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Blasim: A Computational Tool to Assess Ice Impact Damage on Engine Blades

E.S. Reddy and G.H. Abumeri
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio

and

C.C. Chamis
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

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BLASIM: A COMPUTATIONAL TOOL TO ASSESS ICE IMPACT DAMAGE ON ENGINE BLADES

E. S. Reddy† and G. H. Abumeri‡
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park OH 44142

and

C. C. Chamis*
NASA Lewis Research Center
Cleveland OH 44135

ABSTRACT

A portable computer code called BLASIM has been developed at NASA LeRC to assess ice impact damage on aircraft engine blades. In addition to ice impact analyses, the code also contains static, dynamic, resonance margin and supersonic flutter analysis capabilities. Solid, hollow, superhybrid and composite blades are supported. An optional preprocessor (input generator) was also developed to interactively generate input for BLASIM. The blade geometry can be defined using a series of airfoils at discrete input stations or by a finite element grid. The code employs a coarse, fixed finite element mesh containing triangular plate finite elements to minimize program execution time. Ice piece is modeled using an equivalent spherical object that has a high velocity opposite that of the aircraft and parallel to the engine axis. For local impact damage assessment, the impact load is considered as a distributed force acting over a region around the impact point. The average radial strain of the finite elements along the leading edge is used as a measure of the local damage. To estimate damage at the blade root, the impact is treated as an impulse and a combined stress failure criteria is employed. Parametric studies of local and root ice impact damage, and post-impact dynamics are discussed for solid and composite blades.

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† Senior Research Engineer, Senior Member AIAA,
‡ Research Engineer, Member AIAA
* Senior Aerospace Scientist, Associate Fellow AIAA

INTRODUCTION

When aircraft flies through clouds of super-cooled water droplets at high altitudes, ice formation can occur on forward facing structural components, such as the engine inlet. With time, ice accretes on the inlet and eventually sheds due to structural vibrations. A schematic of this phenomenon is shown in Figure 1. As a result, blocks of ice traveling at high speed impact the engine blades rotating at a high speed. This process can cause severe damage to the blade and subsequently the engine. To sustain ice impact, it is necessary to properly assess the damage of ice impact on engine blades. A computational tool called BLASIM (BLade ASsessment for Ice iMpact)[1] has been developed at NASA LeRC to assess ice impact damage on engine blades.

Engine blades can be solid or hollow, and they can be made of isotropic or fibrous composite materials. Fibrous composites are ideal for structural applications such as high performance aircraft engine blades where high strength-to-weight and stiffness-to-weight ratios are required. These factors combined with the flexibility to select the composite layup and to favorably orient fiber directions can limit ice impact damage and stresses arising from high rotational speeds.

The objective of this paper is to present and demonstrate the capabilities and features of the BLASIM code emphasizing the local and root response caused by the ice impact. The impact analysis is conducted using modified form of the foreign object damage option discussed in References 2 and 3. A brief description of the local damage, root damage and sequential impact analyses is provided. Important features of the BLASIM code are discussed including the optional interactive input generator (preprocessor), the airfoil or finite element grid input options, and the composite ply or fiber-matrix material input options. Lastly, numerical results are presented for the local and root damage and post-impact dynamics of SR-2 unswept solid isotropic and composite propfan blades.

BLASIM CAPABILITIES

Analysis Types

The analysis capabilities supported by the BLASIM code include: local and root ice impact damage, local and root Foreign Object Damage (FOD), static, dynamic, resonance margin calculations, flutter, and fatigue (Figure 2). Only the analyses requested in the input are carried out as shown in Figure 3. Several types of loading, namely, pressure, temperature, moisture and centrifugal, can be included in these analyses. A theoretical discussion of these analyses is provided in Reference 3. BLASIM can also perform the above analyses for consecutive (identical) ice impacts with geometry update after each local ice impact. Further details of ice impact analyses are given in a later section.

Blade Construction and Modeling

A computationally efficient triangular coarse mesh with five chordwise stations and eleven spanwise stations is used to model the blade. The model has a total of 55 nodes and 80 NASTRAN TRIA3 type triangular finite elements [4,5]. For local impact analysis a model consisting of 35 nodes and 48 elements is used. The blade model can be input using a NASTRAN type finite element grid or description of stacked airfoil sections. The input to the code can also be generated interactively using a preprocessor by selecting one of the built-in symmetric airfoils at four or more blade input stations. An option is also available to input finite element grid through a file instead of selecting an airfoil.

Composite material properties can be specified by inputting individual ply properties or specifying fiber/matrix combinations from a data bank. The data bank contains a wide spectrum of fibers and matrices, and the corresponding properties. When fibers and matrices are input, the code utilizes Integrated Composite ANalyzer (ICAN)[6] to generate the temperature and moisture dependent ply properties of the blade material.

To increase computational efficiency, Guyan reduction scheme[7] is employed to include only the predominant degrees-of-freedom (DOFs). In general, the predominant ones are the translational DOFs near the blade tip and normal DOFs away from the blade tip. The DOFs included in the analysis are shown in Figure 4 by open and solid circles. The six nodes with open circles correspond to the normal DOFs and the six nodes with solid circles correspond to the normal, tangential and radial DOFs. Centrifugal stiffening effects due to rotation are included in the formulation via a differential stiffness approach.[8]

Computer Systems

The BLASIM code and the interactive preprocessor have been installed and tested on VAX, CRAY and Silicon Graphics workstation at NASA LeRC. A typical single impact analysis requires approximately 10 seconds on CRAY XMP. Hence, the code provides a quick estimate of the ice impact response and can be interfaced with an optimization module for design optimization purposes. The interface capability is demonstrated through an example in Reference 9.

Blades Types

As mentioned in a previous section, the BLASIM code can analyze solid, hollow, superhybrid and composite blades. The solid blade is composed of a single material where as hollow and superhybrid blades are constructed with prescribed composite layups. BLASIM composite blade models can have a maximum of seven different material layers with a total of twenty five composite plies. Hollow blades have a titanium surrounding a borsic/titanium composite, with a hollow region at the center (Figure 5). The location and size of the hollow region can be defined by the user. Superhybrid blades have a special composite layup: [Titanium (skin)/Borsic-Aluminum/Graphite-Epoxy/Titanium]$_s$ (Figure 6). For general composite blades, users can specify the ply materials and the corresponding layer thicknesses and fiber orientations. The layup is assumed to be symmetric and in each material layer the plies are laid with alternating angles as shown in Figure 7. Last material in the input (usually a metal) is considered to be a core with a variable thickness. The blade is constructed from elements having varied thicknesses and material layup of each element is subject to the following considerations:

(i) If the total thickness of an element can accommodate *1* to (*n-1*) materials to their specified maximum limit, the remaining element thickness is assigned to the n^{th} material (core).

(ii) If the total thickness cannot accommodate all the material layers to their thickness limit, plies are deleted from the material layers in the order (*n-1*), (*n-2*),..*2*. That is, material *1* is always present and plies in $(n-1)^{th}$ are deleted first.

(iii) If the element thickness is less than twice the thickness of material *1*(skin), element thickness is adjusted to be equal to that value.

ICE IMPACT ANALYSIS

Ice Impact Model

The schematic diagram of ice impact on the leading edge of an engine blade is shown in Figures 8(a,b). The ice piece is modeled as a spherical object impacting the leading edge of the blade. The impact on the blade arises from the momentum of the ice piece. The impulse component normal to the chord, which is primary cause of spanwise bending damage, is included in the response computation. The impact velocity direction relative to the blade is a function of the ice speed and the rotational speed of the blade (Figure 8a). The resulting impact is dependent on the relative velocity and mass of ice piece. Depending on the blade spacing (i.e., number) and the relative velocity, the ice piece, approaching the blade under consideration, is sheared off by the adjacent blade as shown in Figure 8b. As a result, only a portion of the ice piece (unsheared mass) impacts the leading edge of the blade. Effectively, the mass that finally impacts the blade depends on the blade spacing, blade speed and ice speed. The spherical shape assumption of the ice simplifies only the determination of unsheared part, and once the impulse is computed, the remaining analysis does not depend on the ice shape.

Local Damage Analysis

The damage due to impact is considered to be highly localized and hence, only the portion of the blade around the impact region (local patch) is modeled as shown in Figure 9. The spanwise impact region is specified using two parameters: lower and upper bounds of radial fractions, a and b, respectively. However, the impact model along the span is approximated to be the region between the two finite element radial stations (defined in the blade geometry) nearest to a and b. Along the chord, only half of the blade is considered for impact analysis. The impact is considered at the midpoint of the local patch (finite element node 16) along the leading edge. All edges except the leading edge are assumed fixed, as the impact response beyond these boundaries is negligible. At a given instant of time during impact, only the finite element nodes coming in contact with spherical ice are loaded and nodal forces are adjusted for blade flexibility (see Reference 3 for details).

Large scale deflections accompany the impact event within the impact zone.[3] To simulate this behavior, the blade is assumed fully stressed near the impact region. This assumption is implemented in the code by modifying the membrane stiffness in the radial direction and by zeroing-out the spanwise bending stiffness. These special elements are shaded in the Figure 9. A detailed justification for these assumptions is given in Reference 3.

Transient response of the local patch is obtained by modal integration.[10] The modal analysis is based on the principle that a statically deformed structure can be described by a combination of the structure's mode shapes. Once the coefficient of each mode's participation is calculated, the impact event can be simulated by the integration of a series of linear steps through time. Only first five modes of the local patch are used to compute the undamped response. At each time step, radial strains in the finite elements along the leading edge are obtained using nodal displacements.

Among the elemental average strains at all time steps, maximum is picked as a representative of the local damage.

Root Damage Analysis

Response Analysis: The blade root is generally distant from the location of ice impact and the duration of impact is considerably short. Hence, for response computation at the root, the impact is considered as an impulse on a single node along the leading edge of the blade. The response at the root is computed via modal superposition techniques. For computational efficiency, only the first three modes are utilized in the calculation. The equations, as implemented in the code, are described in Reference 11. The resulting stress response at the root is a continuous function of time and is expected to be predominantly first mode. Hence, the maximum stress occurs at or near the quarter cycle of the first bending mode frequency[2], ω_1, i.e., at time, $t = \pi/2\omega_1$.

Computation of Root Damage: To account for the complex loads and microscopic failure mechanisms, a combined stress failure function based on the Modified Distortion Energy (MDE)[6] is used as a measure of blade damage at the root. The stress function values are computed for all elements (second row) at the blade root and the maximum is used as a measure of blade root damage. Material is considered failed when the function value is equal to or greater than unity. An option is also available to choose Hoffman criteria, instead of MDE, for the estimation of root damage.

Sequential Impacts

The identical sequential ice impact option updates the blade geometry following each impact. The local patch impact displacements obtained from the local damage analysis are transformed to global nodes of the finite element model using a linear numerical interpolation scheme. Once the global blade geometry has been updated, all the analyses are carried out for the new blade configuration.

This process can be repeated a prescribed number of times to simulate identical sequential impact. Ice size, impact location and speeds remain unchanged throughout the analysis.

DEMONSTRATION CASES

A modified SR-2 unswept propfan blade[12] was considered to demonstrate BLASIM's capability to assess the local and blade root damage and to study the post-impact dynamics of the blade using the sequential impact option. The plan form of the blade is shown in Figure 10. The setting angle is 57° and the number of blades is eight.

Assessment of Local Damage[10]

For local damage assessment demonstration, the composite material option was used. The composite layup consists of [Titanium/ ±45 Graphite Epoxy/ Titanium]$_S$. The properties of these materials are given in Table 1. The finite element idealization of the blade is shown in Figure 4. The impact modeling region is assumed to be 50-90% along the span and the effective ice radius is 0.8". Since the bulk of the material is Titanium near the leading edge, the effective yield stress for element stiffness modification is assumed to be 206 *ksi.*

For an engine speed of 3000 rpm, the variations of average leading edge strain and the impact angle with ice speed are shown in Figure 11. The strain is zero at ice speeds 0 and 211 knots, and it reaches a maximum value at 100 knots. This is due to the fact that only impact force normal to the chord ($f \sin\theta$) gives rise to the strain. When the ice speed is equal to zero, the impact force is zero and when the ice speed reaches 211 knots, the impact angle (θ) is zero. Initially, the value of θ is equal to the stagger angle (55° at the impact radius) and gradually decreases to 0° as the ice speed increases. More details concerning the parametric study can be found in Reference 10.

Figure 12 illustrates the effect of ice size and ice speed on the local damage using a 3-D plot. The results indicate that the damage is higher for larger ice and has a peak response at a critical ice speed. The critical speed dependent upon the ice size.

Assessment of Root Damage[11]

The root damage assessment study was conducted for a solid Titanium blade. Elastic properties of the material are given in Table 1. The strengths used in combined failure function are: S_{11} = 7.4x10^4 *psi*, S_{22}= 7.4x10^4 *psi*,· S_{12}= 4.4x10^4 *psi*, The range of engine speed considered was 3000 - 8000 RPM and the maximum ice radius considered was 0.8".

For an engine speed of 5000 rpm, the effect of ice size and ice speed on the root damage function is shown in Figure 13. The damage is maximum for larger ice size. However, for a specified ice size, the damage reaches a maximum at relatively low ice speeds, and, thereafter decreases continuously. This behavior is similar to the local damage response as explained in the previous subsection.

Figure 14 shows the dependence of impact location along the span on the blade root damage. As the impact nears blade tip, the damage is higher and has a nearly linear relationship with the impact location. However, the engine speed has a stronger effect on the root damage response and hence the slope of the curve is greater for higher rpm. For example, at 8000 rpm, the root damage is 0.33 at 30% span and increases to 1.0 at 75% span indicating blade failure at the root.

Post-Impact Dynamics[13]

The sequential impact option was used to study the free vibration characteristics of the blade after one impact. Titanium blade material was and the properties are given in Table 1. An engine speed of 4000 rpm was used. The first three mode shapes of the blade before impact are shown in Figure 15 and are respectively, first bending, second bending and first twisting. Centrifugal stiffening due to rotation was including in computing these mode shapes. After impacting the blade at 80% of the span with an ice radius of 0.8" traveling at 120 knots, the blade geometry is updated to account for local permanent deformations. Figure 16 illustrates vibration analysis results for the impacted blade. Comparing the corresponding modes before and after impact, it can be seen that the dent due to impact is reflected in the post-impact mode shapes. Also, the impact resulted in stiffening of the blade in the bending mode. However, the impact reduced the twisting stiffness of the blade. The change in the natural frequencies is marginal (≈8%) and occurred only in the second and third modes.

SUMMARY AND CONCLUSIONS

A portable stand-alone computer code called BLASIM has been developed to conduct ice impact analyses on aircraft engine blades. The code capabilities and features have been outlined. The capabilities include ice impact damage (local, root and sequential), static and dynamic, resonance margin analyses. Important features of the code include: interactive input generator (preprocessor), airfoil or finite element blade definition, solid, hollow, superhybrid or composite blade construction, and composite ply or fiber-matrix material input options. A brief description of the local damage, root damage and sequential impact analyses was given.

Several cases demonstrating the ice impact damage assessment capabilities were presented. Two types of blades, namely, solid and composite were considered. In both local and root damage analysis, damage was maximum at some critical ice speed. The critical speeds were different for local and root damage studies. The root damage was found to increase linearly as the ice impact location moved towards blade tip. Additionally, the post-impact mode shapes due to local permanent deformations remain similar to those before impact except the natural frequencies changed marginally. These numerical examples indicate that BLASIM code can capture local and root damage response, and post-impact dynamics with relatively simple models and less computational effort.

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Table 1: Properties of the Composite Blade Constituent Materials

Material Type	E_{11} (*psi*)	E_{22} (*psi*)	G_{12} (*psi*)	ν_{12}	ρ ($lb.sec^2/in^4$)	ply thickness (inches)
Titanium (Ti6)	16.5×10^6	16.5×10^6	6.4×10^6	0.30	0.00044	----
Graphite-Epoxy	32.0×10^6	1.0×10^6	0.7×10^6	0.25	0.00015	0.005

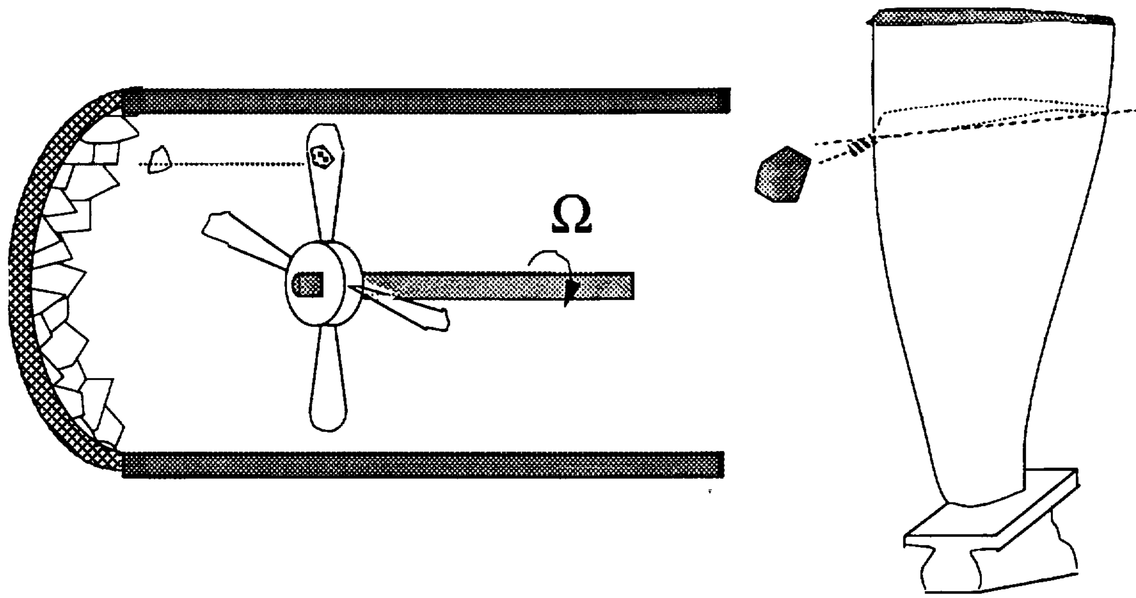


Figure 1. A Schematic of Ice Impact on an Engine Blade

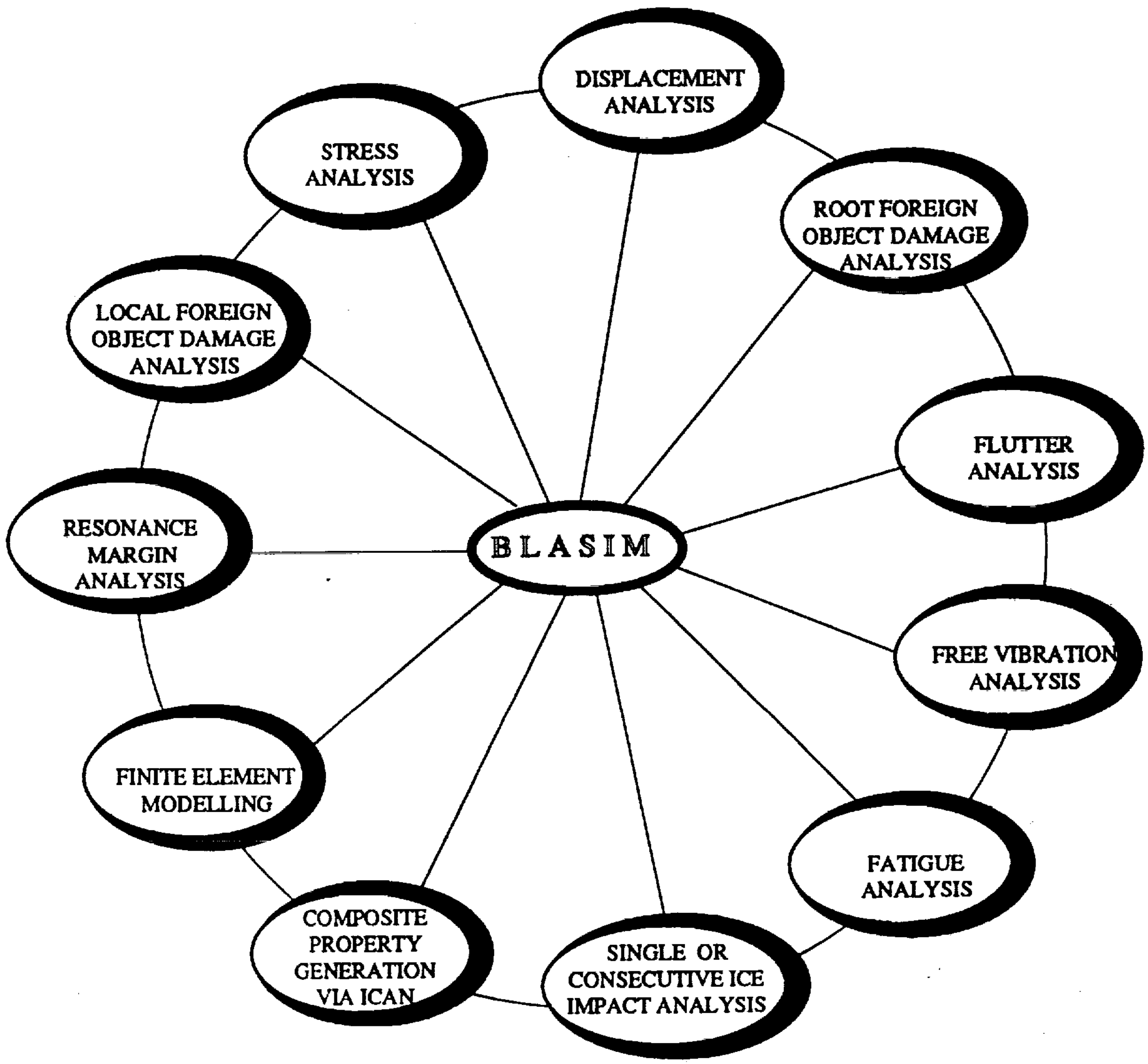


Figure 2. BLASIM Code Analysis Modules

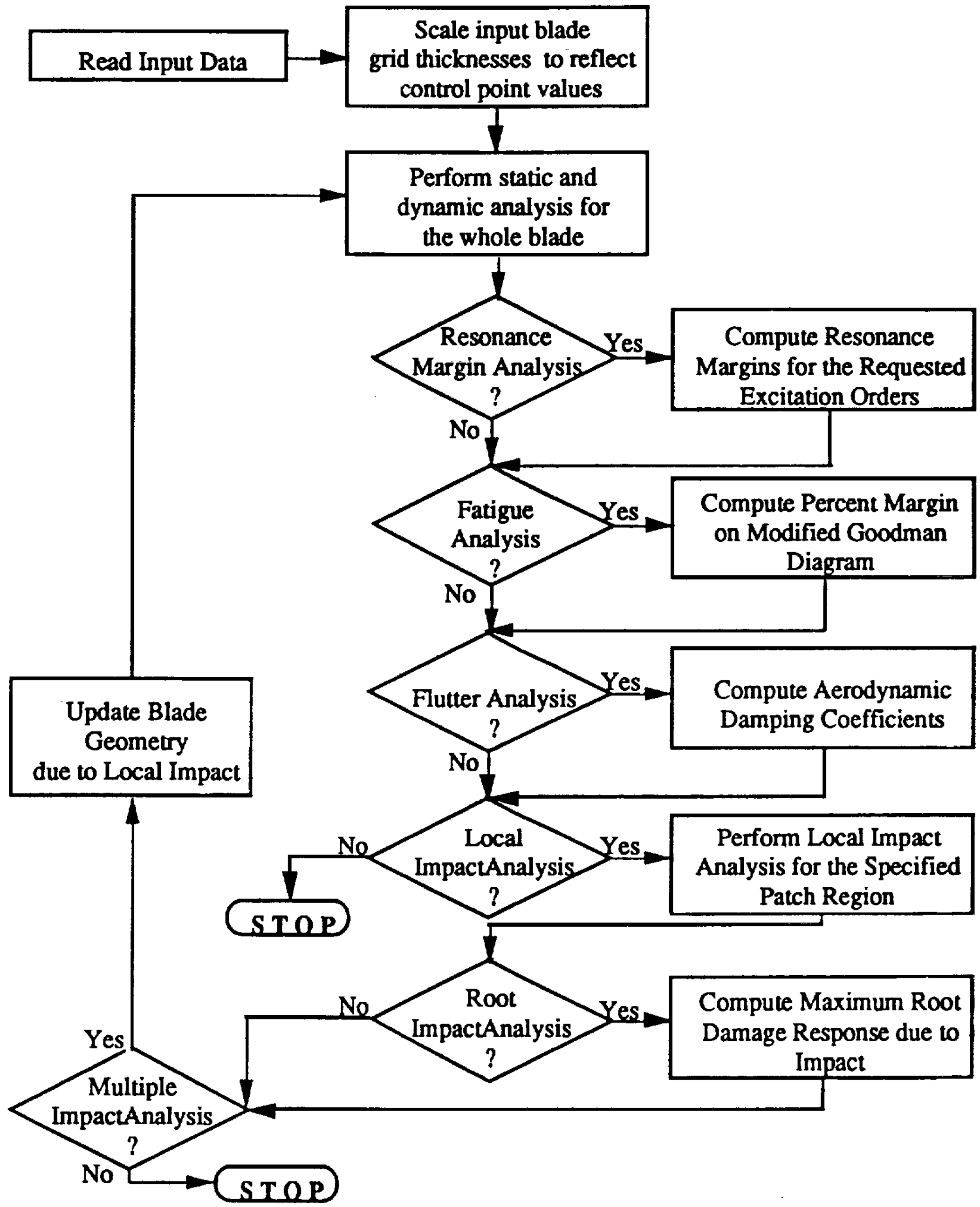


Figure 3. BLASIM Code Flowchart

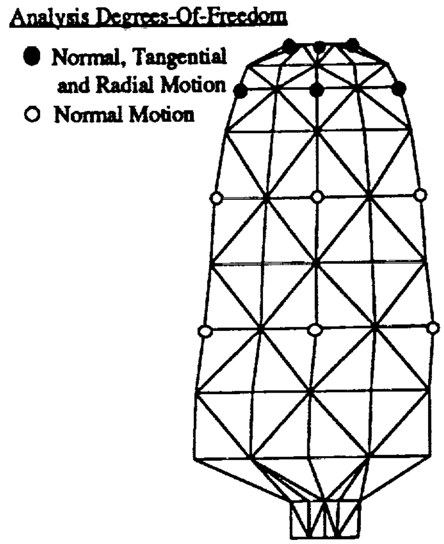


Figure 4. Blade Finite Element Model and Analysis Degrees-of-Freedom

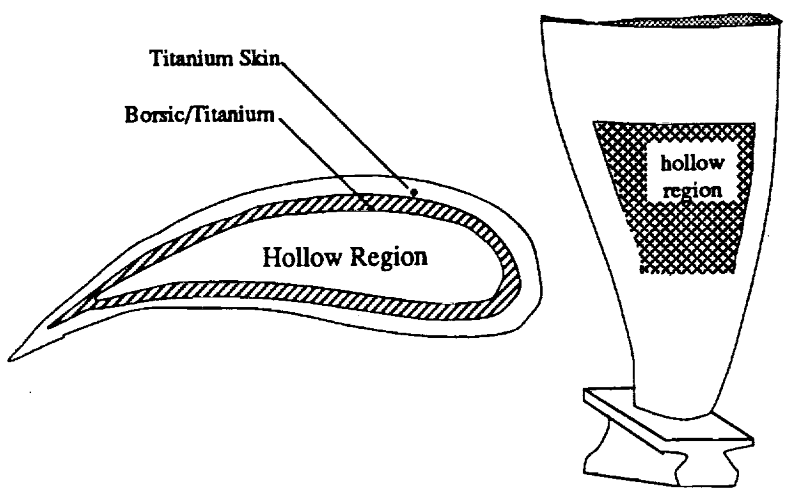


Figure 5. Hollow Blade and the Associated Layup

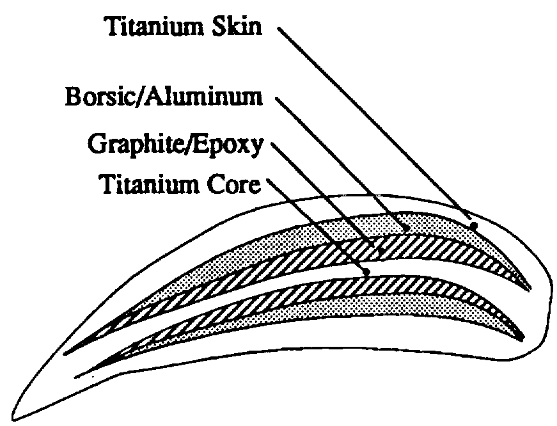
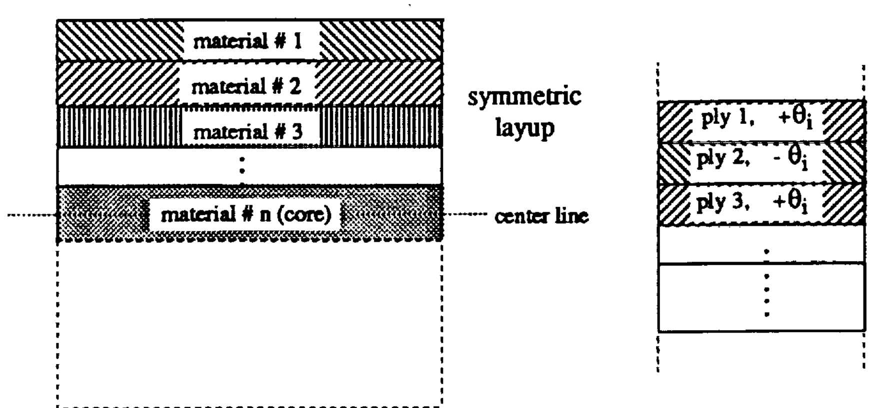


Figure 6. Cross Section of a Superhybrid Blade



(a) Material Layup

(b) Fiber Orientation in i^{th} Material

Figure 7. Composite Blade Layer Configuration

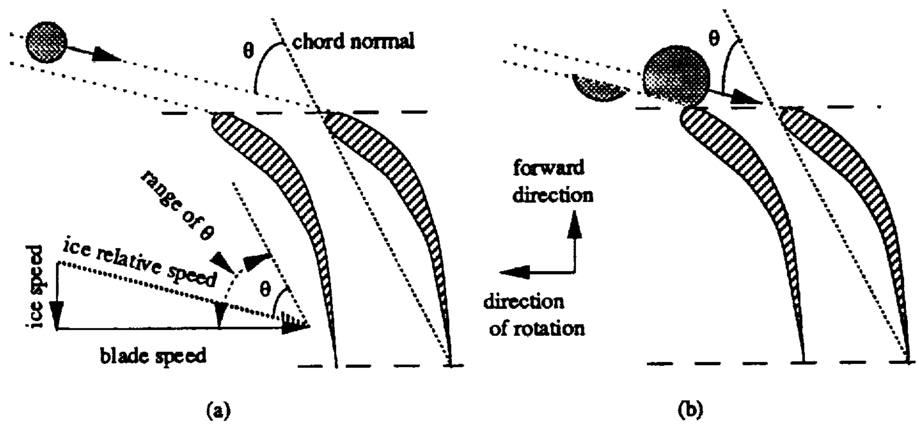


Figure 8. Geometry of Ice Impact on an Engine Blade

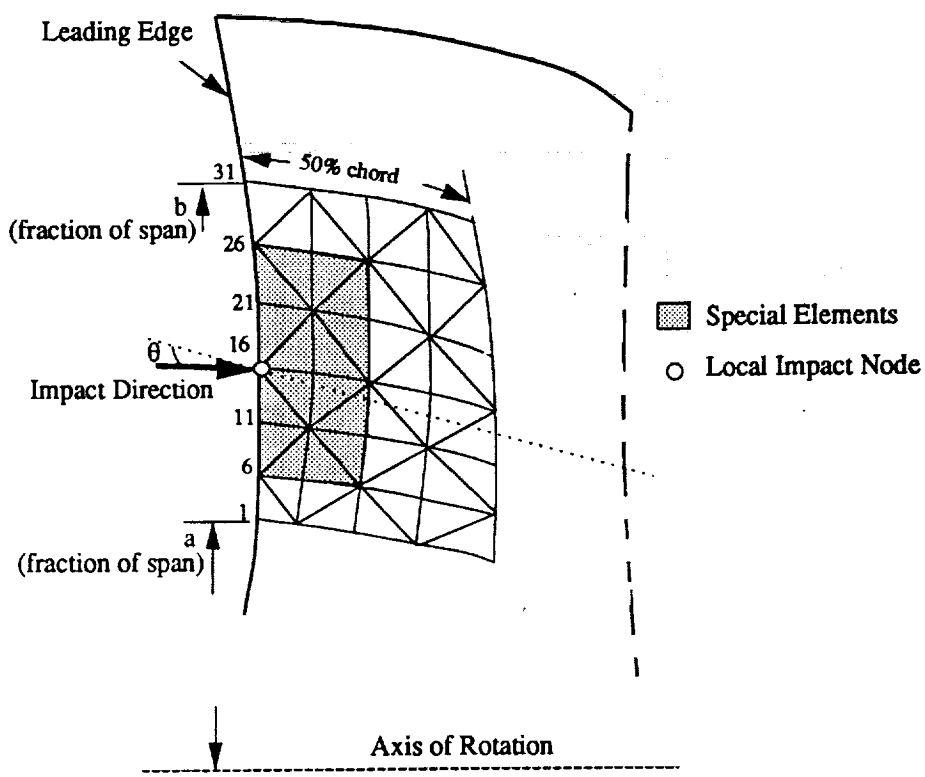


Figure 9. Local Damage Finite Element Model

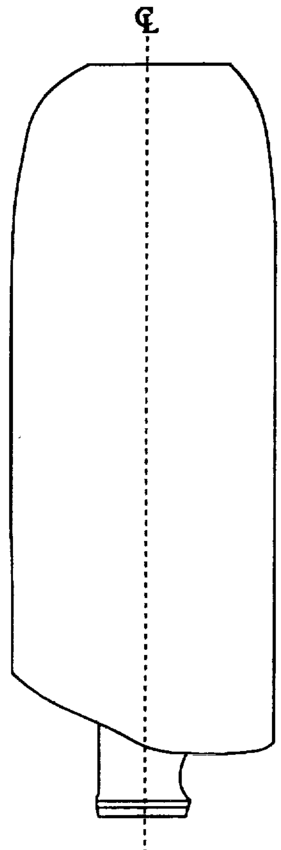


Figure 10. Planform of the SR-2 Blade

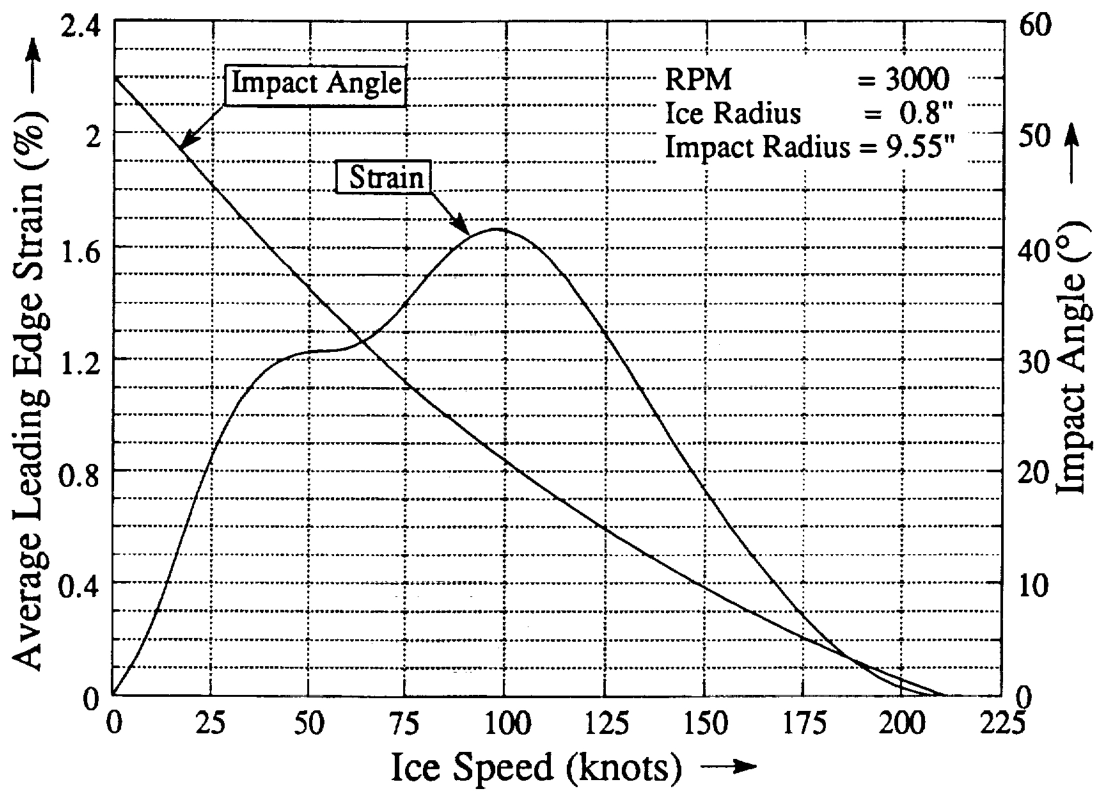


Figure 11. Variation of Leading Edge Strain and Impact Angle with Ice Speed (Composite Blade)

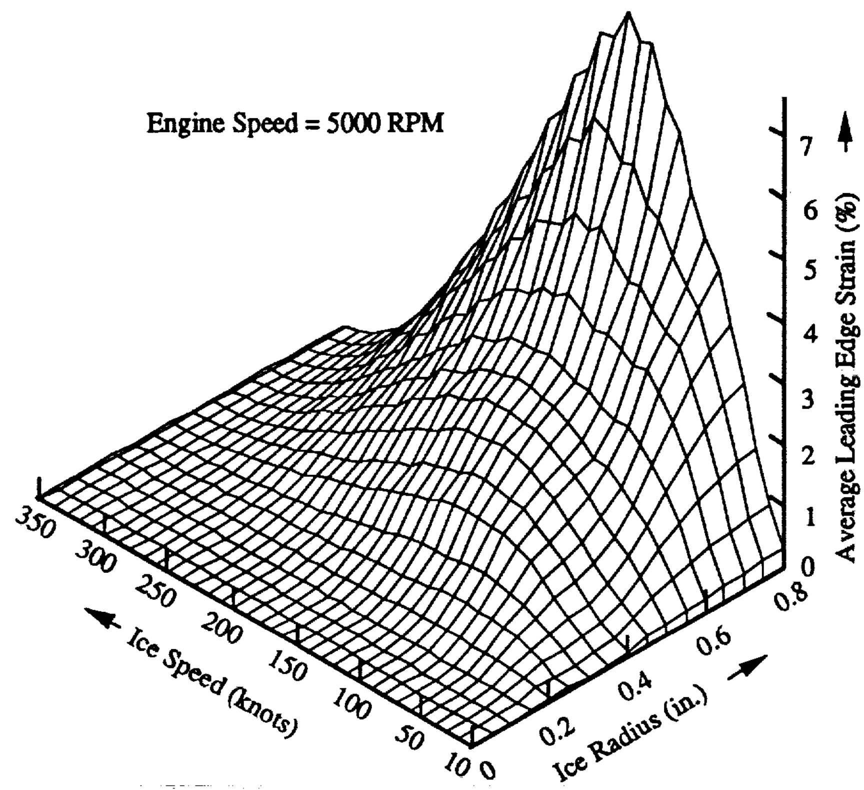


Figure 12. Effect of Ice Size and Ice Speed on Blade Local Damage (Composite Blade)

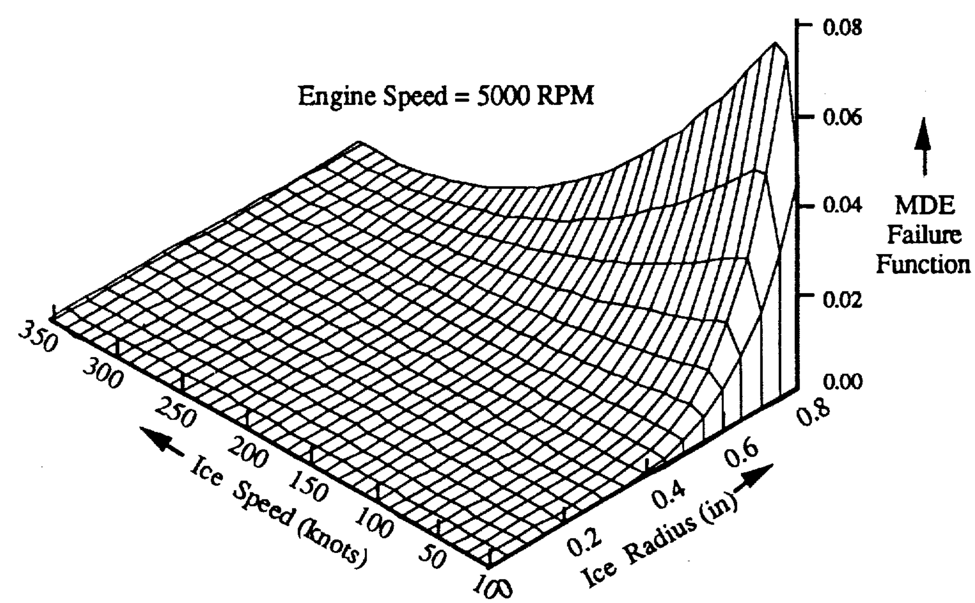


Figure 13. Effect of Ice Size and Ice Speed on Blade Root Damage (Titanium Blade)

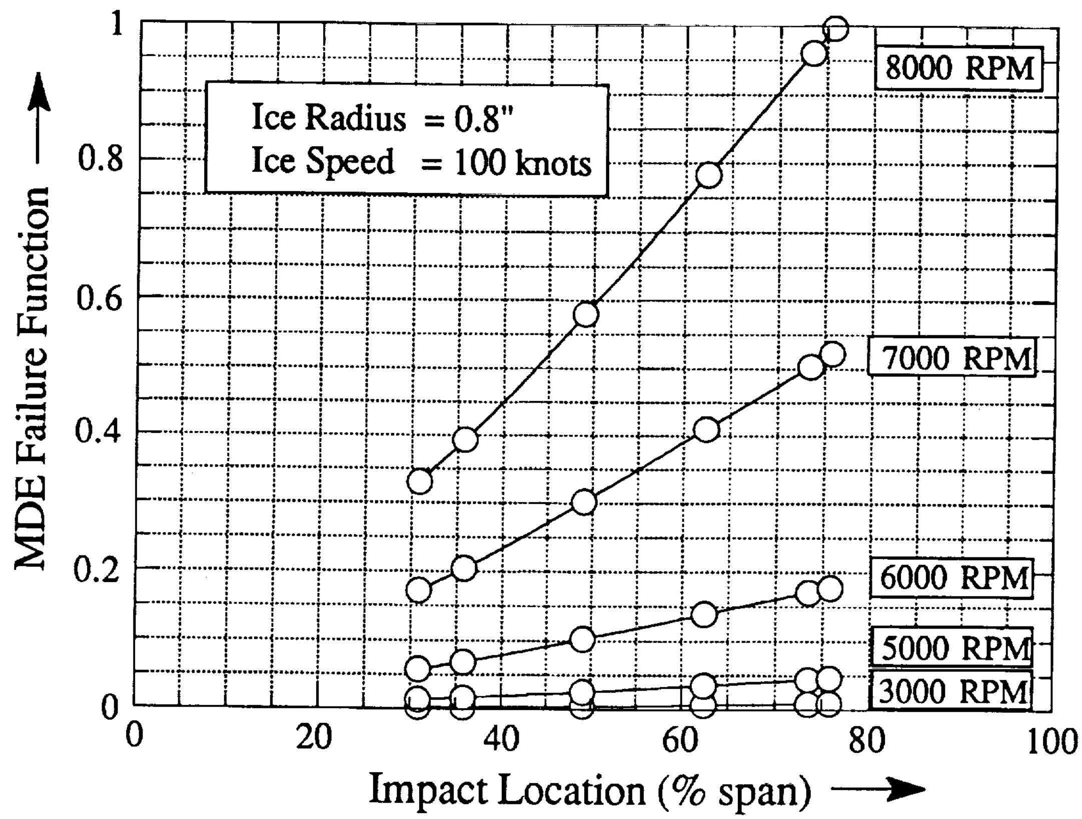
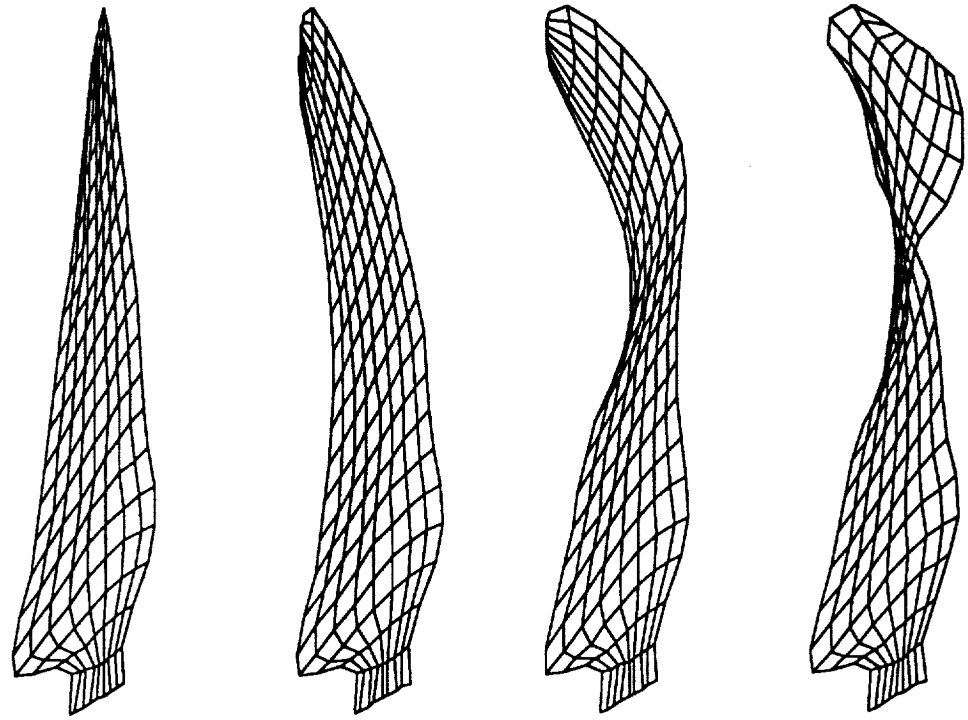


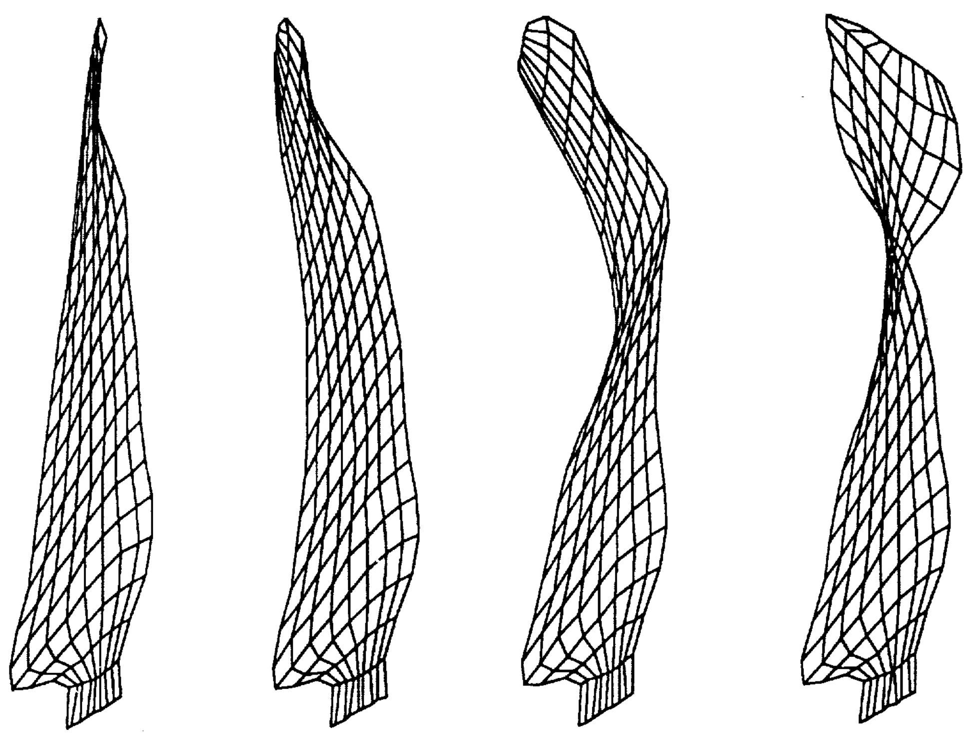
Figure 14. Effect of Ice Impact Location on Blade Root Damage (Titanium Blade)



SR-2 Blade | First Mode | Second Mode | Third Mode

$\omega =$ 161.0 c/s | 492.2 c/s | 766.5 c/s

Figure 15. Blade Mode Shapes Before Ice Impact



SR-2 Blade | First Mode | Second Mode | Third Mode

$\omega =$ 162.4 c/s | 531.3 c/s | 708.0 c/s

Figure 16. Blade Mode Shapes After Ice Impact

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

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