SPACE SHUTTLE ORBITER WINDSHIELD BIRD IMPACT ANALYSIS

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Abstract

This paper describes an analysis of the Space Shuttle Orbiter windshield's resistance to failure by bird impact. The Orbiter windshield is a system of three glass panes separated by air gaps. Since glass is brittle, these windshield panes offer much less energy absorption capability than the laminated polycarbonate windshields of other high speed aircraft. This analysis shows that at some speed between 150 knots and 175 knots, impact with a four pound bird will not cause the windshield system to fail. The analysis did not attempt to further define this limiting velocity. This velocity is substantially slower than the average Orbiter approach and landing speeds. The risk of a catastrophic bird impact is being established to determine whether this deficiency should be corrected. Since the Orbiter design is fixed and window redesign would be costly, solutions to this problem are in reducing the risk by controlling the bird population around landing sites and in modifying operation times. For a hypersonic aerospace plane, windshields will have to be composed of glass to satisfy the thermal design condition of atmospheric reentry. Designing glass windshields to be bird impact resistant may be very expensive in weight, but will greatly improve the safety of a vehicle which will have many more hours of flight time than the Space Shuttle.

I. Space Shuttle Orbiter Windshield Design

The Space Shuttle is a multifunction vehicle, serving as a space craft and as an aircraft. Because of the duality of its mission, designing the windshield was a challenge. The windshield serves as a thermal barrier and as part of the crew module pressure vessel while providing suitable visual ports to flight crews. As launch vehicle and aircraft windows, they are subject to flight dynamics loading. Flight safety issues require that the windshield be redundant in its function as a pressure vessel, and that the system perform through one hundred nominal missions. The product of these requirements is the windshield illustrated in Figure 1.

The forward segment of the Orbiter is divided into two structures: the pressure vessel is called the Crew Module, and it is suspended inside the Forward Fuselage by links which allow for thermal deformations. To satisfy redundancy requirements, there are two window panes for each windshield segment in the Crew Module: the Pressure pane and the Redundant pane. There is one pane for each segment in the Forward Fuselage called the Thermal pane. Figure 2 shows a typical cross section of the windshield.

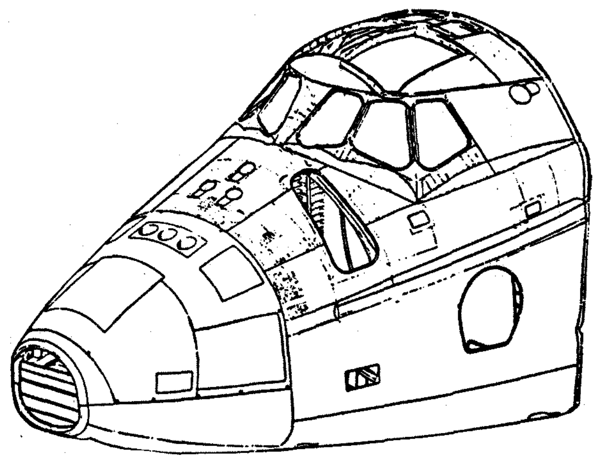


Figure 1

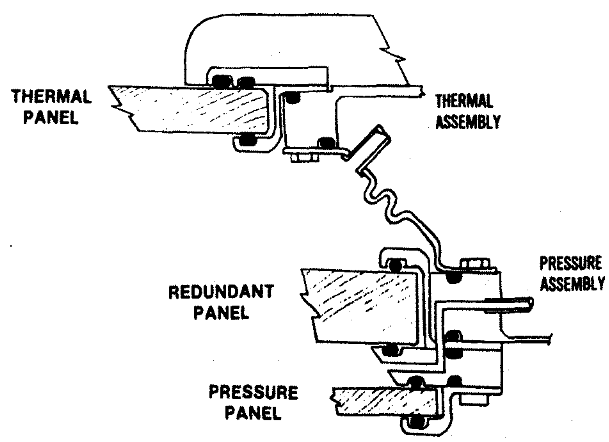


Figure 2

The thermal environment of reentry dictated that the Thermal pane be composed of low expansion fused silica glass, since temperatures may reach 2000° F during that phase of the mission. The next pane, the Redundant pane, is also made of fused silica, since it was meant to serve as a backup Thermal pane as well as a redundant pressure pane. The third pane is made of high strength tempered aluminosilicate glass to accommodate the high pressure differentials of orbital operations.

The glass panels used in the Orbiter windshields are proof-tested before installation to establish the maximum allowed flaw size, .0018 inches. Since the strength of a glass plate is a function of its inherent flaws and the stress-time history applied to it, it is very important to know the size and location of all surface flaws. The stresses of Space Shuttle missions have been accurately mapped for each pane so that flaws discovered during vehicle inspections after flights can be evaluated. Any flaw detected during these inspections is assumed to be three times larger than its visible depth. This assumed flaw depth is then used in a fatigue life analysis of the pane to ensure the window will survive its required one hundred missions. The load conditions of a nominal mission include the aerodynamic environments of ascent and descent, the thermal environment of reentry and the pressure environment of orbital operations. A nominal mission does not include an event such as a bird-transparency impact.

II. Bird Impact Hazard

The risk of bird impact to all aircraft has been well established in the history of flight. The first recorded bird strike casualty was the 1912 death of the pilot of a Wright Flyer that struck gulls. Since then, there have been many incidents involving hundreds of casualties and millions of dollars of damage to aircraft. In fact, one astronaut was a victim of a bird strike to his airplane canopy during a training flight in 1965. And the Space Shuttle has hit at least one bird already, during a landing at the Kennedy Space Center.

For most military and commercial jets, the biggest danger is ingestion of a bird or birds into jet engines. In twenty-two percent of bird strikes with U.S. Air Force airplanes in 1983, the impact point was the engine or the engine cowling. Nearly twenty-one percent of impacts to Air Force airplanes were to the windshield and canopy.[1]

When assessing the risks of bird impact, considerations must include the location of the flight, the season and time of day of the operation, and the duration of the flight, especially the duration below a 10,000 foot ceiling. Since trainer aircraft spend an inordinate amount of time in the airdrome (0 - 500 feet AGL), it is not surprising that these planes account for nineteen percent of the strikes reported above.[1] Any aircraft with missions involving high speed, low level flying runs a great risk of bird impact, and an especially great risk of windshield penetration.

The Space Shuttle Orbiter is designed to fly in any season and land at any time of day or night. During a normal mission, the vehicle's velocities below 10,000 feet are around 300 knots, and decrease to a landing speed of about 195 knots. Also, if the Shuttle pilot sees birds in his flight path, he has little freedom to avoid collision, since the Shuttle is not a powered vehicle during entry and landing. For gliders such as the Space Shuttle, clearly the biggest bird impact danger to crew and vehicle is penetration of the windshield by a bird.

To protect a flight crew from windshield penetrations, the FAA and the American military have established ground rules for transparency design. Windshields are required to sustain an impact of a four pound bird at design cruising speed without failing. (The four pound bird represents about ninety-two percent of the birds likely to be encountered in the continental United States). Fulfilling this design and test requirement involves full scale testing of the transparency system, which is usually time consuming and expensive. Of course, once an aircraft is designed to this requirement, safety is not guaranteed. It is the probability of catastrophic bird impact that is limited by this requirement.

To help reduce the costs of testing, the United States Air Force Flight Dynamics Laboratory (FDL) sponsored development of computer analysis methods to simulate the dynamic response of transparency systems to bird impact loading. MAGNA, the Material and Geometrically Nonlinear Analysis program, was the result of this project and was delivered in 1979. Its application to the aircraft transparency bird impact problem was largely validated via FDL in-house correlation studies. These correlation studies compared MAGNA computed results with full scale bird impact test results for a variety of Air Force aircraft transparency system. The success of these studies allowed a new trainer aircraft (the T46-A) to be released for initial flight testing based in part on a MAGNA analysis.[2]

The Structures and Mechanics Division at the NASA/Johnson Space Center was aware of these developments in solving the bird impact problem analytically. Based on a 1970's statistical analysis of the risks of bird strikes to the Space Shuttle, it was decided not to consider transparency penetrations in the testing requirements for the Orbiter windshield. An analysis was made during this phase of the design which concluded that the impact of a four pound bird could be sustained at 175 knots, without failure of the windshield system. This risk assessment, combining the statistical model and the analysis, are currently being updated to reflect new data and new methods of analysis like MAGNA. Because of the Air Force's success with the Flight Dynamic Laboratory's computer modeling and analysis using MAGNA, the NASA chose to use this same method to determine the capabilities of the Space Shuttle windshield.

III. Analysis of Orbiter Windshield

Analysis Approach

The objective of the analysis was to predict the maximum velocity with which a 4 lb bird can strike the Orbiter windshield without failing the pane nearest the crew. In other words, the two outer panes can fail and the Pressure Pane can absorb as much load as possible without reaching its rupture stress.

The analysis was performed in steps. First, the free vibration properties of the panel are examined and the lowest modes extracted. Next the impact "footprint" is defined, and load is applied to the windshield surface in time increments about 1/100th of the period of the pane's first mode of vibration. Maximum principal tensile stress (as a function of time) is determined for the pane, and used to determine the time of panel failure. This failure time is then used in the analysis to start loading the next pane in the sequence. An initial velocity is chosen and then iterated based on the analysis results until windshield system failure is prevented. NASA and the Air Force Wright Aeronautical Laboratories (AFWAL) agreed that the effect of glass debris resulting from the failure of one windshield pane was not a significant contributor to the failure of the next pane and would not be considered.

Finite Element Model. The analysis process, once initiated through the NASA and the Air Force, began with modeling the windshield. The design of the Space Shuttle windshield is such that the two center panes (refer to Figure 1), called the Forward panes, present the maximum angle for bird impact. The pilot and commander sit directly behind these panes. Of these two panes, it was arbitrarily decided to model the left Forward windshield. The geometry of the three left forward windshield panels was provided to AFWAL. Coordinate systems for each windshield panel and the basic (Orbiter) coordinate system and transforms between them were given to the AFWAL as well. The spacing of the windshield panels and their relative orientations are shown in Figure 2. AFWAL generated finite element models for each pane separately, using nine super elements as a first approximation, as shown in Figure 3 for the Thermal pane case.

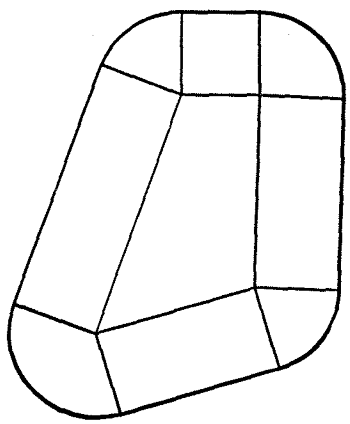


Figure 3

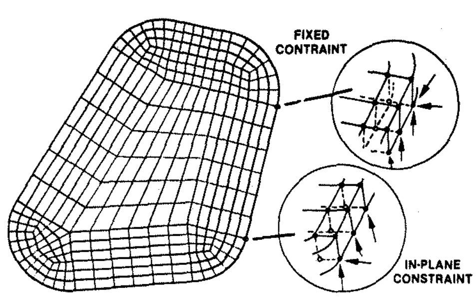


Figure 4

A MAGNA preprocessor was used to refine the initial model to the final mesh obtained for the Thermal pane as shown in Figure 4. Four hundred twenty three 16 node solid isoparametric elements were included in the model with a total number of 2672 nodes. The MAGNA model had one element through the thickness of the panel.

The same approach was used for the Redundant pane and the Pressure pane models, shown in Figure 5. Three hundred ninety six 16 node solid isoparametric elements, with a total of 2514 nodes, were used in the model of the Redundant pane and also in the model of the Pressure pane.

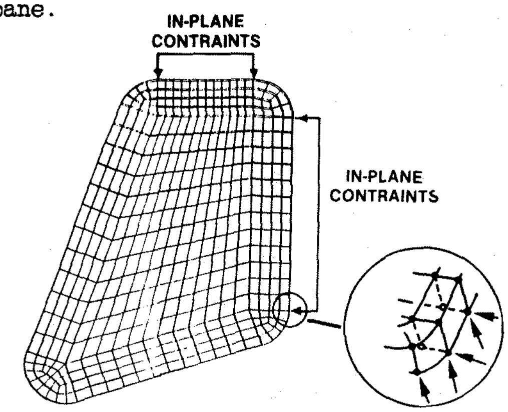


Figure 5

Boundary Conditions. The windshield is supported by very stiff, massive frames, made of beryllium, aluminum alloy and steel. No glass to metal contact is allowed, so the window edge is beveled and the inside of the frames are covered with narrow teflon pads. Sealing is accomplished with several fluorocarbon elastomer O-rings and a ceramic cord which provides a seal against hot gases during reentry. The windshield frame was not included in the MAGNA finite element model--for this analysis the support was assumed to be rigid.

All edge nodes on the side of the pane models opposite the side loaded by bird impact were constrained in out-of-plane deflections. To prevent rigid body motion of the panels, all three translational degrees of freedom were constrained at a single node, the location of which is shown in Figure 4. To prevent rigid body rotation about a line normal to the surface of the panels, another node was selected at which to constrain one in-plane degree of freedom (see Figure 4). For the Thermal pane model, the resulting number of unconstrained degrees of freedom was 7881. The number of unconstrained degrees of freedom resulting for the Pressure pane model was 7403.

Because of the minimal set of constraints employed, and with an earlier experience at AFWAL of a similar analysis on the British Vulcan bomber, there was concern about false modes of free vibration, as shown in Figure 6. The free vibration displacements indicated by dotted lines in the figure are unscaled, and represent unrealistic strains around the single fixed node in the Vulcan windshield model. Constraints like those described above were successfully used in free vibration analyses for both the Thermal and Pressure windshield panels, but a different set of constraints had to be used for the Redundant panel, when results similar to those illustrated in Figure 6 occurred. For the Redundant panel, none of the nodes in the model were completely fixed, but in-plane constraints were applied along both the aft and outboard edges of the panel. Figure 5 shows both the location and orientation of these in-plane constraints. The number of unconstrained degrees of freedom resulting for the Redundant pane model was 7356.

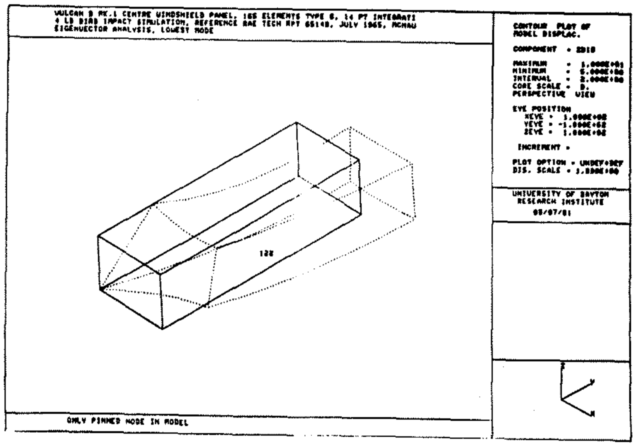
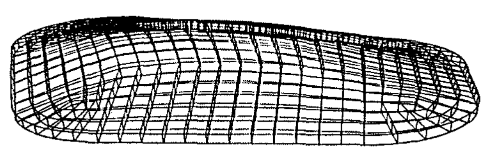


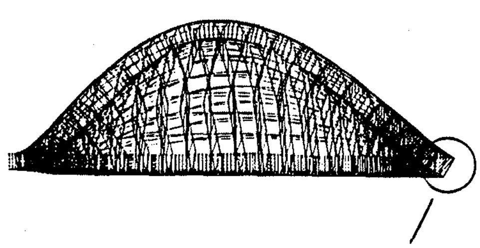
Figure 6

<u>Free Vibration Analysis</u>. MAGNA free vibration analyses were conducted primarily to determine the size of the time step to be used in subsequent linear dynamic impact analysis. Illustrations of the eigenvectors extracted during free vibration analysis were also used to verify the definition of model boundary conditions. Figures 7,8, and 9 each show the eigenvector for the first mode of free vibration which was extracted for the models of the Thermal, Redundant and Pressure panes, respectively. Only the first mode was extracted, because it was assumed that only the first mode was primarily excited by the bird impact event to be analyzed.



FREQUENCY - 167 Hz

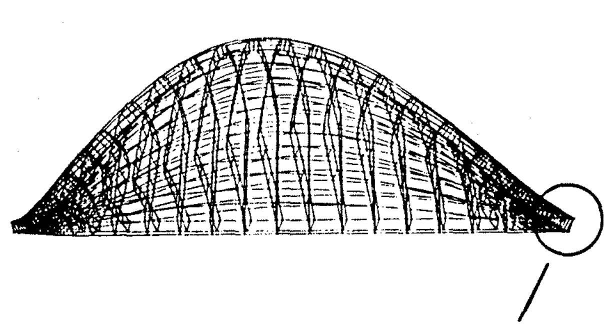
Figure 7



FREQUENCY - 478 Hz

ROTATION OF EDGE

Figure 8



FREQUENCY - 261 Hz

ROTATION OF EDGE

Figure 9

The plots of the eigenvectors show that the principal deformation of each of the panes occurred at its center. The frequency corresponding to the Thermal pane eigenvector was 167 Hz. The frequency for the Redundant pane eigenvector was 478 Hz, much higher because of the greater panel thickness involved. The frequency corresponding to the Pressure pane eigenvector was 261 Hz, higher than that obtained for the slightly thicker Thermal pane because of the stiffer material involved.

<u>Bird Impact Loads</u>. In mathematically simulating bird impact, several assumptions must be made regarding the mechanics of the impacting mass. A considerable amount of work has been accomplished in studying the physics of bird impact on both rigid and compliant targets. Much of this work has been sponsored by the US Air Force and has provided an extensive data base for the case of an inclined, flat, rigid target like the Orbiter windshield. This data base defines both the spatial and temporal distribution of bird impact pressures over the surface of the target.[3-12]

The following points are essential in defining the loads for a rigid target:

1. The bird behaves as a fluid during impact.
2. The impulse delivered to the structure is equal to the component of the bird's linear momentum which is normal to the target surface.
3. The bird may be represented as a right circular cylinder having a length to diameter ratio of 2.0.
4. The pressure resulting from bird impact is relatively constant at any point on the surface of the target (quasi-steady fluid flow).

Also, the loads are assumed to be completely uncoupled from the dynamic response of the windshield. This procedure assumes a regular geometry for the bird, ignores spikes of shock pressure which occur very early in the impact event, and assumes a spatially uniform pressure distribution. Even with these assumptions, though, bird impact simulation results have been found to be useful and realistic. The practical use of the rigid model for loading is apparently limited, however, to glass transparency designs which exhibit only very small deflections before fracturing.[13]

The first step in defining bird impact loading for a rigid windshield is the calculation of the bird impact angle, Θ, which is done using the transformations for the windshield geometry from the basic Orbiter coordinate system. Then the impulse **I** delivered to the windshield can be calculated:

$$I = (M)(V)\sin\Theta, \qquad (1)$$

where

M = bird mass
V = vehicle velocity.

It is assumed that the bird is a right circular cylinder traveling in the direction parallel to its axis of symmetry. Experimental studies have been conducted with simulated birds formed as right circular cylinders to determine the effects of bird attitude or orientation upon the target damage resulting from impact.11 This work has shown that the most damaging attitude for bird impact is end-on.

Next the impact footprint is defined. The locus of the footprint boundary is estimated based on data gathered from previous laboratory tests using instrumented rigid targets.[8] This footprint is graphically laid out on the MAGNA mesh.

Within this footprint boundary, a set of elements is selected which best represents the area of the footprint. Usually the mesh is iterated at this point so that there is a relatively large number of elements within the footprint (10 to 20) for good resolution of the impact pressure distribution, and to locate element boundaries so that they correspond closely to the boundary of the footprint. Figure 10 shows the footprint determined for a center impact on the thermal pane.

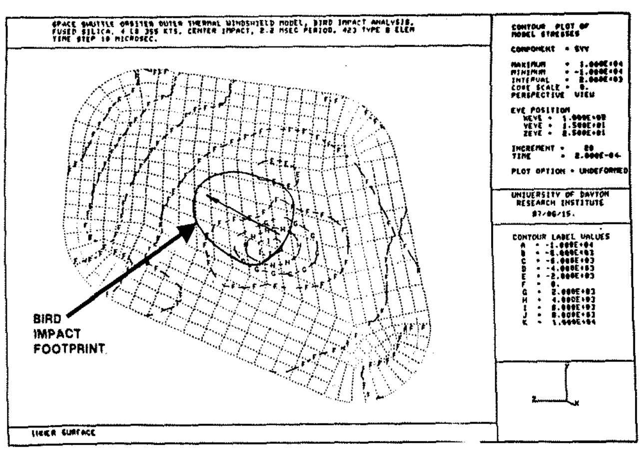


Figure 10

To calculate the times at which elements in the loading footprint become loaded and subsequently unloaded, distances measured on the windshield surface are divided by velocities at which geometrical intersections between the bird cylinder and the windshield surface move.

Once the speeds at which the leading and trailing edges of bird material move over the surface of the panel are calculated, the total set of elements in the loading footprint is subdivided into groups which will each be assigned the same loading and unloading times. Then distances from the initial point of bird contact on the surface of the windshield to the forward edge of each group of elements selected is measured. These distances are then used to calculate loading time for each group. Unloading times are calculated in a similar way.

To find the magnitude of the pressure applied to the windshield surface, all the loading and unloading times are listed in ascending order. The time intervals between each pair of times is calculated (**T**). Next, the windshield surface areas within each loaded group is calculated (**A**). A sum of the products of areas and respective loading time intervals is formed. Finally, the constant value of the bird impact pressure is determined by dividing the impulse I from equation (1) by the value of the sum.

$$P = I/(\sum_i A_i T_i) \qquad (2)$$

Input data defining bird impact loads for the MAGNA dynamic analysis is simply the single value of pressure magnitude and the list of loading and unloading times along with the corresponding finite element numbers and element surface numbers.

At the beginning of the study, it was agreed that the entire remaining portion of the bird mass which had not yet reached the surface of a given windshield pane at the time of that panel's failure would be applied to the next windshield pane in sequence. The rationale for this approach is based on extensive experimental work which has demonstrated that the windshield bird impact problem may be considered the same as the steady impingement of a fluid jet on the surface of the target.[3-12] While the target is intact, fluid is deflected to flow in directions parallel to the surface of the target. When the target is removed suddenly (fails), fluid which has not yet impinged the surface continues to move in its original direction of travel (i.e., along the trajectory of the bird).

<u>MAGNA Analysis</u>. After free vibration analyses were conducted to determine the frequency of the first mode for each of the windshield panel models, linear dynamic analyses simulating bird impact were done. In each dynamic analysis, all elements in the models were formulated with linear stiffness. The time step chosen was .000010 seconds, considerably less than 1/100th the period of any of the first modes obtained from the free vibration analysis.

To obtain the stress results required, contour plots of in-plane normal stresses on the tension side of the glass panel were prepared. From these plots, a group of two or three nodes was chosen at which the maximum value of in-plane normal stress occurred for each solution time increment. For each of these nodes, maximum tensile stress versus time was extracted using a postprocessor. This history was transmitted to NASA for calculation of the pane's failure time.

Fracture Analysis

A FORTRAN program, written at NASA/JSC, calculated flaw growth and fracture time for glass panels, given a stress-time history. This program was developed using empirically determined flaw growth constants for the fused silica and aluminosilica glasses used in the Orbiter windshield. Flaw growth is computed using a form of Griffith's Method, a semi-logarithmic crack growth curve. The initial flaw is assumed to be the size of the flaw screened by proof tests of the windshield panes.

The stress-time history received from AFWAL is input to this program. The results are the final flaw depth and a time of failure, or a message which indicates that no failure has resulted from this loading. This result is transmitted back to AFWAL.

IV. Results

Once AFWAL is apprised of the panel failure time, the MAGNA analysis for that particular glass panel is stopped, and the load sequence for the next panel in the three pane system is begun. This procedure is repeated for each pane in the three pane system until all three panes have failed, or until all 4 lb of the impacting bird are absorbed. The initial velocity at the start of each windshield system failure analysis is adjusted based on the previous result and the limiting velocity, the objective of this analysis, is approached.

The first velocity chosen for this analysis was 355 knots, the maximum cruising speed of the Orbiter below 10,000 feet.

Thermal Pane, Center Impact, 355 knots

Figures 11 and 12 show contours of in-plane normal stress on the tension (inboard) surface of the thermal panel at .00020 seconds, for a 4 lb bird impact in the center at 355 knots. Contour plots like those shown in the figures were prepared for times out to .00030 sec, and showed that maximum in-plane normal stress always occurred at one of three nodes in the mesh.

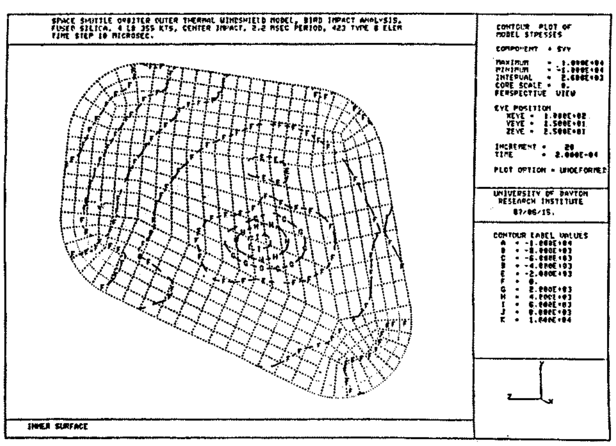


Figure 11

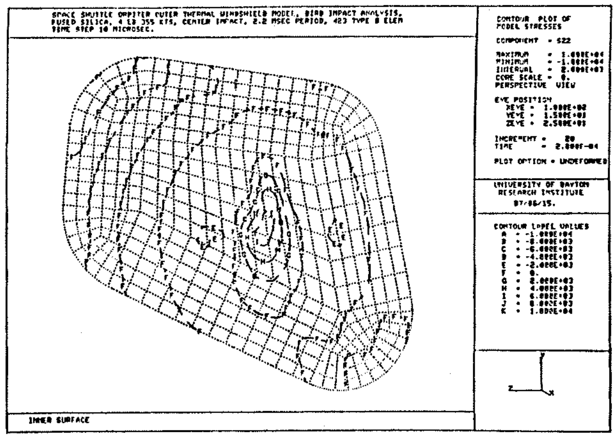


Figure 12

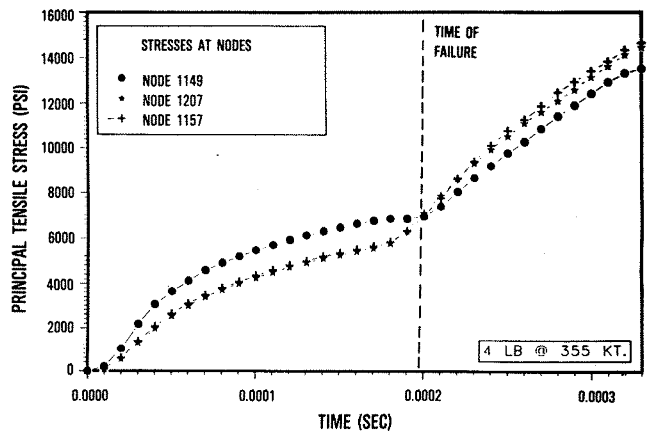


Figure 13

Figure 13 shows the histories of maximum principal stress extracted by the MAGNA postprocessor for the three nodes of interest. The lack of a smoothly increasing stress vs. time plot indicates the discontinuity with which the bird impact pressure loading was defined. The sharp increase in slope corresponds to the second group of finite elements in the impact footprint. The failure time calculated from this data was .000197 seconds. Analysis indicated that 1.2 oz of the bird would be "consumed" by this panel.

AFWAL also computed stress vs. time for the case of a corner impact, to check which impact location produced the smaller time to failure. The failure time for the corner impact was .000220 seconds.

The center impact was chosen because of its slightly earlier failure time. A vector representing the bird path for this impact was carried through the planes of the redundant and pressure panes in order to define corresponding bird impact loads for each.

Redundant Panel, Center Impact, 355 knots

The bird mass, minus 1.2 oz consumed by the Thermal pane, was applied in center impact analysis to the Redundant pane.

Figures 14 and 15 show contours of in-plane normal stress on the tension (inboard) surface of the Redundant pane at .000272 seconds. Careful attention was paid to the distribution of stress shown in these figures along the two edges which had been arbitrarily constrained in-plane to avoid anomalous first mode free vibration results. No unrealistic stress concentrations were apparent in the figures.

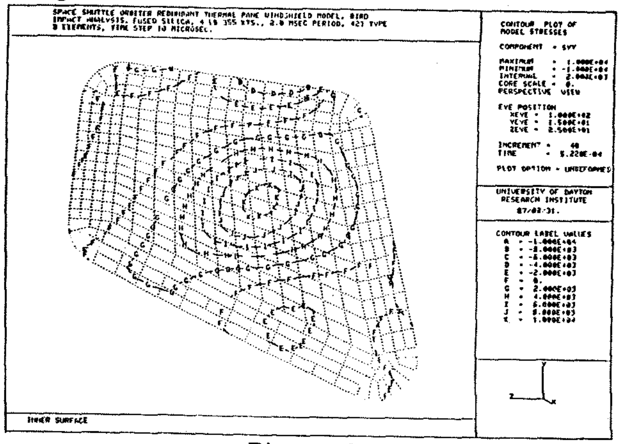


Figure 14

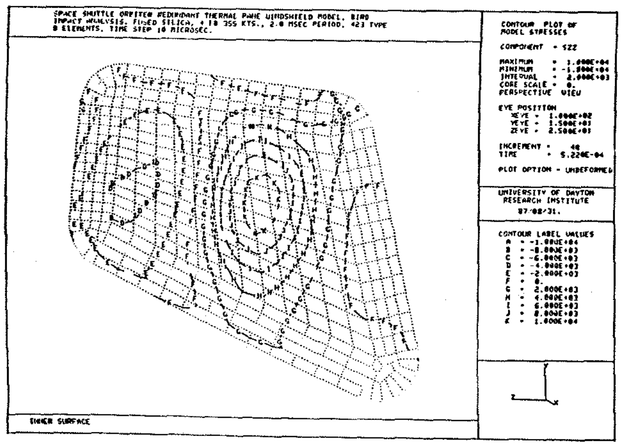


Figure 15

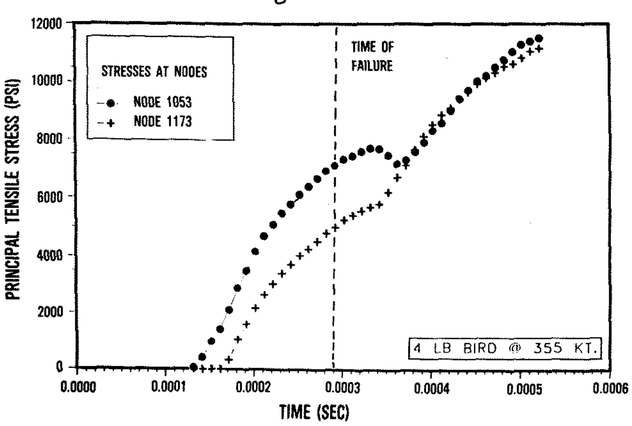


Figure 16

Figure 16 shows the histories of maximum principal stress extracted for the nodes of interest. Time 0.0 seconds in the figure corresponds to the first contact of an entire 4 lb bird on the Redundant pane. Redundant pane analysis for the 3 lb 14.8 oz bird was initiated at .000122 seconds on the time scale shown in this figure.

The failure time resulting from these stress-time histories was .000290 seconds. At this point in time, only the first two of the six groups of elements within the bird impact footprint had been loaded with impact pressure. This failure time corresponds to an additional consumption of 3.2 oz of bird by the Redundant pane. The total bird mass consumed by the first two windshield panes was 4.4 oz.

Pressure Pane, Center Impact, 355 knots

Again, a reduced bird mass was applied to the Pressure pane. After .000108 seconds of loading, the Pressure pane failed. At this point in time, only 2.7 oz of the 4 lb bird was consumed by the Pressure pane. A total of 7.1 oz of bird mass was consumed by the windshield system for the 355 knot impact velocity.

Because the 355 knot velocity was obviously well above the capabilities of this windshield system, a next velocity of 175 knots was chosen. This was based on the earlier Rockwell International analysis mentioned above.

Summary of Results

The results obtained from this analysis are summarized in Table 1. It shows, for each of the Orbiter airspeeds analyzed, that portion of the 4 lb bird required to fail each of the three respective panels.

Table 1

Mass Required to Fail Forward Window

Airspeed	Mass consumed (oz.)			
(knots)	Thermal Pane	Redundant Pane	Pressure Pane	Total
355	1.2	3.2	2.7	7.1
175	6.8	15.4	18.1	40.3
150	7.7	56.3+	----	64.0

Once it was determined that the limiting velocity was between 150 knots and 175 knots, the analysis was repeated for the 175 knots impact case, with different material flaw growth properties. The properties used in the primary analysis were conservative, "three sigma" flaw growth properties. The second attempt at 175 knots used mean value data for these parameters. The windshield system did not fail under these analysis conditions.

Conclusions

The Space Shuttle Orbiter windshield is a poor barrier to bird impacts. The glass provides no resistance to four pound birds at operational velocities. At 175 knots, the analysis shows that in most cases, the windshield will resist the impact of a 4 lb bird. An important qualification of this analysis is that no factor of safety was used in determining the failure time of the glass. There is ample conservatism built into the failure criteria, though, for all cases except the last attempt at 175 knots.

A new hypersonic vehicle will have many things in common with the Space Shuttle. What will make it unique, however, is its function as a regular, possibly commercial transport between Earth and space, or between distant Earth cities. A vehicle like this must have safety features which accommodate frequent flights and civilian passengers. Since bird impact will be a significant risk for a vehicle that performs regular operations around airports, designing for bird impact resistance will be crucial.

Design options for this kind of vehicle are not limited to glass panes. The hypersonic plane of the future may have no cockpit windows at all save for shielded ones that are used only for airport operations. These could be made, like current aircraft windows, out of polycarbonates. Another option is the use of very small windows, made of glass, supplemented by some kind of video support for visual operations. A third possibility is the use of mixed media windows, with a thermal pane made of glass and an inner pane made of a polycarbonate material.

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