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Influence of Aerodynamic Forces in Ice Shedding

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Stresses in accreted ice on a typical airfoil impact ice caused by aerodynamic forces have been studied using finite element analyses. The objective of this study is to determine the significance of these stresses relative to values needed to cause ice shedding. In the case studied, stresses are not significant (<10%) when compared to the fracture value for airspeeds below a Mach number of 0.45. Above this velocity, the influence of aerodynamic forces on impact ice stresses should be considered in the analyses of ice shedding.

Introduction

IMPACT ice formations on airfoils, rotating propellers surfaces, and helicopter blades are subjected to various forces during normal aircraft operation. Stresses that develop in the accreted ice and at the metal-ice bond during normal operation are caused from the following sources: 1) flexing of the aerodynamic surface caused from structural vibration and aerodynamic forces; 2) from direct loading of aerodynamic pressure forces acting on the ice; 3) inertia forces in the case of rotating propellers or blades; and 4) thermal stresses developed from phase changes in the accreted ice.

If the stresses from these sources exceed a critical value, shedding results. The significance of each source of stress relative to the fracture strength of ice is of interest to the aircraft deicing designer.

Mechanical deicing systems, such as the pneumatic boot, the electric impulse deicing system (EIDI),[1,2] and the pneumatic impulse ice protection system (PIIP)[3] develop stresses in the accreted ice that fracture the ice. In all cases, both inertia forces caused by the surface motion of the deicer and flexure or bending of the surface develop both tensile stresses in the ice and shear stresses at the ice/surface interface. These stresses from the deicer add to those from operational sources. Often aerodynamic forces carry the fractured ice from the airfoil surface. The significance of stresses in the ice caused directly from aerodynamic loading must be evaluated to determine if these stresses should be added to other values. It is the purpose of this article to use finite element analyses to evaluate stresses from these aerodynamic loads and to relate these stresses to the fracture strength of impact ices.

Approach

Many experiments have been conducted to determine the shape of ice accreted on an airfoil under different conditions. The ice geometry employed in this study was a glaze ice shape on an NACA 0012 airfoil as shown in Fig. 1. This particular geometry was used in extensive experimental aerodynamic studies conducted at Ohio State University.[4–6] This well-defined geometry consisting of circular arcs and line segments facilitated easy mathematical modeling. Figure 1a is a profile of a standard NACA 0012 airfoil and Fig. 1b shows this particular ice accretion on the leading edge of the airfoil.

A plane two-dimensional finite element model was developed for the analysis using the PC ANSYS finite element program. This code was chosen because it has excellent graphic capabilities, it is interactive, and is easy to use.

Considering the curved shape of the ice and the airfoil, six-node higher-order plane stress triangular elements were employed to generate the mesh through the automesh generation routine available with the ANSYS package. This element has a quadratic displacement behavior and is well-suited to model irregular meshes. All the nodes at the interface between the ice and the airfoil were constrained for zero displacements and rotations. The airfoil was considered to be rigid. Thirty-six elements were used to model the impact ice geometry (Fig. 2).

A computer code which solves the Navier-Stokes equations in two-dimensional for the flowfield characteristics around the iced airfoil was used by Potapczuk[4] to calculate the pressure coefficients. These pressure coefficients have been correlated with experimental measurements made by Bragg[5,6] and others, and were found to be in good agreement. In the current analysis these pressure coefficients were used to calculate the pressure distribution around the ice profile from the formula

$$P = \tfrac{1}{2} C \mu V^2$$

where

P = surface pressure
μ = density of air
V = velocity of flow
C = coefficient of pressure

Figures 3–7 show the pressure profiles for different Mach numbers and angles of attack. Pressures were applied normal to the element faces. The element numbering was chosen such that it increases in a counterclockwise order starting at the bottom edge. Negative pressure (suction) acts normally inward to the ice. Positive pressure always exists at the stagnation point of the leading edge of the accreted ice shape. At an angle of attack of 0 deg, negative pressure exists above

Table 1 Peak interfacial stresses in psi

Mach number	Angle of attack, deg	Normal-X, psi	Normal-Y, psi	Shear-XY, psi
0.6	0	−10.54	8.48	−8.76
0.3	0	−2.47	1.87	−1.86
0.12	0	−0.43	1.30	−0.20
0.12	2	−0.51	0.38	−0.40
0.12	4	−0.54	0.48	−0.50
0.12	6	−0.46	0.49	−0.41

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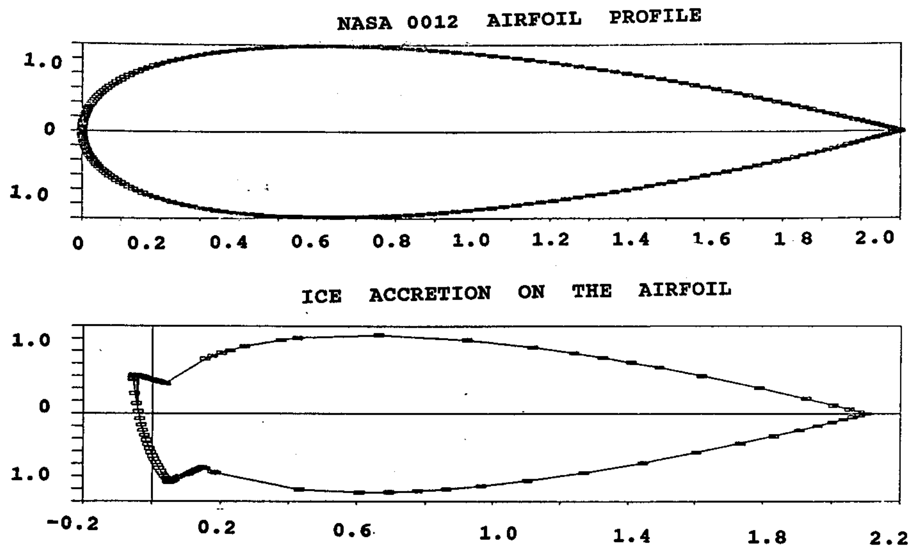

Fig. 1 Airfoil profile with and without impact ice.

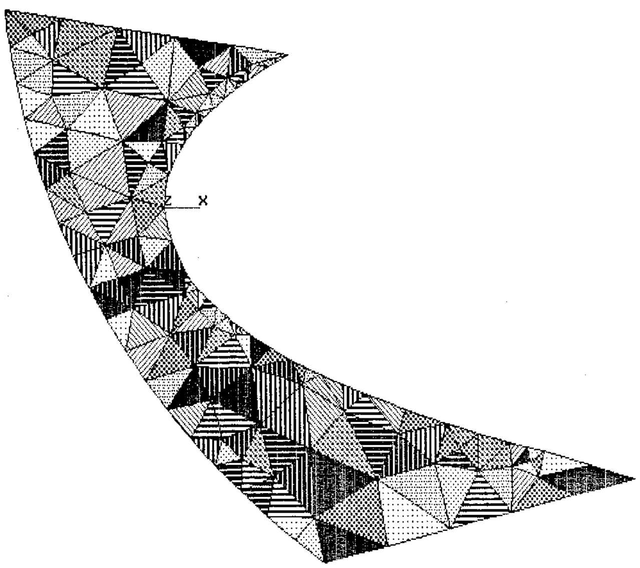

Fig. 2 Finite element model of impact ice.

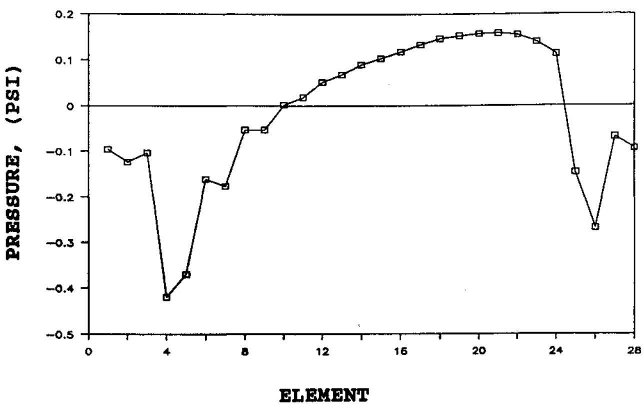

Fig. 3 Pressure profile for a Mach number of 0.12 and a 0-deg angle of attack.

and below the ice shape. As the angle of attack increases, the pressure acting on the bottom edge of the ice becomes more positive because of the smoother flow of air over the bottom edge. On the upper edge, the pressure becomes more negative as the angle of attack increases. It should be noted that the pressures increase approximately as the square of the velocity.

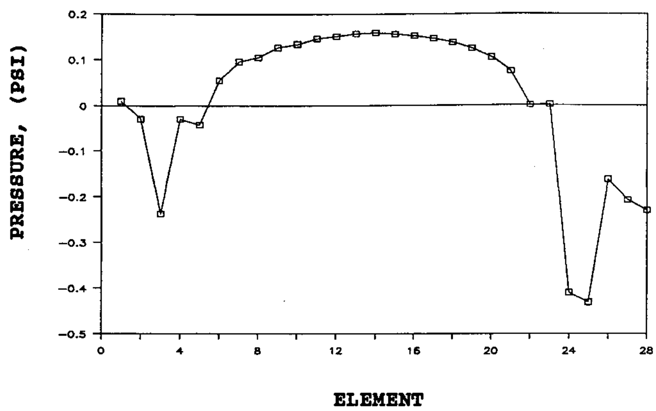

Fig. 4 Pressure profile for a Mach number of 0.12 and a 4-deg angle of attack.

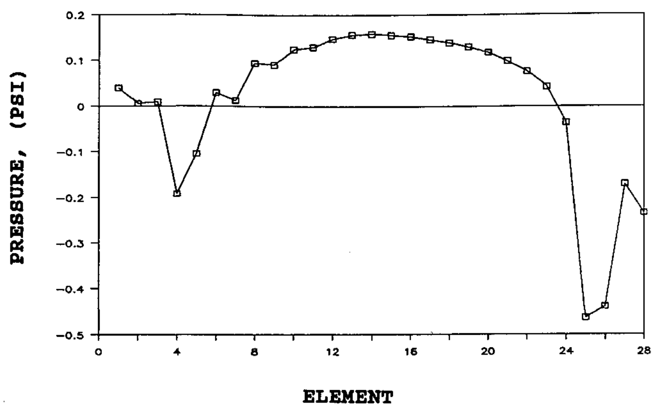

Fig. 5 Pressure profile for a Mach number of 0.12 and a 6-deg angle of attack.

Pressure loading on the accreted ice were calculated at Mach numbers of 0.12, 0.3, and 0.6. For a Mach number of 0.12 the angles of attack investigated were 0, 2, 4, and 6 deg, whereas for a Mach number of 0.3 and 0.6 the analyses were run only for a 0-deg angle of attack.

Results

The nodal normal, shearing, and principal interfacial stresses between the ice and the airfoil as obtained from the analysis

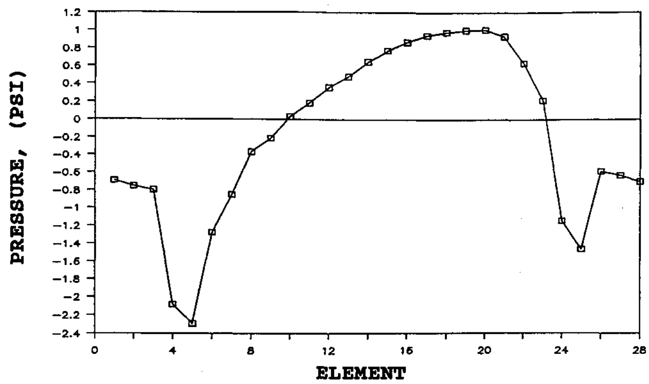

Fig. 6 Pressure profile for a Mach number of 0.3 and a 0-deg angle of attack.

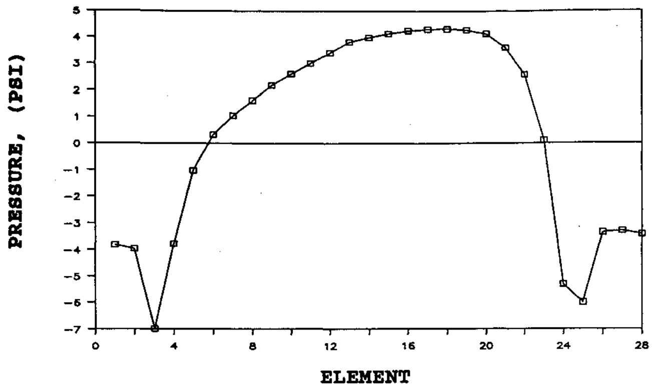

Fig. 7 Pressure profile for a Mach number of 0.6 and a 0-deg angle of attack.

for different Mach numbers and angles of attack are plotted on Figs. 8–11. The node numbering in all plots is such that the interface is traversed in a counterclockwise order starting from the top corner. Peak stresses are listed in Table 1. Peak shear stresses at the interface are plotted on Figs. 12 and 13. As can be seen on Fig. 12, the maximum stresses occur at a Mach number of 0.6 and vary linearly as the square of the Mach number. The stresses at airfoil velocities below 0.3 are in the order of fractions of 1 psi.

The shearing strength of ice has been determined to be typically between 40–60 psi.[7] At a Mach number of 0.6 the maximum shear stress was found to be about 9 psi, which is about 20% of the shear bonding strength. The maximum normal tensile stress for the same case was also found to be about 9 psi, and the maximum principal stress was found to be in the range of 8–10 psi. Stresses reach about 10% of the shear debonding strength at a Mach number of 0.45.

Variation of the interface shear stress with the angle of attack is about a factor of $2\frac{1}{2}$ (Fig. 13) at 0-deg angle of attack and a Mach number of 0.12. The maximum value occurs at an angle of attack of 4 deg.

Conclusions

The stresses at air velocities of less than a Mach number of 0.45 are insignificant and are not expected to contribute to ice shedding. However, for a Mach number of 0.6 the maximum shear stress is about 20% of the shear ultimate debonding strength.

Shear stresses at the impact ice airfoil interface vary about a factor of $2\frac{1}{2}$ as the angle of attack increases from 0 to 4 deg. Therefore, at high speeds and at a high angle of attack, stresses from direct aerodynamic loading must be considered in the analysis of stresses of impact ice accreted on aerodynamic surfaces.

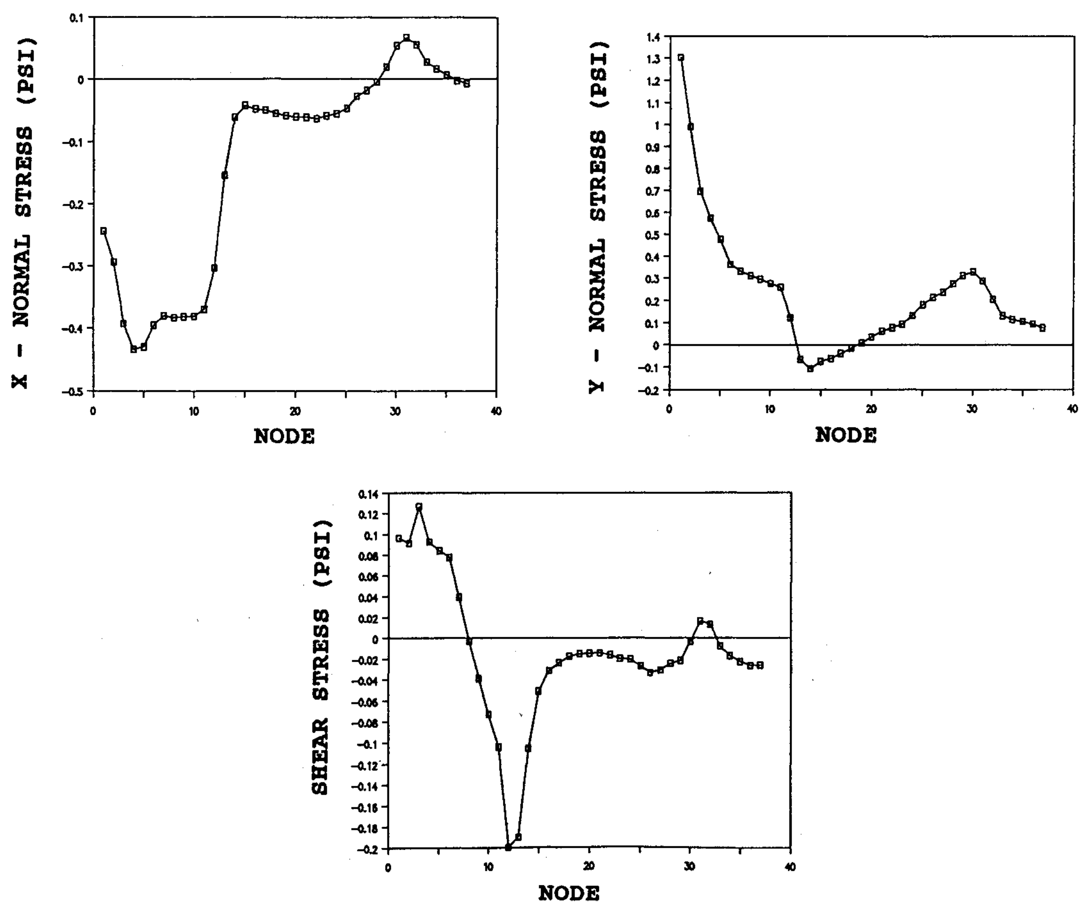

Fig. 8 Interface stresses Mach number of 0.12 and a 0-deg angle of attack.

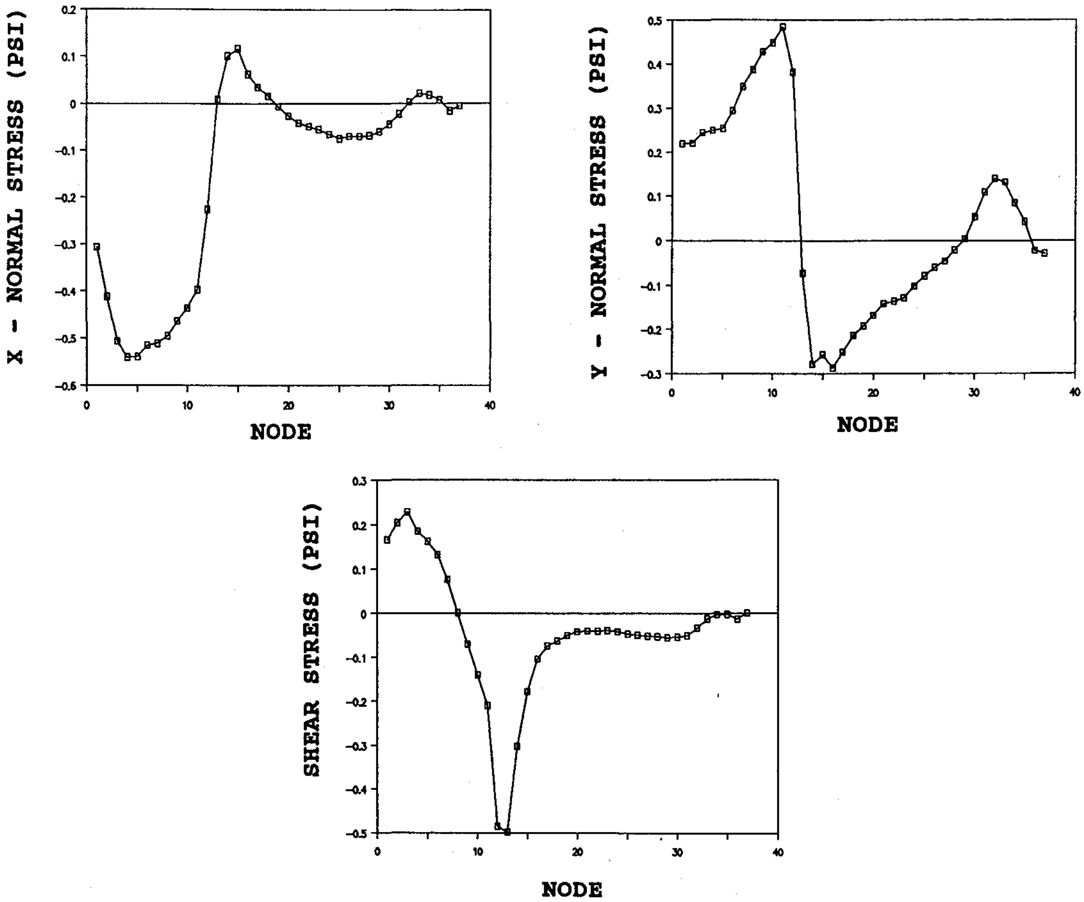

Fig. 9 Interface stresses Mach number of 0.12 and a 4-deg angle of attack.

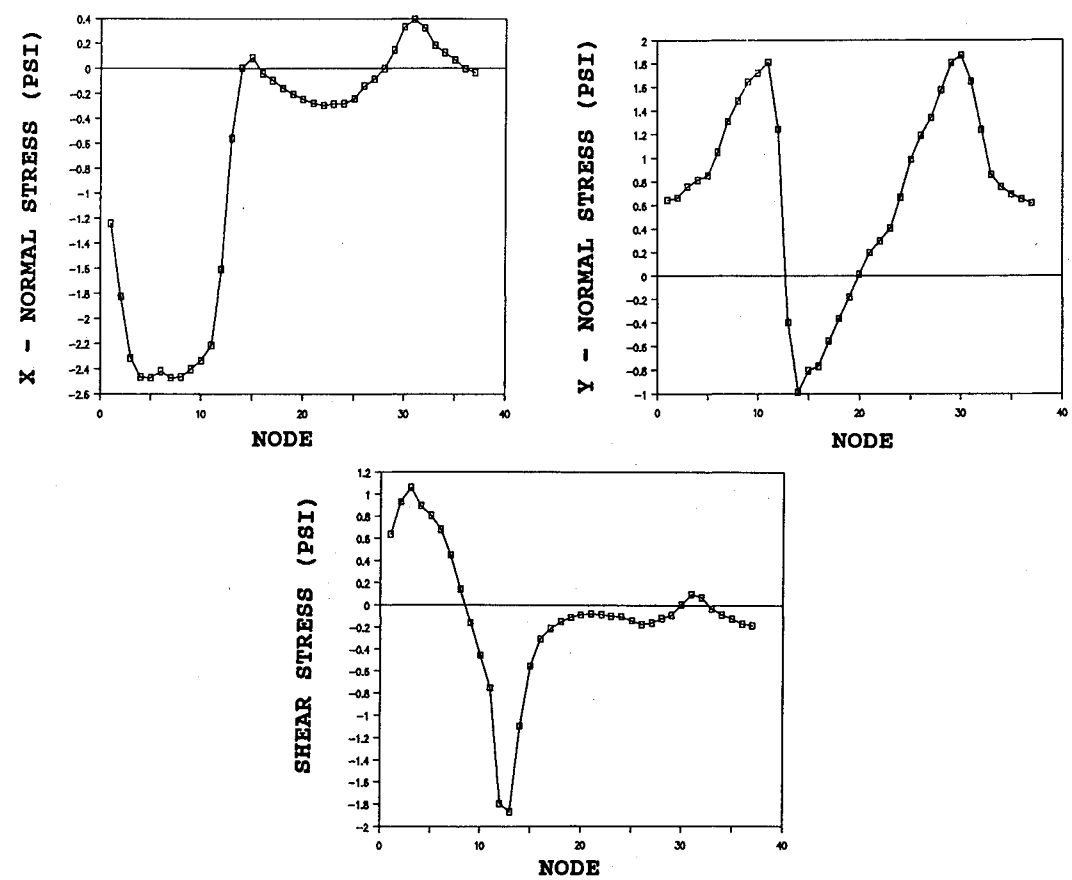

Fig. 10 Interface stresses Mach number of 0.3 and a 0-deg angle of attack.

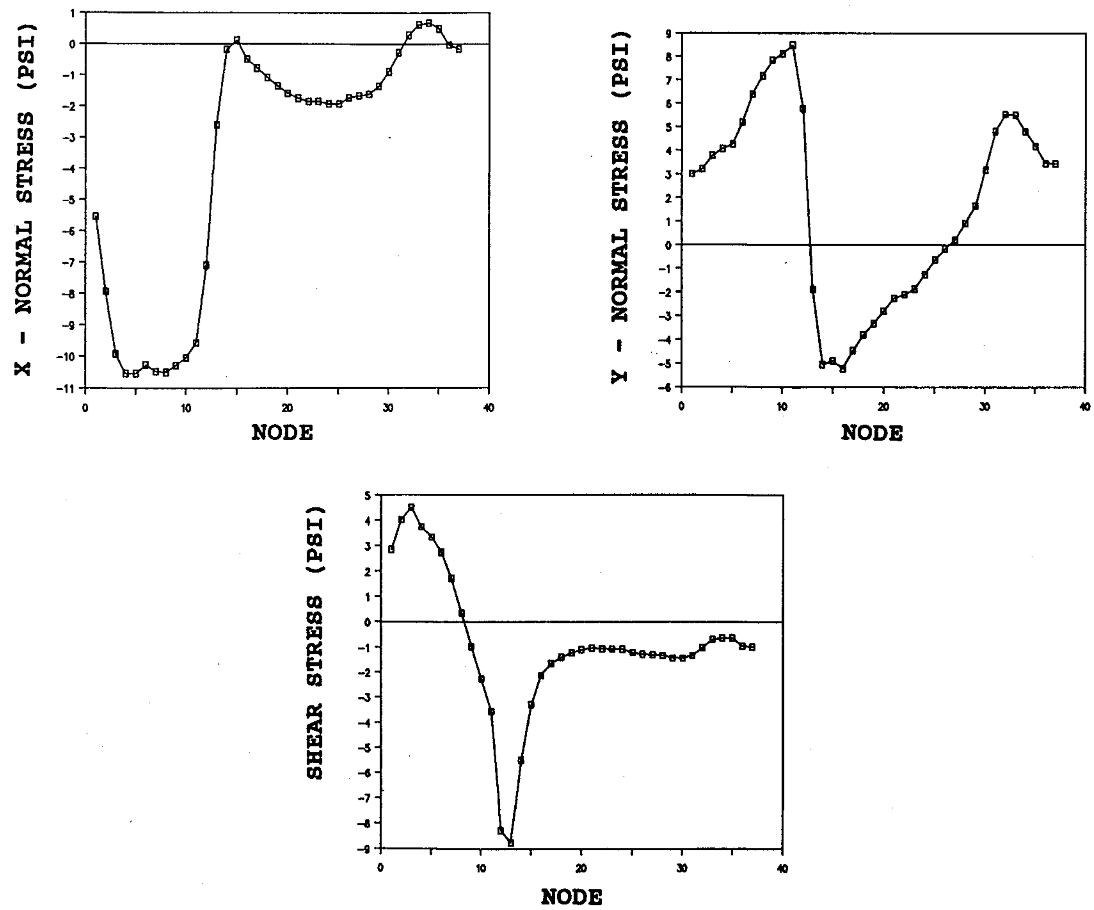

Fig. 11 Interface stresses Mach number of 0.6 and a 0-deg angle of attack.

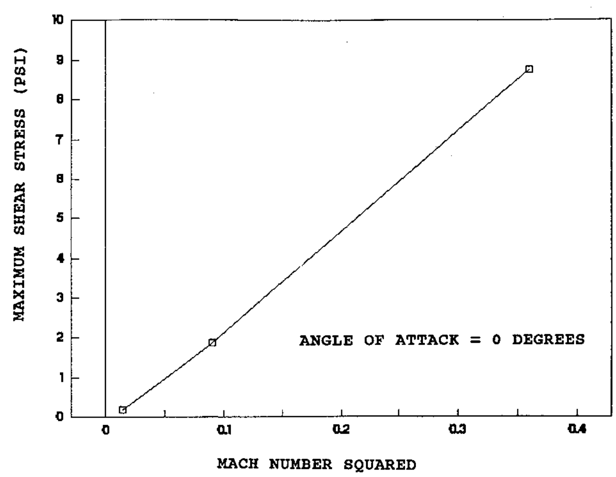

Fig. 12 Peak shear stresses as a function of Mach number squared at 0-deg angle of attack.

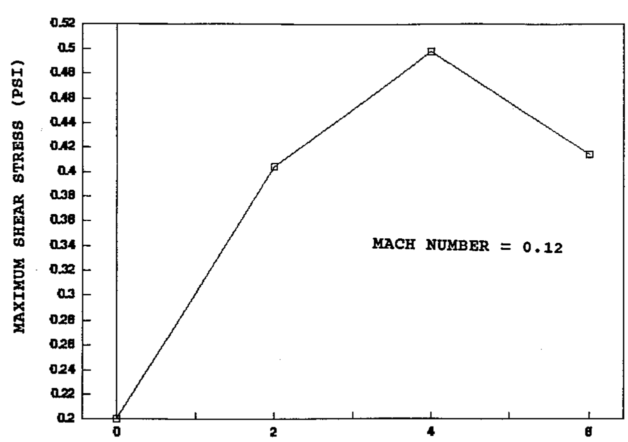

Fig. 13 Peak stresses as a function of angle of attack with a Mach number of 0.12.

Acknowledgment

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