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Structural Evaluation of Exo-Skeletal Engine Fan Blades

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STRUCTURAL EVALUATION OF EXO-SKELETAL ENGINE FAN BLADES

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ABSTRACT

The available computational simulation capability is used to demonstrate the structural viability of composite fan blades of innovative Exo-Skeletal Engine (ESE) developed at NASA Glenn Research Center for a subsonic mission. Full structural analysis and progressive damage evaluation of ESE composite fan blade is conducted through the NASA in-house computational simulation software system EST/BEST. The results of structural assessment indicate that longitudinal stresses acting on the blade are in compression. At a design speed of 2000 rpm, pressure and suction surface outer most ply stresses in longitudinal, transverse and shear direction are much lower than the corresponding composite ply strengths. Damage is initiated at 4870 rpm and blade fracture takes place at rotor speed of 7735 rpm. Damage Volume is 51 percent. The progressive damage, buckling, stress and strength results indicate that the design at hand is very sound because of the factor of safety, damage tolerance, and buckling load of 6811 rpm.

INTRODUCTION

Revolutionary Exo-Skeletal (ref. 1) Engine (ESE) concept in new aircraft propulsion technologies is developed at NASA Glenn Research Center, to meet the more demanding and challenging requirements for next generation jet engines. ESE concept omits shafts and disks at the engine center, instead replaces them by rotating casings that supports the blades in spanwise compression. Therefore, it provides an open channel at the engine centerline. The ESE design is a good example of technological ingenuity because it offers many great benefits over conventional aircraft engine design, such as: (1) light weight because of reduced number of parts and elimination of shafts and disks, (2) improved fatigue life because rotors operate in compression stress fields, (3) minimization or elimination of the foreign object damage effect and unbalance resulting there from, and (4) improved fan efficiency over conventional fan rotors because of the elimination of blade tip losses. A projected view of a typical ESE drum rotor is shown in figure 1. The blades are attached to a drum rotor and supported by a stress tuner ring at the inner diameter in order to avoid flutter and buckling. A race shell bearing case is supporting the rotating casing. The bearings will transfer the loads between the drum rotor and the static backbone shell and permit relatively free rotation with minimum friction.

The objective of this paper is to demonstrate the structural viability of composite fan blades of ESE through EST/BEST (ref. 2) computational simulation software. Composite fan rotor blades of an ESE are designed, modeled, and evaluated for full structural analysis, durability and damage tolerance assessment.

MODULES USED IN COMPUTATIONAL SIMULATION

The aerodynamic design, finite element model, thermo-mechanical properties and loading conditions of the ESE composite fan blade are generated using NASA in-house code EST/BEST (Engine Structures Technology Benefit Estimator). A modular chart of the EST/BEST software system is shown in figure 2. EST/BEST software system is multi-factor, multi-scale, and multi-disciplinary software system to analyze the engine structures. The discipline modules that are used to obtain the results presented in this paper through EST/BEST are (1) Blade Design code (ref. 3) to design the blade shape, (2) Flow (ref. 4) code to asses aerodynamic performance and calculates the blade surface pressure and temperatures, (3) COSMO (ref. 5) to convert CFD surface coordinates to structural coordinates and to generate the finite element model of the blade, (4) COBSTRAN (Composite Blade STRuctural Analyzer) code (ref. 6), used to fit automatically the plies starting from the outer surface, (5) MHOST (ref. 7), finite element analysis module, (6) ICAN (ref. 8) composite mechanics module, (7) CODSTRAN (ref. 9) Progressive Damage Evaluation module. EST/BEST is used to perform stress, displacement, modal, and buckling analyses as well as damage initiation, damage growth, damage progression and fracture analysis of the ESE composite fan blade.

PROCEDURE FOR GENERATING FINITE ELEMENT MODEL OF ESE FAN BLADE

For the results to be presented in this paper, the fan blade is designed. The aerodynamic blade shape is obtained by using flow and blade design modules through EST/BEST for a cruise speed of 2000 rpm and 1.5 pressure ratios. The rotor is part of an aircraft engine for a subsonic mission. The rotor consists of 28 blades and is designed to meet an overall aerodynamic efficiency of 93 percent. Table I summarizes the various parameters that pertain to the design of the fan blade. The component structural modeling code is used for the structural modeling. From the CFD (Computational Fluid Dynamics) surface coordinates are converted to structural coordinates for utilization in finite element analysis using COSMO (ref.5). Pressure and temperature loads are interpolated from flow to nodal coordinates. The geometry of the ESE fan blade consists of the following: hub drum rotor attachment radius of 68.3 in., the corresponding aerodynamic chord of 18 in., blade tuner radius of 31.6 in., and the corresponding aerodynamic chord of 13.2 in. The maximum thickness of fan blade at the hub where it is fixed is 0.95 in. while the maximum tip thickness at the blade tuner where it is fixed only along y and z directions is 0.41 in. The boundary conditions for the blades of ESE are fixed at the drum rotor and it is fixed only along y and z directions at the blade tuner. The applied loads for fan blade are element pressure, and nodal temperatures at rotor speed of 2000 rpm in design.

For the finite element model 4 node shell element is used. The fan blade is modeled with 40 elements and 55 nodes with six degrees of freedom per node. The next step is to select the proper material and ply orientation. To generate the ply lay-up through blade thickness at each node starting from the outer surface, the COBSTRAN module is used. The composite blade is made up of 0.005 in. graphite epoxy plies oriented as follows: $[30,-30,0,0,30,0]_s$ with 55 percent fiber volume ratio and 2 percent void volume ratio. The design parameters for the composite fan blade are summarized in table II. The finite element model for a single fan blade is shown in figure 3. The ESE composite blade weighs 12 lbs. The total fan stage weight is 344 lbs.

STRUCTURAL EVALUATION OF ESE COMPOSITE FAN BLADE

Structural analysis is performed to determine its modal and structural characteristics under static pressure loading that has 1.5 pressure ratio and rotor speed of 2000 rpm. Displacement, stress, modal, and buckling analyses for the composite fan blade are conducted by the finite element module in EST/BEST. The spanwise and resultant displacements are shown in figure 4. The maximum displacement (0.38 in.) is at the center of the leading edge. Since the composite fan blade at the tip (inner section) is fixed in y and z directions, but all remaining degrees of freedom are free, spanwise displacements are encountered.

The longitudinal, transverse, and shear stress distributions at the outer ply of the pressure and suction surfaces of the ESE composite fan blade are shown in figure 5. As it is shown in the figure 5, stress field of ESE composite fan blade is in compression. The longitudinal, transverse and shear stresses for the suction and pressure blade surfaces at the outer ply are tabulated in table III. The strength for each ply is also listed in table III. The longitudinal, and transverse tensile stress of outer most ply of the pressure blade surface is 12.8 ksi, and 4.2 ksi, respectively while the longitudinal, and transverse stress in compression for the same ply is 43.7 ksi and 3.4 ksi, respectively. Maximum shear stress for the outer most ply of the pressure surface is 3.8 ksi. As summarized in table III, the ply longitudinal, transverse and shear stresses are significantly lower than the allowable ply strength limits. In terms of assessing the safety of the blade at design conditions, the maximum margin of safety, so called safety factor, is 15.67 for the ply longitudinal tensile stress and minimum safety factor is 1.17 for the shear stress. This means ply failure will take place if the ply shear stress reaches to the shear stress level of 117 percent of the current stress level. The stress and strength results indicate that the design at hand is very sound because of the factor of substantial safety.

The modal analysis of the ESE composite fan blade is performed at design speed of 2000 rpm and 1.5 pressure ratio. The first three mode shapes and their frequencies are presented in figure 6. Eigenvectors are normalized to the maximum displacement. At the design speed of 2000 rpm, the blade first, second and third natural frequencies are 222 cps, 321 cps, and 358 cps, respectively. The ability to predict frequencies and mode shapes early in the design phase is important to the understanding and analyzing blade flutter characteristics and the development of the ESE composite fan blades. As shown in figure 7, the Campbell diagram is constructed for different engine orders and first five frequencies of the ESE composite fan blade. The results obtained showed that second, third and fourth natural frequencies interfere with engine orders at the operating speed and minimum cruise speed. These crossings at higher frequencies can be avoided by changing the composite lay-up, which will result in a modified stiffness. Figure 7 depicts a small reduction in natural frequency as the rotor speed increases. The reduction in the frequency is consistent with the physical boundary conditions of the ESE composite fan blade. In the case of conventional blade design, since the conventional blades operate in tensile stress field, the frequency increases with the increase of rotor speed due to increase in centrifugal stiffening.

In order to predict the buckling rotor speed, buckling analysis of the ESE composite fan blade is performed. The result of the buckling analysis is presented in figure 8. The fan blade would buckle at speed of 6811 rpm. That is about 3.5 times the design rotor speed. The result of buckling analysis indicates that the designed composite fan blade is satisfactory to be used for the ESE design configuration.

The modal analysis is performed at a rotor speed of 2000 rpm. The first 3 mode shapes are extracted and plotted as in figure 6. The fan blade first, second, and third frequencies are 222 cps, 321 cps, and 358 cps, respectively. In order to know what operating frequencies need to be avoided, the Campbell diagram is plotted for different engine order and for first five modes as shown in figure 7.

In addition to the modal analysis, buckling analysis is performed to predict the critical loading speed of ESE composite fan blade. The buckling shape of the blade is shown in figure 8. The fan blade would buckle at the speed of 6811 rpm which is 3.5 times the desing speed of 2000 rpm. Buckling analysis also agrees that the blade design is satisfactory to be used for ESE design.

The evaluation of structural durability of the composite fan blade is investigated trough the progressive damage and fracture computational simulation module CODSTRAN (Composite Durability STRuctural Analysis) in EST/BEST. The detailed description of approach to progressive damage simulation is discussed in separate paper (ref. 10). CODSTRAN has three modules: (1) composite mechanics module ICAN, (2) finite element analysis module MHOST, and (3) damage propagation tracking CODSTRAN. The composite mechanics module is called before and after each finite element analysis. The same module computes the composite ply properties at each node of the finite element model. The computation is based on fiber and matrix constituent properties, and the composite lay-up. The ICAN module is used in CODSTRAN to assess individual ply failure modes. The overall evaluation of composite structural durability is carried out in the damage propagation sub module in CODSTRAN. As structural fracture becomes imminent, the structural damage volume increases rapidly. This can be used as an index of structural integrity and an indication of rapid degradation. The damage energy is an alternative to the damage volume as a measure of structural degradation. The damage energy is defined as the sum of the discharged strain energies due to local ply failures through each node.

The progressive damage evaluation shows that initial damage occurs at 4870 rpm, which is 2.4 times the design speed of 2000 rpm, with damage volume of 0.069 percent. Total damage energy release rate and damage volume versus rotor speed are plotted in figure 9. The common failure modes for initial damage are longitudinal compressive, combined stress, and relative rotation criteria. The initial damage takes place near the leading edge and close to the hub. Blade fracture took place when the rotor speed exceeded 7639 rpm, which is 3.8 times the design speed. At fracture, the damage volume was about 51 percent. Damage progression of the ESE composite fan blade for advanced subsonic engine is shown in figure 10. The information plotted in figure 11 shows the effect of material degradation and structural deformation at increased rotor speed on the buckling load.

CONCLUSIONS

Based on the results of structural and the durability evaluation of the ESE composite fan rotor blades that is presented in this paper, the following conclusions are drawn:

1. The computational simulation software EST/BEST is readily available and capable of doing full structural and progressive damage analysis of the revolutionary ESE composite fan blades.
2. The designed ESE composite fan blade operates under compression stress field. Therefore, the ply longitudinal, transverse and shear stresses are significantly lower than the allowable ply strength limits.
3. The stress and strength results indicate that the design at hand is very sound because of the factor of safety. Maximum safety factor is 15.7 and minimum safety factor is 1.2.
4. The buckling analysis shows that the buckling load is 3.5 times the design rotor speed.
5. Based on the damage tolerance evaluation, the designed ESE composite fan blade has the functional capability to sustain damage from initial damage at 4870 rpm, until the rotor speed of 7639 rpm while the design speed is 2000 rpm.
6. Buckling evaluation also agrees that the blade design is satisfactory to be used for the ESE design.

REFERENCES

1. Halliwell, I., “Exoskeletal Engine Concept: Feasibility Studies for Medium and Small Thrust Engines,” NASA Contractor Report 2001-211322.
2. Abumeri, G.H. and Chamis, C.C. “EST/BEST: A Computer Code for Assessing the Benefits of Advanced Aerospace Technologies,” published in the journal of Advances in Engineering Software, 1997 Elsevier Science Limited, Printed in Great Britain., pp. 231–238.
3. Crouse, J.E. and Gorrell, W.T. (1981), “Computer Program for Aerodynamic and Blading Design of Multistage Axial-Flow Compressors,” NASA Technical Paper 1946.
4. Chima, R.V., “RVCQ3D Rotor Viscous Code 3–D, User’s Manual and Documentation,” NASA Glenn Research Center, Cleveland, Ohio, 1999.
5. McKnight, R.L., Maffeo, R.J., and Schwartz, S., Engine Structures Analysis Software: Component Specific Modeling (COSMO)., NASA Contractor Report 195378, 1994.
6. Aiello R.A., “Composite Blade Structural Analyzer (COBSTRAN) User’s Manual,” NASA Technical Memorandum 101461, 1989.
7. Nakazawa, S., Dias, J.B., and Spiegel, M.S. (1989), “The MHOST Finite Element Program: 3–D Inelastic Analysis Methods for Hot section Components: Volume II—User’s Manual,” NASA Contractor Report 182235.
8. Murthy, P.L.N. and Chamis, C.C. (1986), “Integrated Composite Analyzer (ICAN): Users and Programmers Manual,” NASA Technical Paper 2515.
9. Minnetyan, L., Murthy, P.L.N., and Chamis, C.C. (1990), “Composite Structure Global Fracture Toughness via Computational Simulation,” Computers and Structures, Vol. 37, No. 2, pp. 175–180.
10. Kuguoglu, L., Abumeri, G.H., and Chamis, C.C., “Durability and Damage Tolerance: Comparative Evaluation of Metallic and Composite Fan Blades,” AIAA Paper 2002–1527, 43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, April 23, 2002, Denver, CO.

Table I.—Fan Blade Design Parameters
(Rotor for an Advanced Subsonic Mission)

Fan Pressure Ratio	1.5
Inlet Tip Radius	68.5 in
Rotor Tip Solidity	1.40
Fan Hub to Tip ratio	0.36
Tip Max Thickness to chord Ratio	0.030
Hub Max Thickness to chord Ratio	0.09
Tip Aerodynamic Chord	18.0 in
Hub Aerodynamic Chord	13.0 in
Fan Tip Speed	1200 ft/sec
Corrected Speed	2000 rpm
Number of rotor blades	28
Fan Efficiency	91.8%

Table II.—Composite Fan Blade—Fabrication Parameters and Material Properties (Blade Weight = 12 lb)

Material Properties		
Name of the Material Property	Graphite Fiber	Epoxy Matrix
Density	0.063 lb/in^3	0.0443 lb/in^3
Elastic Modulus (E_{f11})	31 msi	0.50 msi
Shear Modulus (G_{f12})	2 msi	0.185 msi
Poisson's Ratio (ν_{12})	0.20	0.35
Tensile Strength	400 ksi	15 ksi
Compressive Strength	400 ksi	35 ksi

Table III.—Summary of ESE Composite Fan Blade Most Outer Ply Stresses and Strengths (Rotor Speed of 2000 rpm)

	Pressure Surface 30º Ply Angle	Suction Surface 30º Ply Angle	Graphite/ Epoxy Ply Strength
Longitudinal tensile	12.9 ksi	12.7 ksi	215 ksi
Longitudinal compressive	43.7 ksi	34.4 ksi	110 ksi
Transverse tensile	4.2 ksi	4.2 ksi	10 ksi
Transverse compressive	3.4 ksi	3.3 ksi	23 ksi

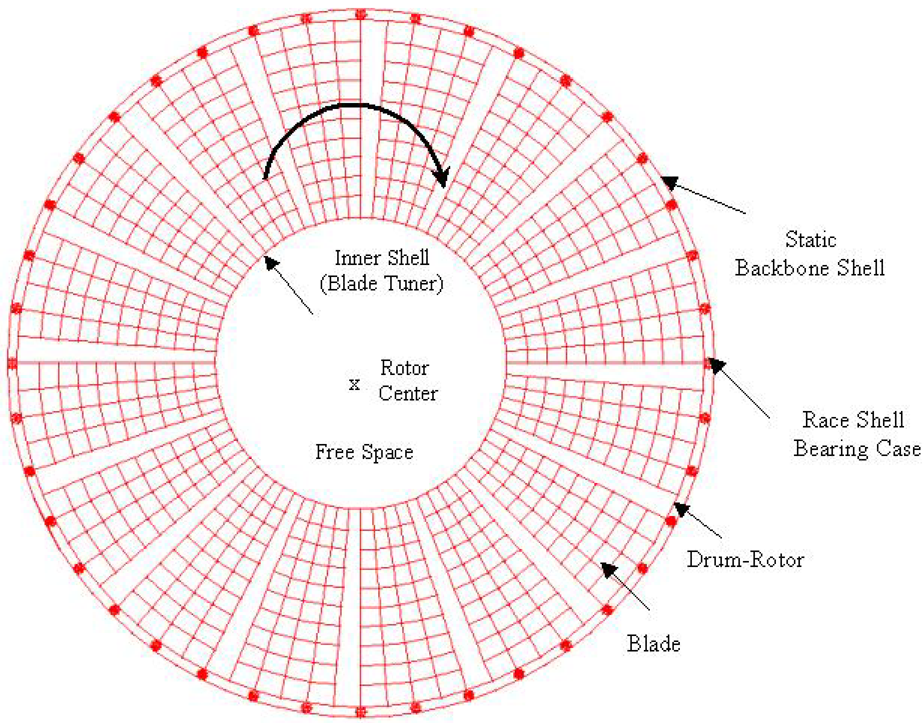


Figure 1.—Projected View of a Typical Exo-Skeletal Engine Composite Fan Rotor.

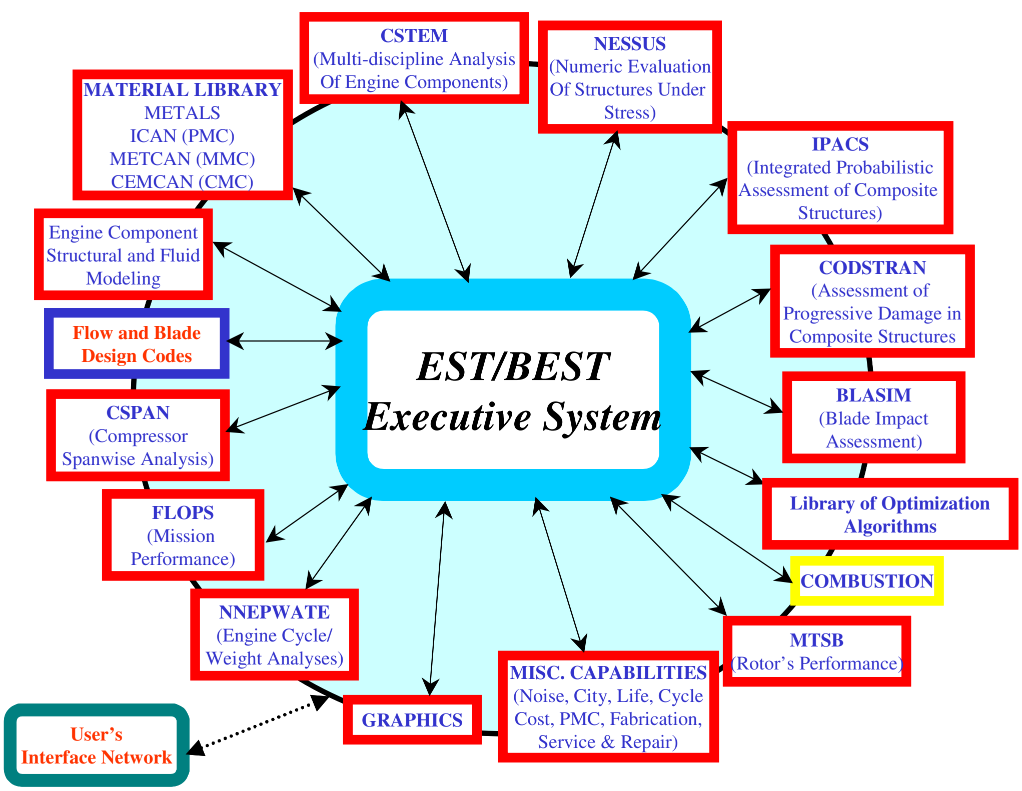


Figure 2.—EST/BEST: Engine Structures Technology Benefit.

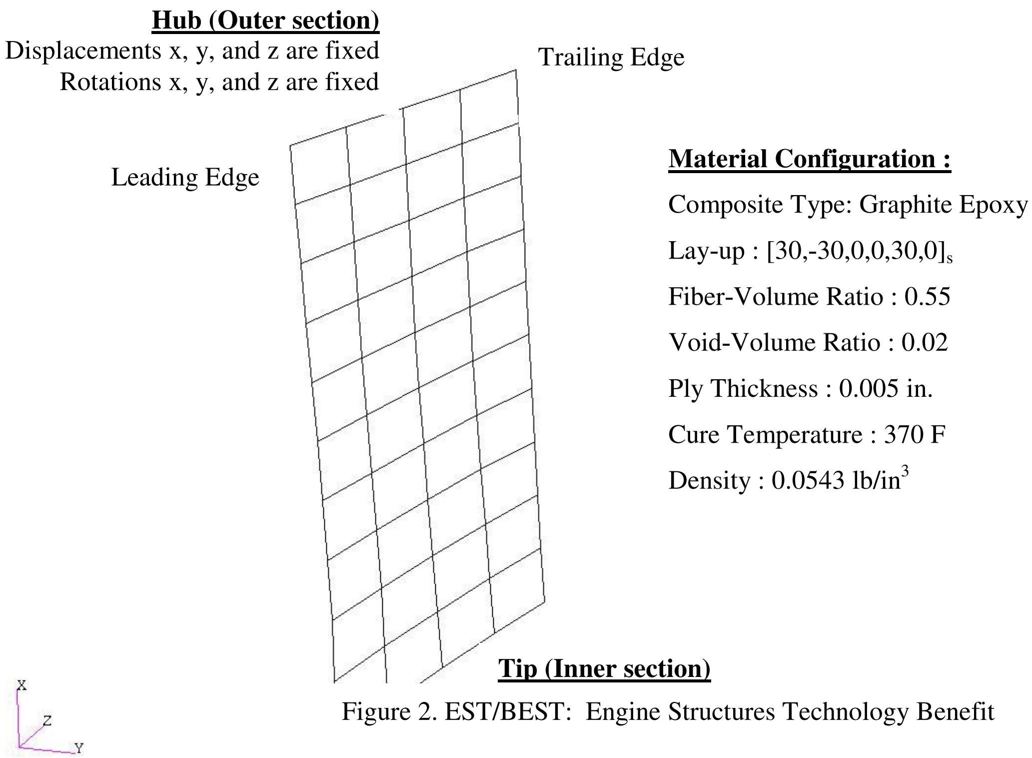
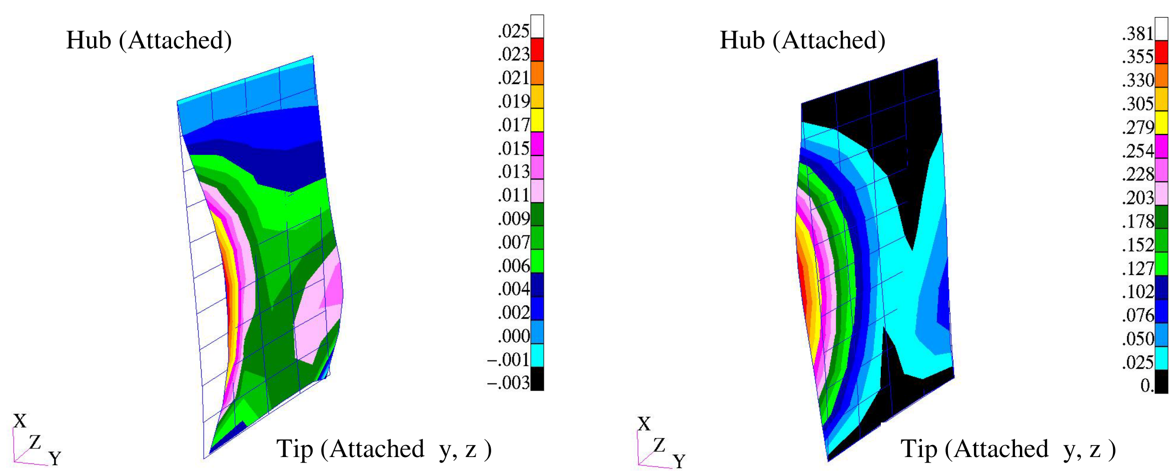


Figure 2. EST/BEST: Engine Structures Technology Benefit

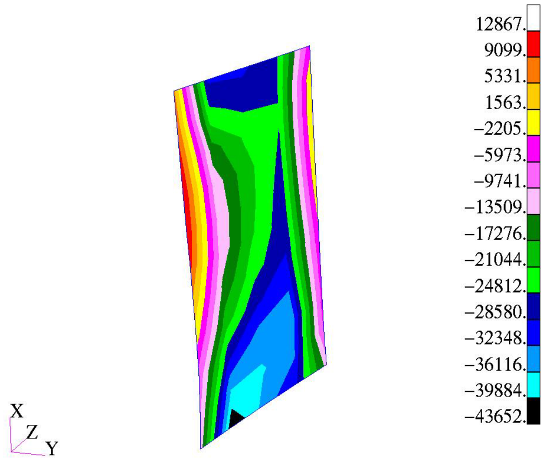
Figure 3.—Exo-Skeletal Engine Fan Blade Projected Finite Element Model to a Reference Plan.



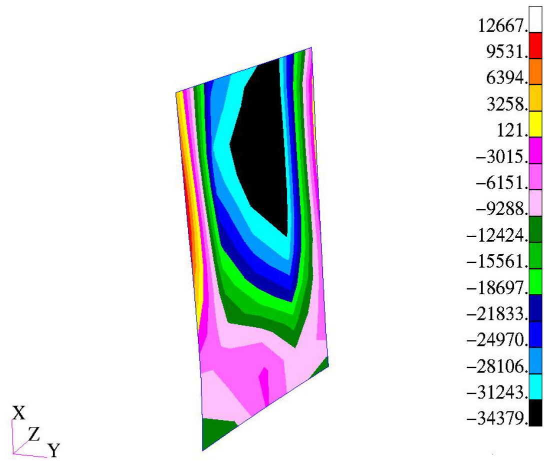
(a) Longitudinal Displacement

(b) Resultant Displacement

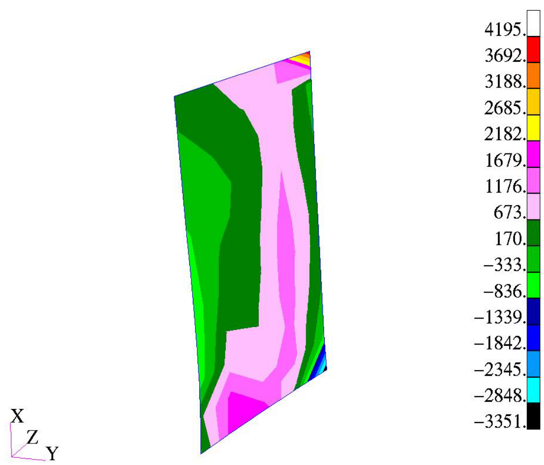
Figure 4.—Exo-Skeletal Engine Composite Fan Blade Displacements.



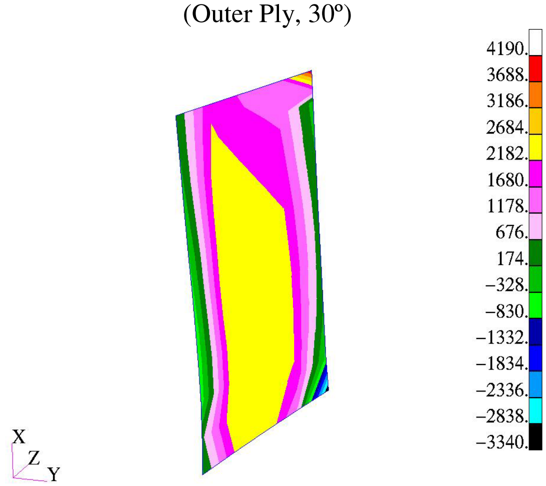
(a) Pressure Surface: Longitudinal Stress (Outer Ply, 30º)



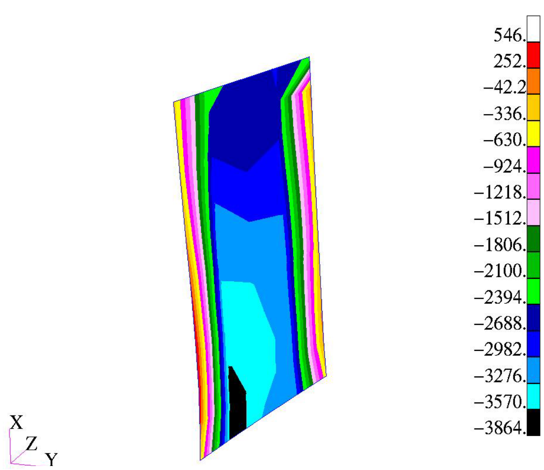
(b) Suction Surface: Longitudinal Stress (Outer Ply, 30º)



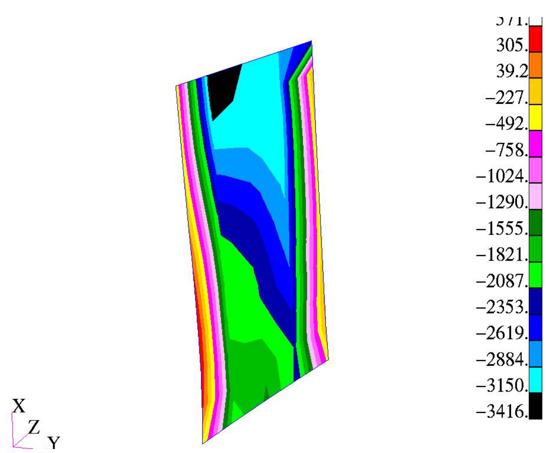
(c) Pressure Surface: Transverse Stress (Outer Ply, 30º)



(d) Suction Surface: Transverse Stress (Outer Ply, 30º)

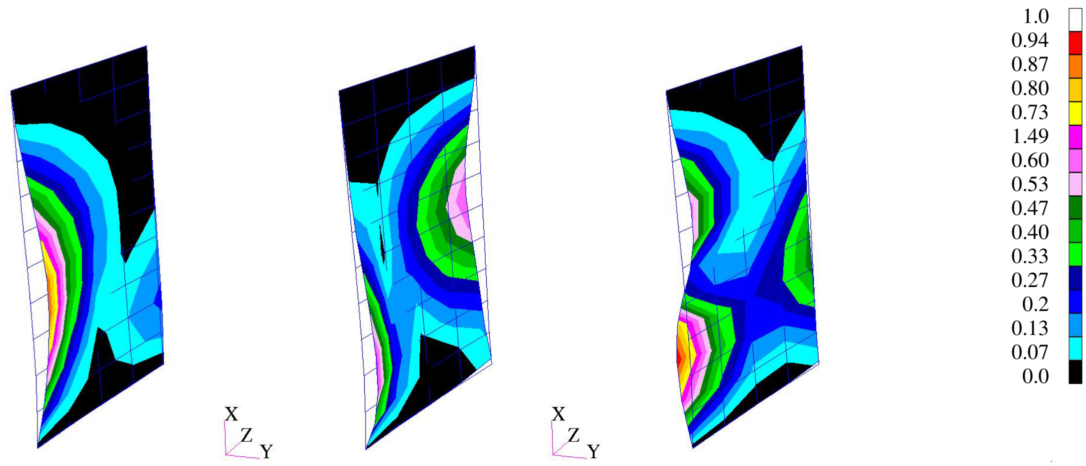


(e) Pressure Surface: Shear Stress (Outer Ply, 30º)



(f) Suction Surface: Shear Stress (Outer Ply, 30º)

Figure 5.—Exo-Skeletal Engine Composite Fan Blade Stress Analysis.



(a) First Mode Shape, Frequency: 222 cps

(b) Second Mode Shape, Frequency: 321 cps

(c) Third Mode Shape, Frequency: 358 cps

Figure 6.—Exo-Skeletal Engine Composite Fan Blade Mode shapes.

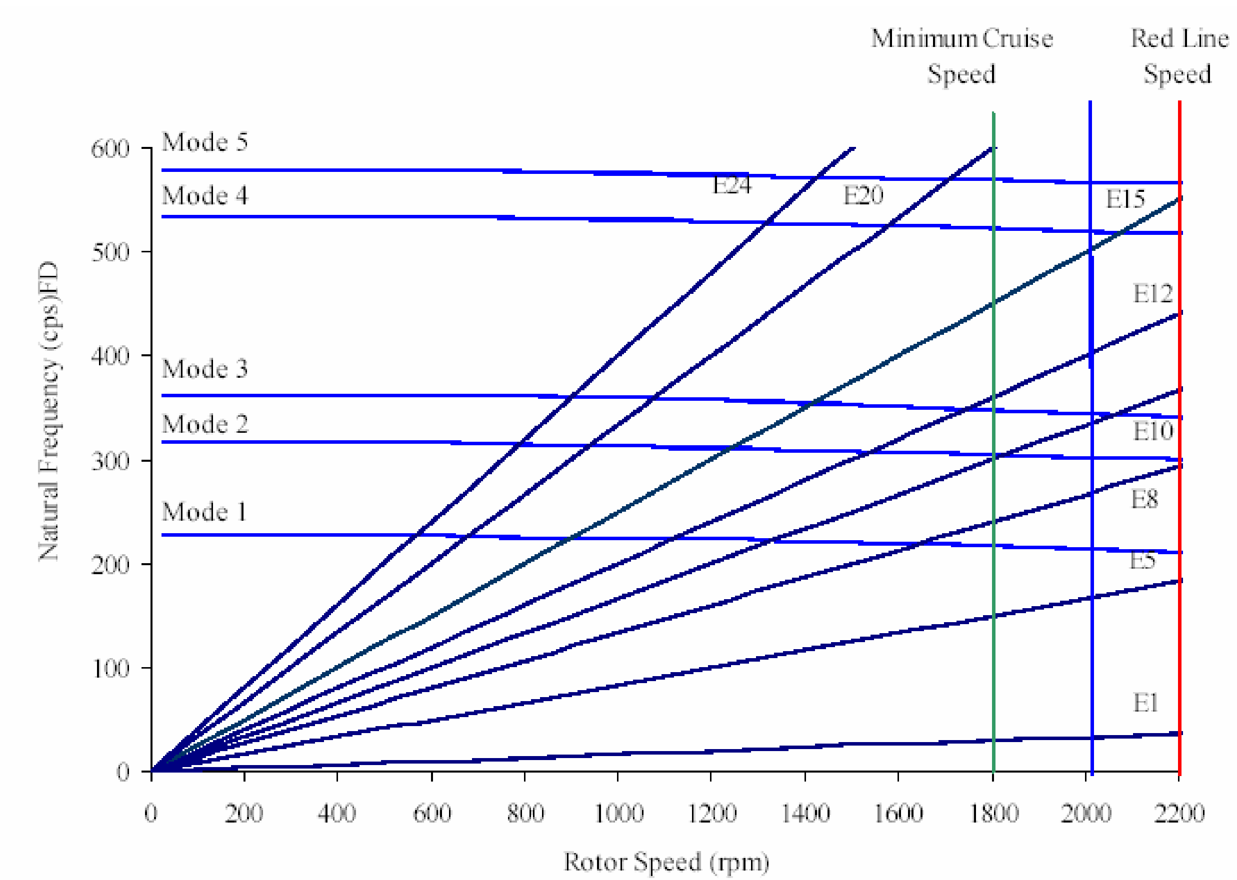


Figure 7.—Campbell Diagram for Exo-Skeletal Engine Composite Fan blade.

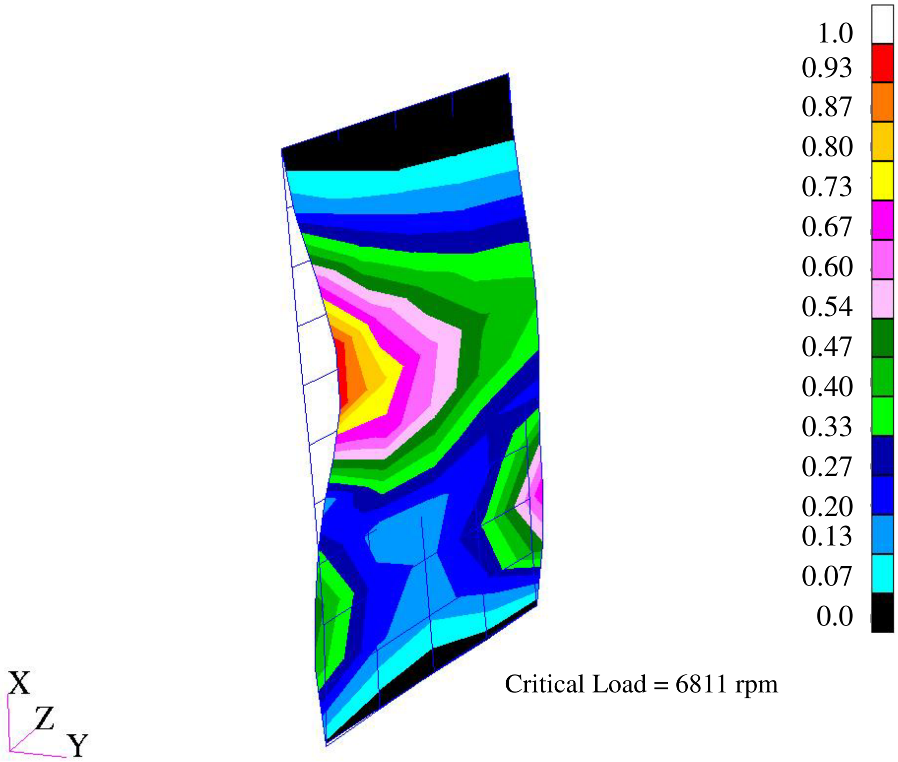


Figure 8.—First Buckling Mode Shape of Composite Fan Blade for Exo-Skeletal Engine.

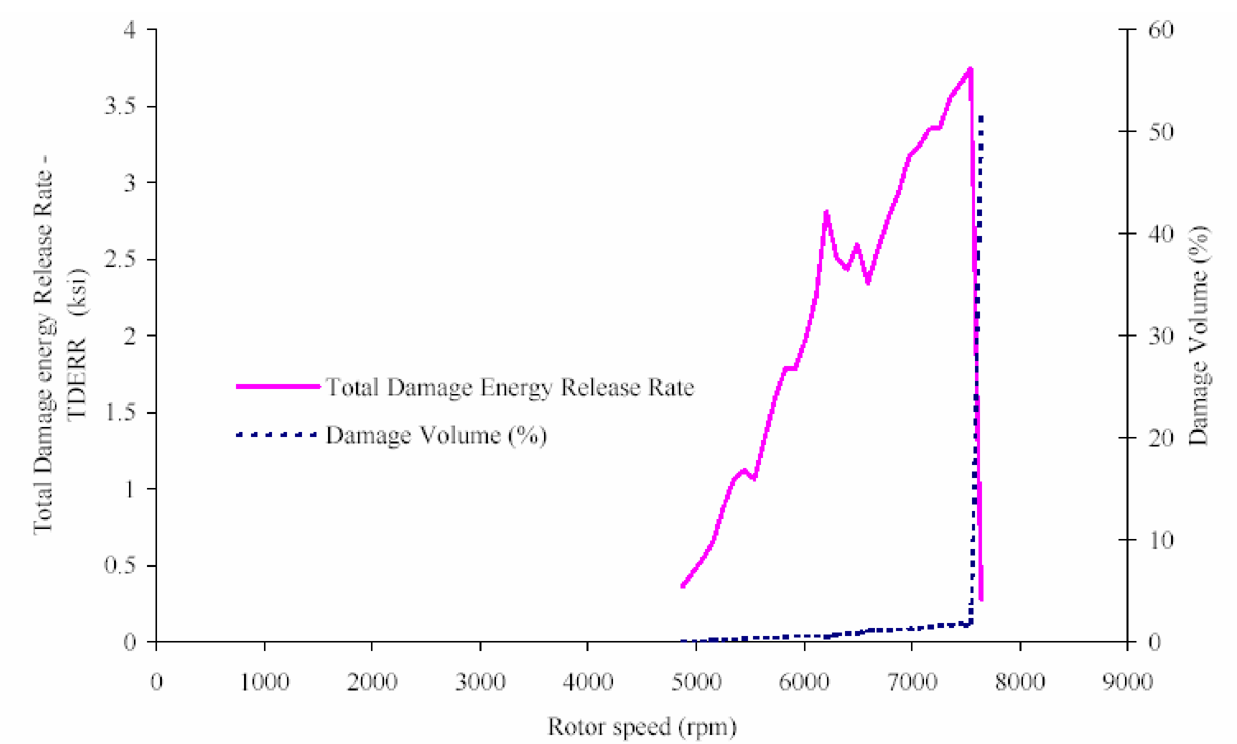
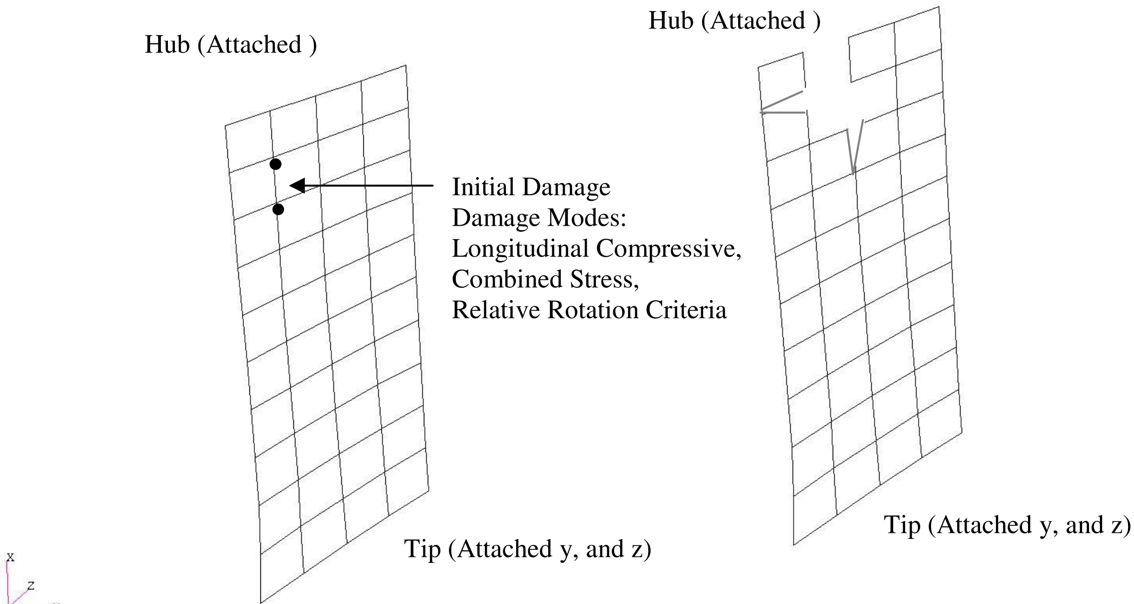


Figure 9.—Total Damage Energy Release Rate and Damage Volume (%) versus Rotor Speed for Exo-Skeletal Engine Composite Fan Blade.



(a) Initial Damage at Rotor Speed = 4870 rpm
Damage Volume 0.069 %

(b) Rotor Speed = 7639 rpm
Damage Volume 51 %

Figure 10.—Damage Progression of Exo-Skeletal engine Composite Fan Blade.

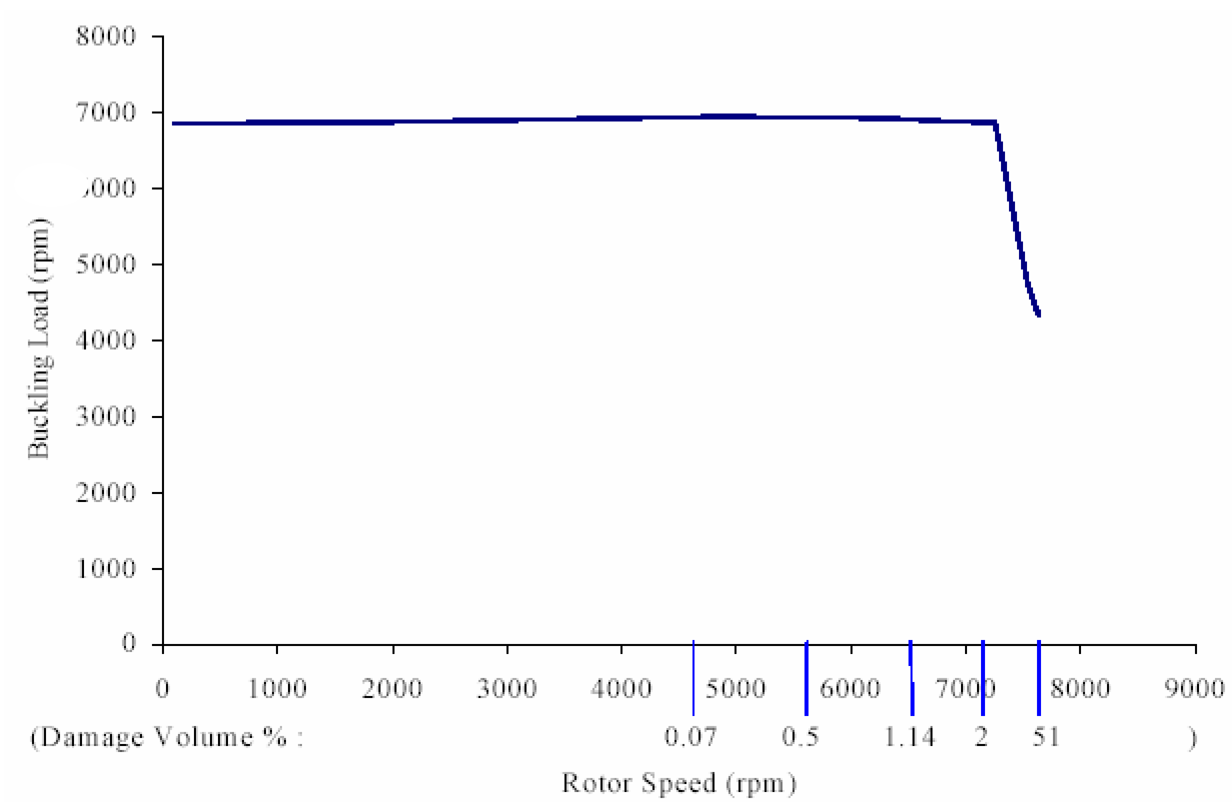


Figure 11.—Effect of Structural Deformation and Damage Progression on the Buckling Load of the Exo-Skeletal Engine Composite Fan blade.

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13. ABSTRACT ***(Maximum 200 words)***

The available computational simulation capability is used to demonstrate the structural viability of composite fan blades of innovative Exo-Skeletal Engine (ESE) developed at NASA Glenn Research Center for a subsonic mission. Full structural analysis and progressive damage evaluation of ESE composite fan blade is conducted through the NASA in-house computational simulation software system EST/BEST. The results of structural assessment indicate that longitudinal stresses acting on the blade are in compression. At a design speed of 2000 rpm, pressure and suction surface outer most ply stresses in longitudinal, transverse and shear direction are much lower than the corresponding composite ply strengths. Damage is initiated at 4870 rpm and blade fracture takes place at rotor speed of 7735 rpm. Damage volume is 51 percent. The progressive damage, buckling, stress and strength results indicate that the design at hand is very sound because of the factor of safety, damage tolerance, and buckling load of 6811 rpm.

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