# Finite-Element Analysis of the T-38 Aircraft Canopy

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**The nonlinear static response to a concentrated load on the inner surface of the student pilot canopy for the T-38 aircraft has been predicted using the MAGNA (Materially And Geometrically Nonlinear Analysis) finite-element computer program. The analyses conducted were intended to simulate the impingement on the canopy inner surface of a breaker located on the student pilot ejection seat. Criteria for defining fracture of the canopy were selected and work required to fracture the canopy was then determined from computed nonlinear load-displacement curves. The static load and work required to fracture two proposed bird-resistant designs for the T-38 student canopy were compared to those required to fracture the current design. It is concluded that transparency penetration for emergency crew escape via ejection seat breaker impingement on the T-38 student canopy is probably not feasible for a 0.68 in. thick monolithic stretched acrylic bird-resistant design. The same mode of transparency penetration might prove feasible for a 0.40 in. thick monolithic polycarbonate bird-resistant design.**

## Introduction

IN recent years Air Force flight missions have involved more high-speed, low-altitude operations. Under these conditions, bird impacts on aircraft transparent crew enclosures pose a significant hazard and have resulted in unacceptable losses of aircraft and crew members. Since 1966 the original purchase cost of Air Force aircraft lost to confirmed transparency bird impact has exceeded $100 million. Replacement cost for these aircraft would of course be many times higher. Seven crew members lost their lives in these accidents.

Since 1972 the Air Force has become a worldwide leader in reducing the scope of this problem. At that time the Air Force Flight Dynamics Laboratory formed the Improved Windshield Protection Advanced Development Program Office (ADPO). Since then a second group, the Subsystems Development Group of the Crew Escape and Subsystems Branch, has also been formed and together the two offices are charged with the development, demonstration, and application of new technology for the design of improved aircraft transparent crew enclosures.

One of the current programs being conducted by the Flight Dynamics Laboratory is development of bird-resistant transparencies for the T-38 supersonic trainer aircraft. Preliminary design studies have already been conducted with various candidate designs being proposed for the student pilot windshield, student pilot canopy, and instructor pilot windshield. Figure 1 illustrates the location of each of the transparencies included in the T-38 system. The instructor's canopy offers no presented frontal area in flight and so has been excluded from consideration for improved bird impact resistance.

Development of an improved student pilot canopy is complicated by emergency crew escape considerations. In the current system the canopy rotates about its normal hinge point and leaves the aircraft before student pilot ejection occurs. In the backup mode, when the canopy fails to jettison, the student canopy remains in place as the student pilot ejection seat begins to move up its rails, propelled by a rocket catapult. A blade-like canopy breaker mounted on the ejection seat impinges on the centerline of the canopy inner surface and applies load to the canopy under the action of catapult thrust. Canopy fracture due to breaker impingement is intended to provide a clear ejection path for the student pilot.

Concern exists over the feasibility of this backup mode for emergency crew escape if an improved bird-resistant student pilot canopy is retrofitted on the aircraft. The additional strength of the new canopy might require too much energy or too high a load to fracture, thus preventing successful escape. Alternatives to the current concept are available but any one of these would involve costly development in conjunction with design of the new canopy. A systems approach would necessarily be required to blend the new provision for backup emergency crew escape with that for increased bird impact resistance.

The goal of this study was to evaluate the need to consider such alternatives to the current backup ejection system for two proposed bird-resistant designs. A finite-element analysis package called MAGNA (Materially And Geometrically Nonlinear Analysis) was used to compare the difficulty in fracturing the proposed designs to that required in fracturing the current canopy. The two proposed designs are both monolithic, one 0.68 in. thick stretched acrylic and the other 0.40 in. thick polycarbonate.[1] The current production canopy is monolithic stretched acrylic, 0.23 in. thick.

The results of this study should provide useful guidance during the conduct of the current contractual program for the development of improved T-38 aircraft transparencies.

## Analysis Capability

The MAGNA computer program was originally developed by the University of Dayton Research Institute, Dayton,

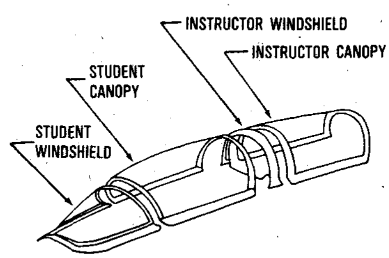


**Fig. 1 T-38 aircraft transparencies.**

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Ohio, in 1978. Since then it has been tailored under Air Force contracts for use as an aircraft transparency analysis and design tool. This special attention to one Air Force area of application does not limit the utility of MAGNA as a very efficient and effective tool for general three-dimensional nonlinear finite-element analysis. Full documentation for the code has been prepared and published for unlimited distribution.[2-4]

MAGNA is a major system of computer programs for the static or dynamic, linear or nonlinear analysis of complex three-dimensional structures. It includes preprocessors, a nonlinear finite-element analysis package, and a variety of postprocessors. MAGNA employs isoparametric modeling as well as state-of-the-art numerical analysis and programming methods. Available elements include a three-dimensional truss element; quadrilateral plane stress, plane strain, and shear panel elements; an isoparametric eight-node thin shell element; an isoparametric solid eight-node element; and an isoparametric solid variable-node (up to 27) element. All elements utilize only translational degrees of freedom at boundary nodes and so are fully compatible in three-dimensional space. Time history solutions are performed using Newmark's implicit method for direct integration of the equations of motion. Each of the available finite elements in MAGNA includes the effects of full geometrical nonlinearities using a Lagrangian (fixed-reference) description of motion. In shell analysis, arbitrarily large rotations can be treated. Material nonlinearities, in the form of elastic-plastic behavior, are analyzed using a subincremental strategy which minimizes the error in following the material stress-strain curve. Isotropic, kinematic, and combined strain-hardening rules are available for use in plastic analysis with MAGNA. Orthotropic elastic material behavior can also be treated. User-written subroutines can be supplied to define mesh geometry, coordinate systems, initial conditions, and incremental applied loading. Plotting utilities in both interactive and batch forms are also available for generating finite-element models and illustrating the results of analyses. Deformed and undeformed geometry plotting are available as are stress, strain, and displacement contour and relief plots.

MAGNA has been designed from the outset primarily for large, nonlinear, three-dimensional problems. Several applications of this class involving Air Force aircraft have already been accomplished and documented.[5-9] These applications have successfully demonstrated the efficiency and capabilities of MAGNA.

The first step in any application of the finite-element method is discretization and modeling of the structure of interest. This will be described for the T-38 student canopy in the following section.

## Structural Modeling

### Geometry

Since for the problem of interest both the loads and the structure exhibited symmetry, only half of the structure was modeled to conserve computer resources. The starting point for the modeling task was information regarding the geometry of the structure obtained from the principal manufacturer, Northrop Corporation.[10,11]

The student canopy for the T-38 is a monolithic part fabricated from stretched acrylic 0.23 in. thick with cross sections taken in vertical planes which are circular arcs. The radius of respective cross sections is a function of aircraft fuselage station and the locus of the centers of these circular cross sections is a curved line lying in the aircraft plane of symmetry. The aft edge of the part lies on a vertical cross section but the forward edge lies on a cross section which is canted forward.

A short FORTRAN computer program was developed from this description of canopy geometry.[10,11] This code was designed to run interactively and to generate coordinates for nodes lying on the outer surface of the canopy. Nodes were generated in lofting line sequences for successive cross sections. Nodes were numbered from the canopy centerline to the outer edge on each respective lofting line. The inclination of the lofting sections generated varied uniformly from the canted forward edge to the vertical aft edge. The coordinate data generated was in the format required for input to the MAGNA preprocessor.[3]

Initially coordinates were generated for nodes in a $14 \times 7$ grid uniformly spaced in the longitudinal and lateral directions, respectively. The short FORTRAN code permits interactive user relocation of grid lines however and this feature was used to place one centerline node at the point of canopy breaker impingement, fuselage station 206.8 in. The grid line relocation feature was also used to define a row of narrow elements roughly 1 in. in length at the canopy forward edge. These narrow elements were intended for use in conjunction with a unique boundary condition capability available within MAGNA and will be discussed more in the next section.

### Discretization

The nodal coordinate data generated as described above was used as input to the MAGNA preprocessor which comprises many modules.[3] First, the CORGEN module was used to generate a coarse two-dimensional grid (surface coordinates), and then the EXPAND module was used to generate through the thickness to get a three-dimensional model. The PREP module was used to refine the basic model in the area of interest, the site of canopy breaker impingement; i.e., additional longitudinal and lateral grid lines were added to make the mesh finest in the area of load application.

The resulting model as shown in Fig. 2 has a $21 \times 9$ grid of 16 node isoparametric solid elements containing 1256 nodes. It was designed to be fine enough to capture the overall deflection pattern and strain energy distribution within the part but not to permit accurate stress analysis. It was not designed to realistically represent the state of stress at or very near the point of load application.

Boundary conditions were applied to prevent lateral motion along the centerline of the canopy to properly account for the condition of symmetry existing there. The remaining three boundaries of the model were pinned as illustrated in Fig. 3. It

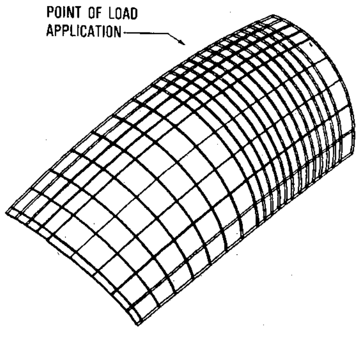


**Fig. 2 MAGNA finite-element model of the T-38 aircraft student canopy.**

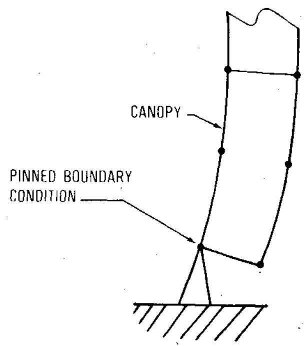


**Fig. 3 Pinned boundary condition.**

has been planned initially to use a unique feature of MAGNA for surface contact analysis to represent the forward edge boundary condition on the canopy. This edge is not bolted on the actual part but rests only on the surface of a metal arch support. The MAGNA contact feature would properly account for sliding contact at such an interface while at the same time preventing penetration of the two surfaces involved. However, lack of sufficient time dictated that plans to include a case with the contact feature be dropped. For this reason, the narrow row of elements built into the forward edge of the model never served their intended purpose. These boundary conditions when applied to the model resulted in 3393 unconstrained degrees of freedom. This model will be referred to as the 0.23 Pinned model.

A second set of boundary conditions was also defined in an attempt to more realistically treat the aft edge of the canopy since it is relatively close to the point of load application. On the actual part, the aft edge carries slotted holes and is clamped with bolts between the aft arch structure and a metal strap. As a result, in-plane loads exceeding the clamping friction result in longitudinal sliding at the aft edge. In the second set of boundary conditions therefore, longitudinal motion of all nodes lying on the aft edge was permitted. This model contained 3430 unconstrained degrees of freedom (more than the 0.23 Pinned model) and will be referred to as the 0.23 XZ model since motion in the $y$ direction was permitted only along the aft edge.

Altogether four models were generated: the two already discussed, and one more for each of the two proposed bird-resistant designs—0.68 in. thick stretched acrylic and 0.40 in. thick polycarbonate. The geometry for the outer surface of all models was the same. The last two will be referred to as the 0.68 XZ model and the 0.40 XZ models, respectively. The XZ models were intended to establish the relative difficulty of through-the-canopy escape among the three designs considered and the 0.23 Pinned model was planned to demonstrate the effect of applying simplistic boundary conditions for a problem of this sort.

**Material Properties**

In general the mechanical properties of the thermoset plastic materials used in the manufacture of aircraft transparencies are not as well known as those of metallic materials. Only a few handbook-type reference sources are available in the literature, and remaining data are fragmented and often unpublished.[12,13] It is a difficult task to describe the behavior of plastics because their properties are strongly affected by so many parameters such as ambient temperature and strain rate.

During the studies described here an attempt was made to gather the same kind of data for both materials involved. For both the polycarbonate and stretched acrylic materials, engineering stress vs engineering strain data from uniaxial tensile testing was chosen as a starting point. (Two transformations of these data are required before it can be used by MAGNA which utilizes the Piola-Kirchhoff stress and Green-St. Venant strain.[2]) Data for an ambient temperature of 72°F and a strain rate on the order of 0.05 in./in./min was used in both cases. A vendor bulletin was used as the source for stretched acrylic data, and raw engineering data from an earlier Air Force study was used to describe the polycarbonate material.[13,14] Figure 4 illustrates the difference between the two materials. Stretched acrylic is seen to have a higher modulus and a very slightly higher yield stress.

Attempts to represent accurately the true strain-softening behavior of polycarbonate which occurs past the yield point would result in numerical instability during nonlinear MAGNA analysis. For this reason, polycarbonate was assumed to strain harden at the same rate as stretched acrylic. This assumption is illustrated in Fig. 4.

In general, the prediction of material rupture or failure is much more difficult when using the finite-element method

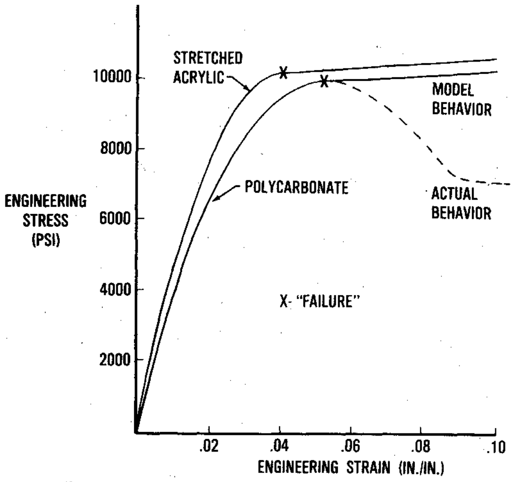

**Fig. 4 Stress-strain behavior of materials.**

than is the prediction of structural response, i.e., stresses, strains, and deflections. Because predicting failures is in general difficult, and additionally because of the lack of data for the plastic materials involved, an arbitrary definition of "failure" was adopted for use in these studies. This does not present a handicap in interpreting results since only a relative comparison of performance was desired. That is, the objective of the study was to compare results for the two bird-resistant canopy designs with those for the current design, not to predict actual failure loads for any of the three designs. The assumption was made that the ratio of the actual failure load for a bird-resistant design to the actual failure load for the current design would be nearly the same as the ratio of "failure" loads obtained from these studies. It was decided to use the first occurrence of material yield in tension as the definite for mechanical "failure" of the materials. The (Piola-Kirchhoff) yield stress for the stretched acrylic material was 9808 psi and that for the polycarbonate was 9392 psi. The engineering values are higher as shown in Fig. 4. This decision regarding the definition of failure reduced the significance of incorrectly representing the strain-softening behavior of polycarbonate. This is true because strains for which significant softening occurs in the polycarbonate were not attained during the analysis.

## Load Modeling

T-38 aircraft in service carry a single canopy breaker mounted on the ejection seat for the student pilot. As mentioned earlier, this breaker impinges on the centerline of the student pilot canopy as the ejection seat begins to move upward along its guide rails. A profile layout of the student pilot cockpit was made to determine the location of the breaker point of contact on the canopy. This point was found to lie at fuselage station 206.8.

The guide rails for the student pilot ejection seat are not oriented vertically in the aircraft coordinate system but are inclined toward the tail of the aircraft at an angle of 13 deg from the vertical. The concentrated load used for MAGNA analysis was inclined at the same angle and applied on the centerline at the point of breaker impingement as shown in Fig. 5. All MAGNA analyses performed were nonlinear static ones with the load being applied incrementally in steps of 20-400 lb. The sequence of load steps will be discussed in more detail in the next section.

## Analysis

As already mentioned, all solutions performed were of the nonlinear static type. The first analyses run were for the 0.23 Pinned and 0.23 XZ models simultaneously. The restart feature of MAGNA was utilized to accomplish just a few increments of each solution at a time.[2] There were two

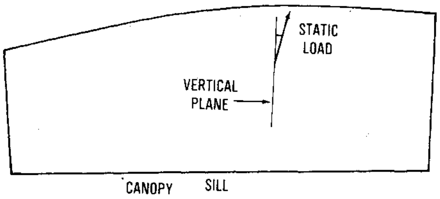


**Fig. 5 Static load on T-38 student canopy.**

primary benefits from using restart. The first benefit was to reduce each job to a size permitting daily turnaround. The second benefit was the opportunity to scrutinize the nonlinear solutions at frequent intervals. In this way solution parameters could be adjusted as need be to obtain an accurate solution while using the minimum computer resources required.

The first few increments of each solution utilized a load step of 20 lb. A constant element stiffness formulation which is available with MAGNA was chosen to economize the solutions.[2] (A group of eight elements near the point of load application utilized the full nonlinear formulation for element stiffness.) A combined rule for equilibrium iteration was chosen for use within each solution increment. This rule uses a small number of full Newton-Raphson iterations followed by a larger number of modified Newton iterations in order to converge rapidly with the least computer resources possible.[2] Using this scheme, convergence was obtained for the first few increments with an average of five iterations per increment.

As the solutions progressed however, convergence became more difficult and as many as 20 iterations per increment were required. To strengthen the convergence of the solutions, subsequent restarts were made with an averaged nonlinear formulation for element stiffness. This change made it possible to increase load step size to 60, 100, and finally 400 lb while performing an average of only three iterations per increment. Convergence with the averaged nonlinear element stiffness formulation was dramatically improved. This feature of MAGNA can provide significant savings in nonlinear analysis; the cost of using the full nonlinear formulation for element stiffness is in general much higher.[2]

All T-38 analyses were run at a core size of 350,000 octal words. MAGNA utilizes an out-of-core, variable-bandwidth (skyline) solution technique; for these jobs the maximum half bandwidth was 340 and the average half bandwidth was 158. MAGNA utilized 31 partitions of the stiffness matrix at the core size chosen and about 375 CPs and 3000 IOs per increment on the CDC CYBER 750 used for the analyses.

Simulations with the 0.68 XZ and 0.40 XZ models were run in a similar manner (averaged nonlinear element stiffness, combined iteration rule) but with a uniform load step of 100 lb. Times required for these two jobs were lower being about 250 CPs and 2000 IOs per increment. Convergence of the solutions was more rapid, typically one or two iterations per increment. This more rapid convergence is attributed to the greater stiffness in these models than for the first two, resulting in smaller incremental displacements and rotations during a given load step.

## Results

### Canopy Failure Loads

MAGNA calculates equivalent stress which relates the three-dimensional state of stress at a point to an "equivalent" state of uniaxial tension.[2] The postprocessor was used to generate contour plots of equivalent stress on the outer surface of the canopies studied. As discussed earlier, the criterion adopted for canopy "failure" was the occurrence of the (Piola-Kirchhoff) yield stress on the outer surface. Figure 6 shows a contour plot of equivalent stress for the 0.23 Pinned model at a load level of 600 lb. Only 10 elements around the point of load application are shown. The dotted lines represent the deformed shape of the structure and the solid lines the undeformed shape. The displacements which are illustrated have not been scaled and so represent the actual deformation of the canopy. The contours enclosing the point of load application represent 25, 50, 75, and 100% of the yield stress, respectively. This load level is the lowest at which the occurrence of any material yield was predicted.

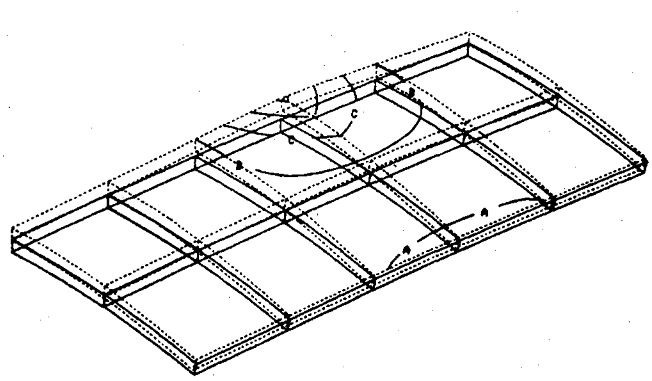

**Fig. 6 0.23 pinned model at 600 lb.**

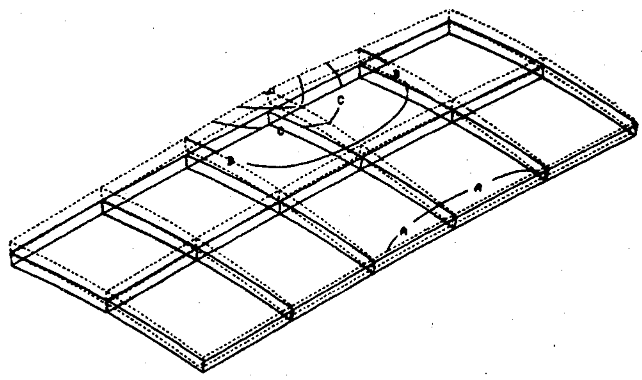

**Fig. 7 0.23 XZ model at 600 lb.**

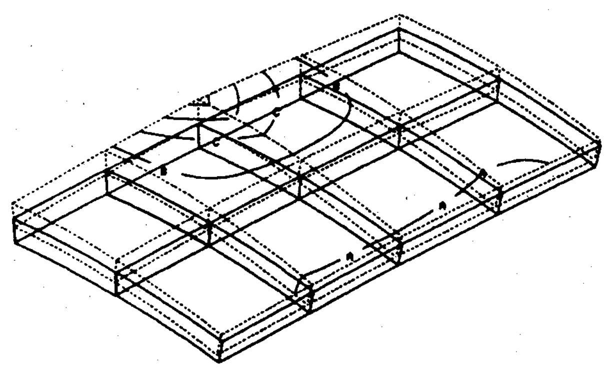

**Fig. 8 0.40 XZ model at 1000 lb.**

Figure 7 shows contours drawn for the same four levels of equivalent stress on the 0.23 XZ model. The load level is again 600 lb. Figure 8 shows the same results for the 0.40 XZ (polycarbonate) model (but for only eight elements) at a load level of 1000 lb and Fig. 9 illustrates results for the 0.68 XZ (stretched acrylic) model at a load level of 2300 lb. As noted earlier, the (Piola-Kirchhoff) yield stress for the stretched acrylic material was taken to be 9808 psi and for the polycarbonate material 9352 psi.

The values of static load corresponding to Figs. 6-9 were taken to represent the "failure" load for the 0.23 Pinned, 0.23 XZ, 0.40 XZ, and 0.68 XZ models, respectively. These loads were conservative and represent a lower bound for the actual failure load for two reasons. The first reason is that

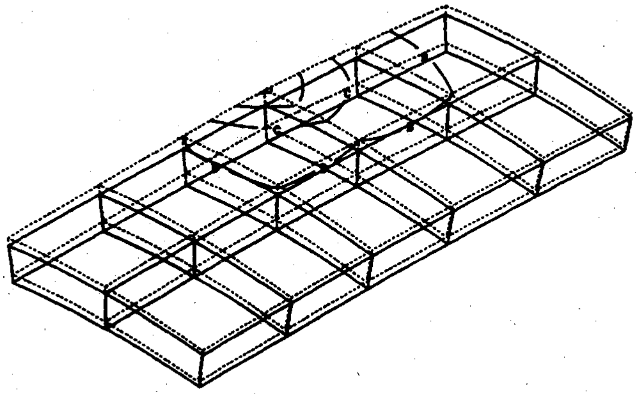

**Fig. 9 0.68 XZ model at 2300 lb.**

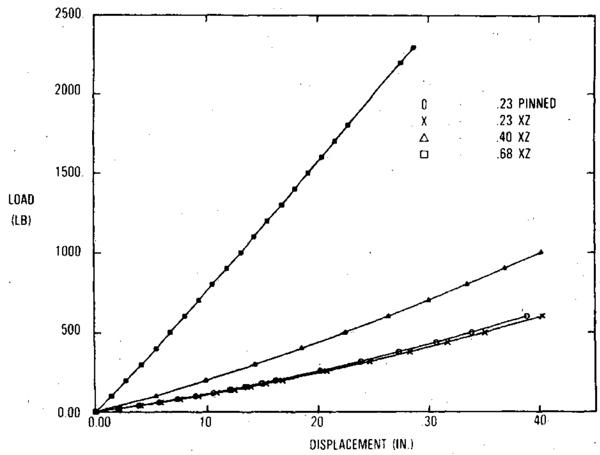


**Fig. 10 Load vs vertical displacement curves.**

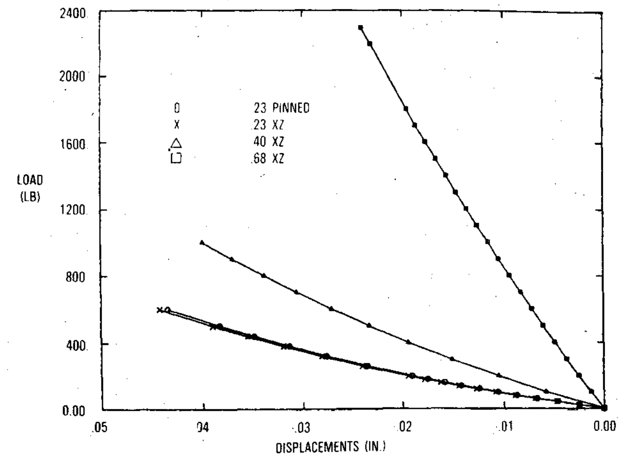


**Fig. 11 Load vs longitudinal displacement curves.**

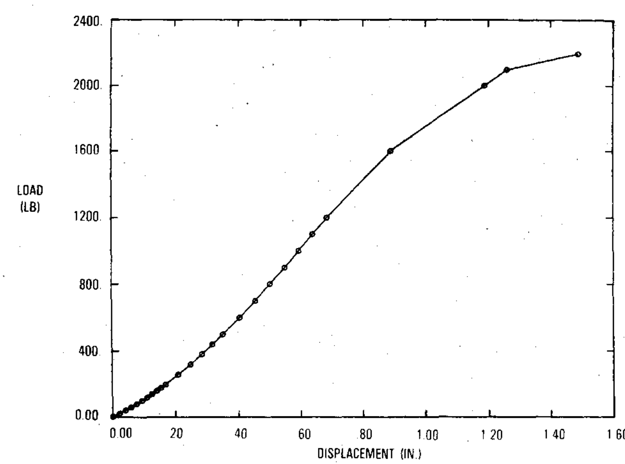


**Fig. 12 Load vs vertical displacement for 0.23 pinned model.**

both of the subject plastic materials normally withstand strains in excess of those corresponding to first yield in laboratory bending tests conducted with rounded load applicators. Since the canopy breaker used for the T-38 student canopy is not sharp but slightly rounded, load levels in excess of those noted above could probably be withstood by each of the respective canopy designs. The second and more significant reason for these loads being conservative is that results obtained from a finite-element solution at the point of application of a concentrated load are in general not valid. Unrealistically high values of stress and strain may be calculated at the point of load application. More realistic states of stress and strain are calculated at regions removed from the point of load application by some distance which includes at least a few integration points in the finite-element model.

**Load-Displacement Plots**

One objective of these studies was to predict the relative values of static load required to fail the canopy designs considered. Another was to define relative values of work required to produce failure. Load-displacement histories were required in order to calculate work and Fig. 10 illustrates these for vertical displacement at the point of load application.

The curves for the 0.23 Pinned and 0.23 XZ models are very similar with the behavior of the 0.23 Pinned model being only slightly more stiff than that of the 0.23 XZ model. The 0.40 XZ results are stiffer than the 0.23 model results but the respective displacements at failure are nearly the same. This is due to the yield strain for polycarbonate being greater than that for the stretched acrylic material. The behavior of the 0.68 XZ model is seen to be the most stiff of all with the displacement at failure for this design being considerably less than that for the others.

Figure 11 shows curves for longitudinal displacement at the point of load application. The same trends as those observed for vertical displacement can be observed. The negative (forward) values of displacement are noteworthy because the longitudinal component of the load was positive (aft) in all cases. The reason for the longitudinal components of displacement being of opposite sign from the longitudinal components of load is that the primary response of the canopy is in bending (out-of-plane motion and not in-plane). This means that displacements normal to the surface are very much greater than those parallel to the surface. Since the canopy surface slopes slightly toward the nose of the aircraft at the point of load application, these primary out-of-plane displacements have negative (forward) longitudinal components.

All the load-displacement curves shown in Figs. 10 and 11 exhibit stiffening behavior. This reflects the fact that the initial response of the canopy is primarily in bending but that at larger deflections, in-plane loading becomes more and more significant. The effect of this is increasing stiffness in the overall response. The effect is most pronounced for the most compliant of the three structures—the 0.23 in. thick stretched acrylic canopy.

Since little confidence had been established in being able to predict actual failure loads from the results of these analyses, and since a rationale had been developed as discussed earlier to define reasonable lower bounds for failure loads, an attempt was also made to establish reasonable upper bounds. This was accomplished by running the solution for the 0.23 Pinned model out to load levels higher than that corresponding to first yield. Figure 12 shows the results obtained. Above 1600 lb the response is dominated by local plasticity in an area near the point of load application. After

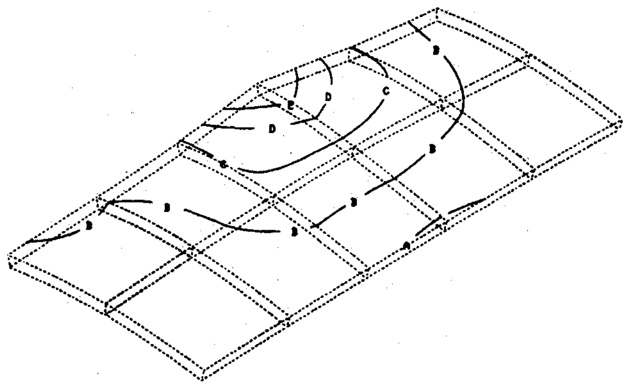

Fig. 13 0.23 pinned model at 1600 lb.

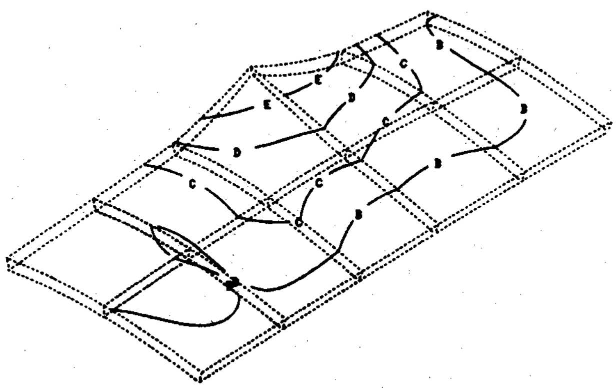

Fig. 14 0.23 pinned model at 2200 lb.

plasticity has propagated all of the way through the thickness of the part, the area near the point of load application begins to exhibit very large plastic strains, resulting in a softening of the overall response. Figures 13 and 14 are plots of deformed geometry which illustrate the localized nature of the plastic behavior which was predicted. The contours shown again illustrate 25, 50, 75, and 100% of the (Piola-Kirchhoff) yield stress for the stretched acrylic material.

It is felt that this grossly plastic behavior would never actually be observed before canopy failure occurred should static loading tests using the T-38 canopy breaker ever be conducted. For this reason, 1600 lb was taken to be the upper bound of failure load for the 0.23 in. thick stretched acrylic design. A similar upper bound was estimated for the 0.68 in. thick stretched acrylic design by assuming the same ratio of upper and lower bounds as those adopted for the 0.23 in. thick part. The failure load upper bound thus obtained for the 0.68 in. thick part was 6133 lb. No attempt was made to estimate a failure load upper bound for the 0.40 in. thick polycarbonate design due to the capability of polycarbonate to sustain large plastic strains without rupturing and the inability to properly account for the strong strain-softening behavior of polycarbonate when using the finite-element method (Fig. 4).

#### Work to Canopy Failure

The work done by the rocket catapult on each of the aircraft canopy designs was taken to be the area under each of the respective curves shown in Figs. 10 and 11. Work was calculated by making piecewise linear fits to each of the load-displacement curves out to the respective (lower bound) fracture loads. The scalar (dot) product for vertical components of load and displacement was positive while that for longitudinal components was negative in every case for reasons discussed earlier.

Work to failure using lower bound failure loads for the 0.23 Pinned and XZ models was about 240 in.·lb, for the 0.40 XZ (polycarbonate) model was 400 in.·lb., and for the 0.68 XZ (stretched acrylic) model was about 650 in.·lb. Work to failure was about 1.7 times higher for the polycarbonate design than for the current design and about 2.5 times higher for the new stretched acrylic design than for the current design. Work to failure using upper bound failure loads was about 1500 in.·lb for the 0.23 Pinned and XZ models and 4000 in.·lb for the 0.68 XZ model.

Regardless of the conditions at which a stretched acrylic canopy would actually fail, it is felt that about 2.5 times as much work would be required to fail a bird-resistant 0.68 in. thick canopy as that required to fail the current design. Because of the ability of polycarbonate to sustain much greater plastic strains than stretched acrylic, it is felt that more than 1.7 times as much work would be required to fail a 0.40 in. thick polycarbonate canopy as that required to fail the current design. The work required to fail the polycarbonate canopy would probably not exceed significantly the work required to fail the bird-resistant stretched acrylic design because both have been designed to withstand the same bird impact conditions.

## Conclusions

#### Boundary Conditions

The utilization of simplistic boundary conditions in the studies reported here had an insignificant effect on the results obtained. The principal action in the structure was confined to an area near the point of load application. There is no need to treat boundary conditions in a complex manner in other similar studies.

#### Ejection Seat Performance

During ejection from the T-38 aircraft under nominal conditions, catapult thrust increases in a nearly linear fashion from 0 to approximately 5000 lb. Since the stroke of the catapult is about 2 ft, the work done on the seat/man mass is between 5000 and 10,000 ft·lb. A second approximation to the work done by the catapult comes from equating it to the kinetic energy of the seat/man at the time of catapult strip-off. Typical velocity for a 400 lb seat/man at catapult strip-off is 40 ft/s corresponding again to about 10,000 ft·lb of energy (work).[15]

Based on the criteria adopted for canopy failure in these studies, between 20 and 120 ft·lb of work would be required from the catapult to penetrate the current student pilot canopy. This means that not more than about 1% of the catapult work under nominal conditions would be absorbed in canopy penetration during backup emergency escape. For the 0.68 in. thick stretched acrylic design, between 50 and 300 ft·lb of work would be required to penetrate the student pilot canopy; i.e., not more than 3% of the catapult work under nominal conditions would be absorbed in canopy penetration.

Based on these results, no significant ejection seat performance degradation as a result of the work required to penetrate the canopy would be expected at the time of catapult strip-off if a 0.68 in. thick stretched acrylic canopy were retrofitted on the T-38 aircraft. The same conclusion is certainly true for a 0.40 in. thick polycarbonate canopy even though the work required to penetrate it is even more uncertain than is that required to penetrate an acrylic canopy.

#### Catapult Thrust at Canopy Failure

It has already been mentioned that under nominal ejection conditions, catapult thrust can exceed 5000 lb. If the static load required to fracture the current canopy lies between 600 and 1600 lb and the seat/man weighs 400 lb, the catapult need not develop more than 2000 lb in straight-and-level flight to fail the canopy—well within its capability. But for the 0.68 in. stretched acrylic canopy with failure load predicted to lie between 2300 and 6300 lb, the situation is entirely different. Even in straight-and-level flight, the thrust required of the catapult to fail the canopy is predicted to be 50-120% of its 5500 lb design thrust. Even though the performance of the ejection seat could remain nearly nominal as discussed earlier if canopy failure did occur, it seems as though it might not be possible to fail the 0.68 in. thick stretched acrylic canopy without encountering dangerously high catapult chamber pressures and inviting catapult explosion. This danger might not present itself for a 0.40 in. thick polycarbonate canopy because of the lower loads involved.

**Biodynamics of the Ejecting Crew Member**

Through-the-canopy escape might not be feasible for a bird-resistant student pilot canopy due to complex dynamics in the body of the ejecting crew member. The body of the ejectee might experience transient acceleration as the ejection seat begins to move up its guide rails, followed by deceleration to nearly zero velocity as the load required to fail the canopy builds up. At the time of canopy fracture, the ejectee might experience an almost instantaneously applied acceleration as the canopy reaction of up to 6000 lb is suddenly removed.

**Through-the-Canopy Feasibility**

Based upon the results of this study, backup through-the-canopy escape via canopy breaker impingement on the student canopy of the T-38 aircraft is not recommended in conjunction with the new 0.68 in. thick bird-resistant stretched acrylic canopy design proposed.[1] The load required to fail this canopy design may approach or even exceed the design thrust of the rocket catapult used on the seat. Even if failure of this bird-resistant canopy via canopy breaker impingement is shown to be possible, the biodynamic response of the body of the student pilot to the resulting complex history of acceleration may be unacceptable. Both of these problems would appear to be less significant for the 0.40 in. thick polycarbonate canopy design which has also been proposed due to the lower failure loads involved.

If backup through-the-canopy emergency escape is pursued in conjunction with the development of either one of these bird-resistant canopy designs, attention should be paid to both of the considerations mentioned above: high catapult pressures and adverse biodynamic response.

## References

[1] West, B.S. and Clayton, K.I., "Alternate T-38 Transparency Development Part I Initial Analysis and Design," AFWAL-TR-80-3132, Pt. I, Nov. 1980.

[2] Brockman, R.A., "MAGNA: A Finite Element Program for the Materially and Geometrically Nonlinear Analysis of Three-Dimensional Structures Subjected to Static and Transient Loading," AFWAL-TR-80-3152, March 1981.

[3] Brockman, R.A., "A Preprocessor System for Finite Element Structural Analysis," University of Dayton Research Institute, Dayton, Ohio, Rept. UDR-TR-80-117, Nov. 1980.

[4] Brockman, R.A., "Structural Analysis Postprocessing Utilities," AFWAL-TR-80-3151, Jan. 1981.

[5] McCarty, R.E. and Venkayya, V., "Analysis of Bird Impact on Port Wing," Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio, Letter report, Aug. 24, 1979.

[6] McCarty, R.E., "Computer Analysis of Bird Resistant Aircraft Transparencies," *Proceedings of the 17th Annual SAFE Symposium*, Dec. 1979, pp. 93-97.

[7] McCarty, R.E., "Finite Element Analysis of F-16 Aircraft Canopy Dynamic Response to Bird Impact Loading," *Proceedings of the 21st AIAA/ASME/ASCE/AHS Structures, Structural Dynamics, and Materials Conference*, Seattle, May 1980, pp. 841-852.

[8] McCarty, R.E., "Aircraft Transparency Bird Impact Analysis Using the MAGNA Computer Program," Paper presented at Conference on Aerospace Transparencies, Society of British Aerospace Companies, London, Sept. 1980.

[9] McCarty, R.E., "Finite Element Analysis of a Bird-Resistant Monolithic Stretched Acrylic Canopy Design for the F-16 Aircraft," AIAA Paper 81-1640, Aug. 1981.

[10] Northrop Corp., Aircraft Group, Hawthorne, Calif., Northrop Drawing 2-13005.

[11] Northrop Corp., Aircraft Group, Hawthorne, Calif., Northrop Rept. 57-84, Lofting Data, Feb. 1958.

[12] *Military Standardization Handbook—Plastics for Aerospace Vehicles, Part II Transparent Glazing Materials*, MIL-HDBK-17A, Pt. II, June 8, 1977.

[13] Greene, F.E., "Testing for Mechanical Properties of Monolithic and Laminated Polycarbonate Materials, Part I, Test Results and Analysis," AFFDL-TR-77-96, Pt. I, Oct. 1978.

[14] "Typical Physical Properties of Swedlow Stretched Acrylic (MIL-P-25690) Sheet-Swedlow Type 350S," Swedlow Inc., Transportation Products Div., Garden Grove, Calif., Engineering Bull. MP-3-100, April 4, 1973.

[15] Peters, J.M., AFWAL/FIER, Wright-Patterson Air Force Base, Ohio, personal communication, Dec. 9, 1981.