. There are also modules available for interactive model input, basic mesh generation, and graphical display of results. The probabilistic mechanics analysis is performed by the PICAN module, the probabilistic structural analysis is conducted by the FPI module, and the NESSUS module performs the individual (deterministic) finite element analyses of the problem as required by FPI for probabilistic computations. The code also has an editable ASCII–format database of properties for various commonly encountered fibers and matrix materials.

The PICAN (Probabilistic Integrated Composite Analyzer) module performs both linear micromechanics and macromechanics analysis for composite materials. Input to the code consists of the ply lay–up schedule at each node, along with probability distributions for ply materials, orientations, and thicknesses. A probability distributions is specified by a mean value, standard deviation, and a distribution type (normal, Weibull, etc.). Probability distributions may be specified for material properties such as the elastic moduli, thermal parameters, moisture diffusively and expansion coefficients, and for strain and strength allowables. Individual distributions are specified for the fiber and matrix materials, and the fiber volume ratio. Using the ply data (lay–up schedule, orientations, and thicknesses), the code performs micromechanics, macromechanics, and laminate analysis, which results in the computation of various ply and composite properties and their probability distributions. Thermal effects may also be accounted for at the probabilistic level. Not all variables need be random. The user may specify which variables are random and which are to be considered as deterministic.

The input for the PICAN module is very logically structured, with a ply definition specified by the identification numbers of a material, orientation angle, and a thickness value. Probability distributions are specified for the individual materials, orientations, and thicknesses. For convenience, plys may be grouped in "independent zones" in which the statistics of all random variables used in the ply definitions in each zone are independent of and uncorrelated to those in the rest of the structure.

An inherent drawback in the PICAN input is that the ply definitions are specified at nodal points in the finite element mesh, not at the element level. Traditional finite element codes treat material properties as element–based. As a result, most property data for large–scale structures is specified at the element level, and a translation of data must be performed in order to obtain the necessary PICAN input.

A well–written user's and programmer's manual is available for the PICAN module (Ref. 2). The theory of the mechanics of multilayered fiber composites is described in the manual, along with all equations which are used to compute composite properties. Failure criteria for composites are also discussed. The programmer's manual gives descriptions of the functions performed by code subroutines, and the pertinent details regarding global storage locations, thereby facilitating modifications and enhancements to the code by the user. However, the manual is somewhat outdated. There are quite a few discrepancies between the current version of the code and what is described in the manual.

The NESSUS (Numerical Evaluation of Stochastic Structures) module is a probabilistic finite element code. It employs probabilistic fault–tree analysis to perform system reliability analysis using a finite element model. Both the mean–value and advanced mean–value theorems are available. The code is efficient in its ability to quickly compute the initial location of the MPP (most probable point); yielding a good starting point in an attempt to minimize the number of finite element solutions for convergence. This feature is essential in order for a probabilistic FE code to be used to analyze large–scale structures.

A choice of solution algorithms is available in NESSUS, for static and dynamic problems, linear and nonlinear, along with perturbation analysis algorithms to evaluate the sensitivity of the structural response with respect to the random variables. The code capabilities include static analysis, transient dynamics, buckling, modal analysis, and harmonic and random excitation. Constitutive models include linear elasticity and J_2 flow theory for modeling the plastic deformation of materials. The effects of centrifugal stiffening are accounted for.

Code input for NESSUS consists of basic FE data such as node locations, element connectivity, and orientation of material systems for orthotropic material behavior, forcing functions and boundary conditions. Probability distributions may be specified for some input, such as concentrated and distributed loads, and spring stiffness. A comprehensive description of code capabilities and input is available in Reference 3 and previous versions of NESSUS documentations which are referenced in it.

A variety of element types are available within NESSUS. However, at the present time, the only element which may be used in the IPACS system is a four–node quadrilateral shell element. This restriction poses some significant drawbacks, such as the accurate modeling of the thick root section of an airfoil.

The FPI (Fast Probability Integration) module is an approximate solution technique for the probabilistic analysis of design performance functions. FPI techniques are generally an order of magnitude more efficient than Monte–Carlo simulation methods. In addition, FPI calculates sensitivity factors for each response function with respect to each of the random variables. These sensitivities, or first–order derivatives, greatly aid the analyst by indicating which of the random variables are most effective in changing the structural response.

Given random variable statistics and the definition of a performance function, FPI computes the cumulative distribution function (CDF) of the response variables. The code will compute a mean–value first–order solution, the accuracy of which can be improved, if desired, by employing the advanced mean–value method (although at a greater computational cost which may be prohibitive for large–scale problems). The details of the FPI algorithm and input are presented in Ref. 4.

IPACS also contains modules for interactive model input, basic mesh generation, and graphical display of results. For small–scale structural analysis, with simple geometry and a limited number of random variables, these modules prove quite useful. However, for modeling and analysis of large–scale structures with complicated geometry, the use of specialty or commercial modeling systems, with the appropriate data translators, is necessary.

Output from IPACS consists of PDF's and CDF's for structural responses, along with the sensitivities of the responses to each random variable. The response values at the 0.001 and 0.999 probability levels are listed for easy reference. The user must specify the structural responses for which probabilistic analyses are to be performed.

In summary, the IPACS code conveniently integrates the individual software packages necessary to perform probabilistic analysis of structures which use the finite element method as a basis for discretization. However, additional work must be done to make the code more generically applicable to different classes of structures (e.g. add solid three–dimensional elements).

3 IPACS MODEL of a COMPOSITE FAN BLADE

The applicability of the IPACS code to the probabilistic analysis of large–scale structures is tested via the analysis of a composite fan blade having a geometry and ply configuration similar, but not identical to, the current GE90 fan blade. The blade is comprised of graphite fibers and an epoxy matrix, with a titanium skin in some regions. Two probabilistic analyses are conducted using IPACS – the first is a stress analysis in response to a rotational speed of 2400 r.p.m., and the second is a frequency analysis for the first five modes.

The test blade is a composite structure which is formed using a compression–molding technique. A view of the blade, looking down an axis normal to the axis of rotation, is shown in Fig. 1. The blade is approximately 50 in. long, and about 16 in. wide at the widest point. The thickness of the blade varies from over 3 in. at the root to less than 0.5 in. near the tip. The plys are approximately 5.5 mils thick, with over 500 plys in the root region, and abut 100 in the tip region. A repeating ply orientation sequence of [0/45/0/–45/0/45/90/–45] is used throughout the blade for the graphite–epoxy laminate.

Modeling the plys in a structure with a cladding with non–uniform thickness was extremely difficult within IPACS. First, the blade is covered with an additional orthotropic ply approximately 8 mils thick. Since IPACS does not have provisions for the direct input of orthotropic properties for a ply, the fabric was modeled using two additional 4 mil plys of titanium at the outer surfaces, with 90–0 orientations. Second, since the thickness of the titanium cladding varies throughout the blade, a set of isotropic titanium "plys", each of a uniform thickness, had to be introduced at the top and bottom surfaces. A total of 50 plys were included in the set. A subset of these plys is used at each node in order to represent the cladding. However, even with 50 plys in the set, an additional uncertainty of two percent is introduced into the cladding thickness. It was felt that it was important to keep the overall number of plys as small as possible so as not to cause problems with accuracy during the solution phase. An engineer at NYMA, Inc., the principle implementors of the code, estimated that the recoding effort to alleviate this problem via a more "user–friendly" input format would be a major task, and should be done in the future.

The material properties for the fibers and matrix were obtained and entered into the IPACS material database. The properties required for the fibers are the filament diameter, mass density, normal and shear elastic moduli, Poisson's ratio, and the tensile and compressive strength. The matrix properties required for the matrix material are the mass density, elastic modulus, and the maximum allowable tensile, compressive, and shear strains and stresses.

Uncertainties for the material properties were quite difficult to obtain. We did not find a source which contained reliable ranges of values for the material properties. Instead, typical uncertainties and data ranges were obtained via conversations with engineers at GEAE. In other cases, reasonable values were estimated using best judgement. It should be emphasized here that for a proper probabilistic analysis of an actual component, that more effort be expended on finding material data (i.e. minimizing the uncertainties in the uncertainties). The uncertainties used in the analysis were: 5% for ply thickness, 2% for ply orientations (i.e. misalignment), and 5% for material properties. Generally, the data for most of the parameters follow a Weibull distribution. For some material properties, a normal distribution was used. In retrospect, the uncertainty in the ply orientations is probably higher than the value used. The fiber volume ratio was taken as 60%, with an uncertainty of 2%.

Initially, the application of the IPACS code to the test blade was very difficult. The initial finite element model of the blade contained just over a thousand nodes, which was a reasonable degree of discretization given the high degree of blade curvature and other geometric considerations. However, IPACS had not previously been used for such a large–scale problem, and several bugs were encountered. These problems were corrected in a very timely manner by an engineer at NYMA, Inc. The code was then allowed to run for several days on a SPARC–10 workstation, until it crashed when it encountered an internal hard–coded model size limitation of 1000 nodes. In addition, the estimated CPU time for completion of the stress analysis was measured in CPU–weeks. At that time, some additional bugs were encountered in the implementation of the centrifugal stiffening effects, which have been corrected.

A revised finite element model of the test blade was generated in order to yield a more practical run time. This coarser finite element mesh is shown in Fig. 2, and consists of 283 nodes and 248 quadrilateral shell elements. We are quite "uncomfortable" with this degree of discretization. At some point, the uncertainties in the material properties and loads become meaningless due to the uncertainties associated with a coarse discretization which will result in a loss of accuracy. In addition, the applicability of shell elements in the root section of the blade is certainly questionable; however, no other elements are available at the present time within IPACS.

Using the coarse finite element model, an investigation into the long run–time was made. Initially, it appeared that just under a CPU–week would be required for the stress analysis. Investigations revealed very inefficient coding in the PICAN module, which is used for the computation of the laminate properties. The code was not taking advantage of the fact that most of the plys are homogeneous, and was recomputing the properties of each individual ply. An enhancement was made to the code to check if such properties have already been computed, and to use them in that case. That change resulted in a code speed–up of a factor of three, bringing the required CPU time down to about two CPU–days.

4 RESULTS

Two probabilistic analyses were performed for the test blade. The first was a stress analysis in response to a rotational speed of 2400 r.p.m. (with centrifugal stiffening effects included), and the second was a frequency analysis for the first five modes. All calculations were performed on a SPARC–10 workstation.

The results for the stress analysis were computed at 8 nodes in the model, as shown in the mesh plot in Fig. 3. An attempt was made to compute stresses at a total of 10 locations, but IPACS crashed for unknown reasons at two of them. Furthermore, the code would crash if results at more than one node were requested. Since IPACS execution can be started at either the PICAN, NESSUS, or FPI levels, this did not result in any additional CPU time to get results at all of the nodes, but did increase turn–around time. It was an inconvenience which should be addressed.

The results computed at each node in the stress analysis are the longitudinal, transverse, and shear stresses, and Hoffman's failure criterion. The code required about 45 min. of CPU time to compute the results at each node. The mean values of the results are shown in Table 1. A positive value for Hoffman's failure criterion represents safety, and a negative value indicates failure, with a value near zero implying impending failure. In all cases, the calculated mean values of Hoffman's failure criterion indicate safety.

The critical data from the probabilistic analysis consists of the cumulative probability distributions function (CDF) for each of the responses at each of the nodes. A typical CDF is shown for the longitudinal shear stress in the outermost ply at node E in Fig. 4. This node was chosen since the longitudinal stress is quite high there. There are 138 plys at this point. Using data at the low and high ends of the distribution say, the 0.001 and 0.999 probability levels, the range of probable values of the responses can be obtained. For stresses, the relevant information would be the maximum probable stress. For the failure criterion, the range of values would be more relevant. The extreme probabilistic values of the responses at node E are shown in Table 2 (the value represents the extreme when all plys are considered). The values of Hoffman's failure criteria range from 0.432 to 1.479 at this location, with a mean value of 0.986.

The probabilistic frequency analysis was performed without any major problems. The analysis was carried out for the first five natural frequencies. The mean values and probabilistic range of values (based on 0.001 and 0.999 probability levels) are shown in Table 3.

The IPACS code needs some revisions with regard to the output which it produces. First, laminate properties computed by PICAN are written to two individual files for each node. Even with our coarse model which has just 283 nodes, this results in so many files that it becomes difficult to find other files in the directory which contains them. These files are not very large, and the data can easily be written into one file with only minor revisions to the code. Also, the way the filenames are generated is such that the code will generate incorrect filenames for node numbers above 999. Unfortunately, the code keeps executing, and eventually crashes. Second, several large output files are generated. These files do not contain data which the user really needs to examine. However, the sheer size of the files (tens of megabytes) did cause our disk to fill to capacity several times, resulting in premature termination of the analysis.

Other results which IPACS produces include the sensitivities of the responses to the random variables (i.e the rate of change of the response with respect to the random variable). This provides extremely useful information on the design. One can quickly ascertain whether a particular random variable is effective when it comes to changing the value of a response. Furthermore, if the sensitivity of a random variable is small, then it is not critical that the uncertainties associated with that random variable be represented with a high degree of accuracy. For purposes of illustration of code output, the sensitivities of the longitudinal stress in ply 1 at node E are shown in Table 4, along with ratio of the design point, measured relative to the mean value, to the standard deviation. From this data, we clearly see that the most effective variables for changing the longitudinal stress are the fiber tensile modulus, fiber volume ratio, and the ply thickness. The normalized values of the random variable values provide an indication as to how much opportunity remains for increasing or decreasing the variable's value.

5 SUMMARY and RECOMMENDATIONS

The capabilities of the IPACS code for probabilistic analysis of composite structures have been tested for applicability to the analysis of a large–scale structure. Probabilistic stress and frequency analyses were carried out for a composite fan blade comprised of several hundred plies. Uncertainties were accounted for in various finite element input parameters, such as fiber and matrix properties, fiber volume fractions, and ply thicknesses and orientations. These were accommodated in the analysis on a quantitative, rational basis, and their effects on the structural responses (ply stresses and frequencies) were determined in a precise manner. These results can be used for reliability and failure predictions of the blade in a more accurate manner than would be possible through the conventional deterministic approach which utilizes a factor of safety.

To assess the accuracy of the coarse model used for the IPACS analysis (248 quadrilateral shell elements), the natural frequencies predicted by IPACS were compared to those obtained from other finite element codes. The mean values of the natural frequencies computed by IPACS are within 20 percent of values computed by GEAE's "MASS" code and the ABAQUS code (the frequencies for modes two through four are within 10 percent), and the frequencies from those codes for modes two through four fall within the range of values predicted by IPACS based on the 0.001 and 0.999 probability levels (see Table 3). These comparisons provide evidence that a coarse model might possibly be used for probabilistic analysis; however, we still refrain from advocating the use of a model with as few elements as in the one used here.

On the basis of the results obtained herein, it can be concluded that IPACS provides a firm technical basis for the probabilistic analysis of composite structures. However, as elaborated upon in previous sections, the present analysis was quite cumbersome and challenging, and required numerous software modifications and debugging at several stages. Also, several approximations and assumptions, which cannot be justified in real–life situations, had to be made in order to carry out the analysis.

Our assessment is that, at the current time, the IPACS code is not yet a practical production tool for applications involving large–scale composite structures such as the GE90 fan blade. Since the code does contain a solid analytical and computational foundation, the software can be modified and enhanced to render the code practical for complex composite parts. However, the changes required for this will be substantial. Foremost in this effort must be a simplification of the specification of the ply lay–up schedule, as well as a significant decrease in the CPU time required for the computation of the laminate properties by the PICAN module. Currently, an inordinate amount of time is required for any realistic FE model of a complex composite structure such as the one analyzed herein. For example, the IPACS frequency analysis, including the PICAN phase, requires well over a day of CPU time for the coarse model with 248 elements. A deterministic analysis of a similar model with 3500 shell elements can be performed in about one CPU–hour using the ABAQUS code.

Listed below are our suggestions for modifications to the IPACS code. These changes must be made to improve the performance of the code, to make it a more robust tool for the probabilistic analysis of large–scale composite structures, and to increase the "user–friendliness" of the code. Some of the items below represent bugs which should be corrected as soon as possible.

Suggested Modifications to IPACS

1) Allow for a variable number of plys at each node in an independent zone.

   A ply–stacking table is currently used to specify the ply lay–up at each node. This table requires the same number of entries at each node, with an entry of zero indicating a ply drop–off. This input format can be very inconvenient for a fan blade structure, and requires enormous amounts of time on the part of the user to prepare the input data. Since the code internally converts this table to a ply list at each node, it is prudent to allow the user to input the nodal lists directly.

2) Investigate ways to speed up calculations in the PICAN module.

This section of the code computes laminate properties, and takes an inordinate amount of time to do so. This may be prohibitive for real–life complex applications. For instance, because of CPU and memory requirements, the number of elements used in the present analysis was far less than it would be for an acceptable model in a practical context. Therefore, there is a strong need for large improvements in the efficiency of the code.

An initial enhancement within the PICAN module produced a speed–up of a factor of three. Additional modifications should be made to minimize the computational effort, which should lead to further substantial performance improvements.

3) Consider the use of an industry–standard FE analysis package.

IPACS presently utilizes NESSUS for the purpose of finite element analysis. However, present industrial design practices are based upon the use of commercial finite element codes such as ANSYS, ABAQUS, and NASTRAN, and special purpose codes like CSTEM. Therefore, the value of IPACS as a general–purpose design tool would be greatly enhanced by integrating it with one of the aforementioned finite element codes.

4) Include an 8–node brick element.

Currently, only a 4–node quadrilateral shell element may be used. This prevents the accurate modeling and analysis of the geometries with sections such as the GE90 shank and dovetail.

5) Include a 3–node triangular shell element.

This element will provide greater flexibility to use external mesh generators, many of which produce some triangular elements, for the preparation of IPACS input.

6) Correct the bug which prevents probabilistic results from being computed at more than one node during execution of the FPI module for a probabilistic stress analysis.

7) Correct the bug which prevents probabilistic results from being computed at some nodes.

   The code completes execution at some nodes, but crashes for no apparent reason at others.

8) Allow direct input of orthotropic material properties for a ply.

   This limitation interfered with the modeling of the woven fabric covering on the outer surface of the fan blade.

9) Specify ply definitions at elements, not nodes.

   Nodal specifications are not consistent with the great majority of FE−based codes.

10) Restrict the voluminous output which IPACS generates.

    At the very least, allow the user to suppress the huge output files which generally aren't needed, and to restrict output to the essential data.

11) Write PICAN output to one master file.

    The PICAN module produces two output files for each node, making it very difficult to find files in the directory where IPACS is executing.

12) Correct the bug which prevents a model with more than 1000 nodes from being analyzed.

    The PICAN module continues executing for quite a while in this case, doesn't produce any additional nodal results (beyond node 999), and eventually crashes.

13) Update the User's Manual.

    There are quite a few discrepancies between the current version of the code and what is described in the User's Manual (dated Dec. 1991).

14) Allow direct input of thickness and orientation data.

    The code requires data sets to be created which contain this data. While this is helpful when many plies exist with the same attributes, it is cumbersome for models in which many plys exist which have unique specifications within the model.

Conclusion

We believe that the IPACS code is a unique and valuable system for probabilistic mechanics analysis, and produces design sensitivity information that no other code provides. We have identified and documented a number of limitations which, in retrospect, are not surprising considering that IPACS is not yet a production tool. Along with the suggested modifications, we also recommend a parallel effort to understand the actual uncertainties associated with the ply properties. Lastly, we would welcome the opportunity to continue the evaluation of IPACS once the suggested modifications have been made.

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3) *NESSUS Version 6.0 Release Notes*, Southwest Research Institute and Vanderbilt University, June 1992.

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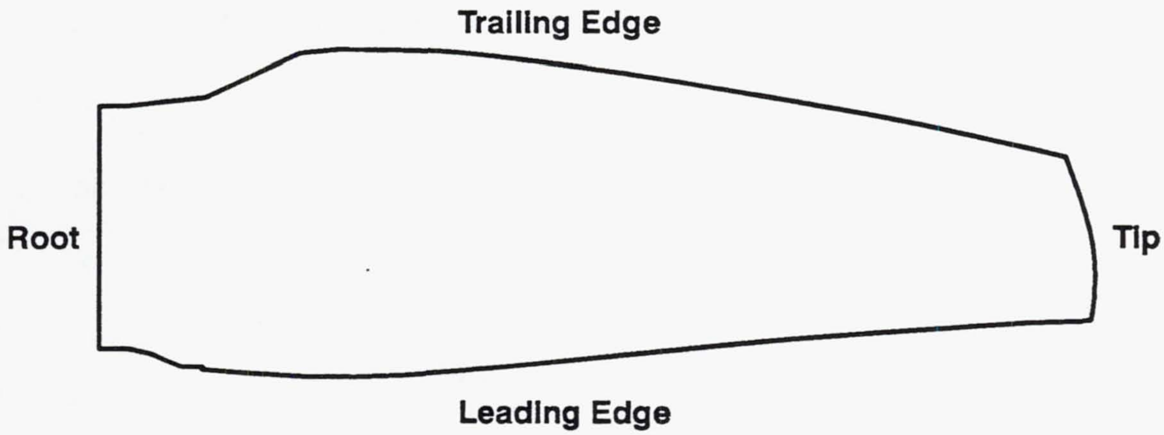

Fig. 1
Composite Blade Geometry

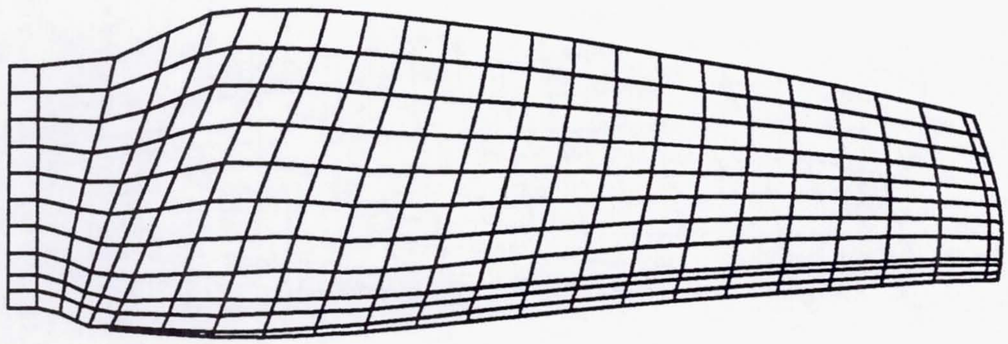

Fig. 2
Finite Element Mesh for IPACS Analysis

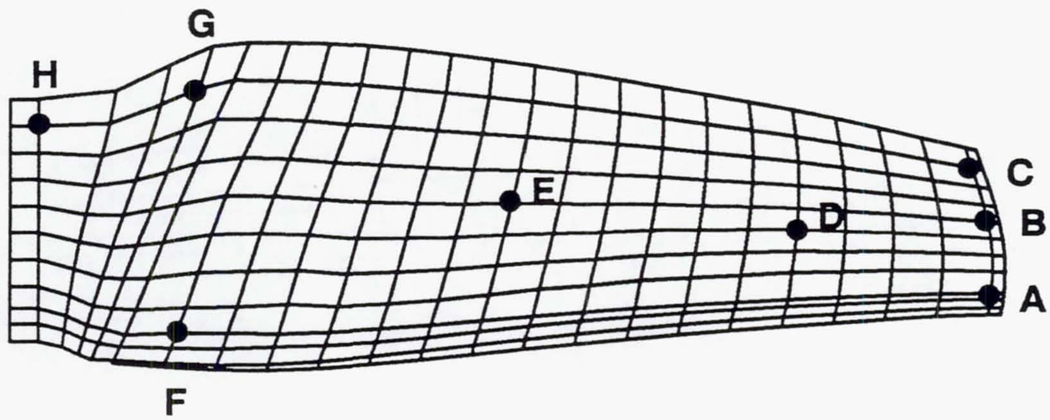

Fig. 3

Location of Nodes for Stress Computation
(2400 r.p.m. rotational speed)

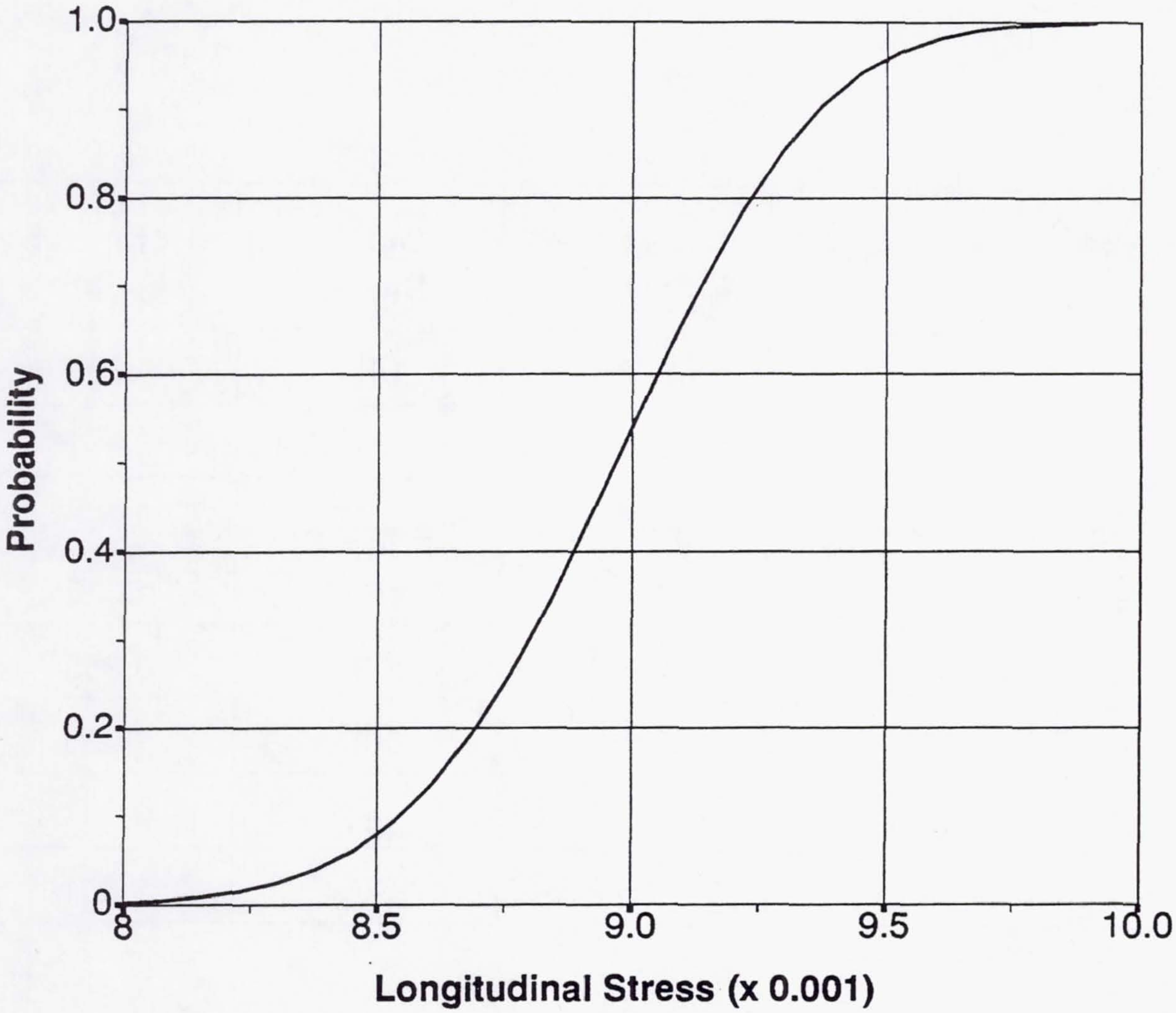

Figure 4

Cumulative Probability Distribution Function
Ply 1 at Node E
(2400 r.p.m. rotational speed)

Node	Longitudinal Stress	Transverse Stress	Shear Stress	Hoffman's Failure
A	2773	795	1489	0.999
B	8601	2786	3093	0.991
C	6041	3608	2075	0.998
D	8944	1981	1539	1.015
E	62477	3256	2787	0.986
F	28897	13811	10956	1.006
G	16088	999	448	0.994
H	12503	572	764	1.001

Table 1

Mean Values of Responses at Nodal Points
(2400 r.p.m. rotational speed)

Response Type	Minimum	Maximum	Mean
Longitudinal Stress	---	66079	62477
Transverse Stress	---	3886	3256
Shear Stress	---	3356	2787
Hoffman's Failure	0.432	1.479	0.986

Table 2

Probabilistic Range of Values for Responses at Node E (2400 r.p.m. rotational speed)

Mode	Mean	Minimum	Maximum
1	62.8	60.6	64.9
2	116.6	108.1	125.1
3	177.8	157.8	197.2
4	280.3	248.5	311.6
5	390.5	345.3	432.2

Table 3

Probabilistic Values for Blade Natural Frequencies

Random Variable		Sensitivity	DP − Mean / STDV
Fiber	Modulus 11	−.418	1.29
	Modulus 22	−.016	.05
	Poisson Ratio 12	−.010	.03
	Poisson Ratio 23	−.009	.03
	Density	.258	−.80
	Tensile Strength	−.008	.17
	Compressive Strength	−.008	.17
Matrix	Tensile Modulus	−.021	.07
	Shear Modulus	−.056	.17
	Poisson Ratio	−.010	.03
	Density	.104	−.32
	Tensile Strength	−.008	.17
	Compressive Strength	−.008	.17
	Shear Strength	−.008	.17
Volume Ratio	Fiber	−.413	1.28
	Voids	−.012	.04
Ply	Misalignment	−.046	.14
	Thickness	−.775	2.33

Table 4

Sensitivities for the Mode 1 Natural Frequency

REPORT DOCUMENTATION PAGE

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An investigation was performed to ascertain the feasibility of using IPACS for probabilistic analysis of a composite fan blade, the development of which is being pursued by various industries for the next generation of aircraft engines. A model representative of the class of fan blades used in the GE90 engine has been chosen as the structural component to be analyzed with IPACS. In this study, typical uncertainties are assumed in the level, and structural responses for ply stresses and frequencies are evaluated in the form of cumulative probability density functions. Because of the geometric complexity of the blade, the number of plies varies from several hundred at the root to about a hundred at the tip. This represents a extremely complex composites application for the IPACS code. A sensitivity study with respect to various random variables is also performed.

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