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Damaged Stiffened Shell Research at NASA Langley Research Center

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Introduction

The structural behavior of stiffened fuselage shells with local cracks is influenced by the local deformations and stress gradients near the cracks, and this behavior must be understood to predict fuselage structural integrity and residual strength. As a crack grows, the stiffness and internal load distributions in a stiffened shell change, affecting the local deformations and stress gradients near the crack. Transport fuselage shells are designed to support internal pressure and mechanical loads which cause a geometrically nonlinear response. Research is being conducted at NASA Langley Research Center to develop and demonstrate a verified nonlinear stiffened shell analysis methodology for accurately predicting the global and local behavior of nonlinear stiffened fuselage shells with local cracks and with combined internal pressure and mechanical loads. The nonlinear structural analysis methodology being developed and planned at NASA Langley Research Center for damaged stiffened fuselage shells and the experiments being planned to verify this analysis methodology are summarized in the present paper.

Analysis and Modeling

The nonlinear stiffened shell analysis methodology being developed for damaged stiffened fuselage shells includes developing analytical methods, developing a hierarchical structural modeling strategy, and conducting analytical studies of stiffened shells with cracks. The analytical methods development effort includes adding crack growth and residual strength analysis capabilities to the STAGS analysis code (ref. 1) for nonlinear structural analysis of general shells. The stiffened shell hierarchical structural modeling strategy is a global-local modeling strategy that provides sufficient modeling details to predict accurately the global nonlinear response of the shell and the local stress and displacement gradients that occur in stiffened shells with cracks. The analytical studies include detailed nonlinear analyses of stiffened shells with cracks and with combined internal pressure and mechanical loads. The analytical studies also include parametric studies to determine the effects of varying structural and crack parameters and loading conditions on the behavior of stiffened shells with cracks.

The STAGS shell analysis code was originally developed to analyze the geometrically nonlinear response of shells with general geometries, boundary conditions and loading conditions. The code can be used to conduct strength, stability and collapse analyses of general shells with discontinuities such as a cutout in the shell wall. STAGS is a finite element analysis code that uses Newton's method for a nonlinear solution algorithm. Large rotations are included in the nonlinear solution by a co-rotational algorithm applied at the element level. The Riks arc-length projection method is used to integrate the nonlinear solution past limit points in the nonlinear solution. A crack propagation analysis capability is being added to STAGS for both self-similar and non-self-similar cracks. A load-relaxation capability has been developed to maintain equilibrium in a nonlinear state as a crack propagates in the model and causes the internal load distribution to change. An adaptive mesh refinement capability is being added to STAGS to provide the necessary modeling capability near a crack tip to represent accurately the stress and displacement gradients associated with a propagating straight or curved crack.

The modeling strategy being developed for the nonlinear analysis of stiffened shells with damage is a hierarchical modeling strategy that is intended to represent the important global and local features of the shell structure. Five hierarchical modeling levels are being evaluated to determine the modeling fidelity required to represent properly all important features of a stiffened shell without generating unnecessarily large models and unnecessarily expensive computational demands. These hierarchical modeling levels range from a relatively coarse global shell model for determining the internal load distribution and global response of the shell to a highly refined local detailed stress analysis model for determining crack growth characteristics from fracture mechanics principles. These hierarchical modeling levels are represented in figure 1. At each level, the results from the analysis of a more global model are used to define the boundaries of a more local detailed model which is more highly refined than the global model. The boundary conditions for each successive local model are kinematic constraints that are based on the results of the analysis of the more global model. The global shell model is used to determine the global behavior of the shell with one or more cracks and with internal pressure p and mechanical loads that represent a bending moment M, a vertical shear load V, and a torsional load T applied to the shell. A nonlinear analysis of the global shell model provides the internal load distribution for the shell and identifies an interior local region that contains all the gradients associated with the crack. The boundary of this interior region is used to define the boundary of the stiffened panel model which is modeled in more detail than the coarser global shell model. The stiffened panel model is used to determine more accurately the interaction between the skin, frames and stiffeners as a crack propagates in the shell. The stress resultants N_x, N_θ, and $N_{x\theta}$, stiffener forces P_F and P_s, and boundary displacements and slopes are consistent with the global shell model results. The results from the stiffened panel model are used to define the local panel detailed model which is used to determine the interaction of a crack and a structural detail such as a lap splice. The results from the local panel detailed model are used to define a global-local panel model which is used to determine the detailed stress and deflection gradients near a crack. These gradients are used in the local detailed stress analysis model to determine crack growth behavior from a fracture mechanics analysis. The results of the crack growth analysis at the local detailed stress analysis model level are used to redefine the crack length and shape in the global shell model. The analyses at all hierarchical levels are repeated iteratively until the crack growth history and shell residual strength are determined. The attenuation lengths of all gradients are examined after each analysis to make sure that the model boundaries are far enough away from any gradient to avoid any boundary interaction effects. If a crack grows enough for its gradients to interact with a boundary, the appropriate local model is enlarged enough to prevent the interaction from occurring.

This hierarchical modeling strategy makes it possible to determine the detailed nonlinear response of a large stiffened shell model with cracks and with combined internal pressure and mechanical loads. The global response and local response phenomena such as local instabilities, modal interaction and stiffener distortion and rolling can be determined. The effects of crack propagation on the nonlinear shell response can also be determined. The changes in the local stiffnesses and internal load distribution in the shell can be determined as the crack grows. The coupling between inplane and out-of-plane deflection gradients and internal forces and moments are accurately represented in the nonlinear analysis and changes in crack growth direction can be determined.

The hierarchical modeling strategy also makes it possible to determine the effects of changing global and local shell model parameters on nonlinear response, crack growth characteristics and residual strength. The modeling strategy allows the effects of varying shell parameters such as shell radius, skin thickness, frame spacing and stringer spacing to be studied. Structural detail parameters such as frame and stringer geometries, joints, splices, repairs, failsafe straps and clips can also be modeled and studied. Different combinations of internal pressure and mechanical loads can also be studied. Skin crack location, length, orientation and propagation direction can be studied as well as broken frames and stringers. The interaction between skin, frame and stringer as a crack propagates can also be determined.

Analytical Results

A limited number of analytical results have been generated to determine the modeling and analysis requirements for a stiffened shell segment representative of a generic narrow-body transport fuselage. The shell model is 240 inches long and has a 74 inch radius, a 0.036 inch skin thickness, a 20 inch frame spacing and a 9.3 inch stringer spacing. The shell is made of aluminum and has flat end caps and floor beams.

Linear and nonlinear analyses were conducted with a global shell model without a crack to determine the differences in shell response up to 8 psi of internal pressure. The stress distribution and local bending in the skin at the skin-frame intersections are different for the two analyses indicating the influence of nonlinear behavior on the results. The hoop stress resultant distribution for these analyses are shown in figure 2. Nonlinear analyses were also conducted for global shell models having a 20-inch-long skin crack, with and without a broken frame at the center of the crack, to determine the shell response up to 8 psi of internal pressure. The crack is located near a stringer at the fuselage crown and is bisected by the frame. The hoop stress resultant distribution for these analyses is shown in figure 3. The effects of the cracks on the hoop stress resultants can be determined by comparing the nonlinear results in figures 2 and 3. The differences in the hoop stress resultant distributions indicate the extent of the effects of the skin crack and broken frame. The hoop stress resultant gradients associated with the cracks extend over three frames, four skin bays between frames, and seven stringers. The radial displacement gradients in the skin near the 20-inch-long skin crack and broken frame are shown along the stringer and along the arclength of the broken frame in figures 4 and 5, respectively. The skin radial displacement is normalized by the skin thickness in the figures. The results for the damaged shell are represented by the solid line in each figure and the results for the undamaged shell are represented by the dashed line. The maximum values of the radial displacements shown in figure 4 occur at longitudinal stations on the model corresponding to locations indicated in the figure as the axial distances along the stiffener at x = 55 in. and x = 65 in. The radial displacement at the location corresponding to x = 60 in. is a lower value than the nearby maximum values because the broken frame at x = 60 in. is stiff enough to prevent a larger radial displacement at that location. The maximum value of the radial displacement shown in figure 5 occurs at a circumferential station on the model corresponding to a location just to the right of the location indicated in the figure as arclength along the frame at s = 70 in. The displacement at the location in the figure just to the left of s = 70 in. is smaller than the maximum displacement because the stringer is attached to the skin to the left of the crack and the stringer is stiff enough to prevent larger displacements for this part of the skin.

Comparisons of radial displacement and hoop stress resultant results from linear and nonlinear analyses of the fuselage shell with a 20-inch-long skin crack and a broken frame are shown in figures 6 and 7, respectively, for internal pressures up to 8 psi. The linear results are represented by the solid lines and the nonlinear results are represented by the dashed lines. The results for the shell without a crack are represented by the circles and the results for the shell with the crack are represented by the squares. The radial displacements in figure 6 are measured at the middle of the crack and are normalized by the skin thickness. These results indicate that the radial displacements in the shell without the crack are larger at this location for the nonlinear analysis than for the linear analysis. Also, the radial displacements in the shell with the crack are smaller at this location for the nonlinear analysis than for the linear analysis. The hoop stress resultants in figure 7 are for the finite element just ahead of the crack tip. These results indicate that the hoop stress resultant in the shell without the crack is larger at this location for the linear analysis than for the nonlinear analysis. Also, the hoop stress resultant in the shell with the crack is larger at this location for the nonlinear analysis than for the linear analysis. These differences in results indicate that the conventional view that a linear analysis is a conservative analysis for predicting the response of a nonlinear stiffened shell with internal pressure is not always appropriate. Nonlinear analyses are needed to provide accurate predictions of the behavior of such shells.

Radial displacement results from a nonlinear analysis of a stiffened panel model with internal pressure of 8 psi are shown in figure 8. The skin, frames and stiffeners are modeled with plate finite elements and the deformations of the skin and the frames are shown in the figure. The results of this stiffened panel analysis helped guide the development of a local panel detailed model of the skin bay between two stringers and two frames with a symmetric mid-bay skin crack. A refined finite element mesh was used for the model of the skin bay region where the crack is located. The undeformed model and the hoop and axial stress resultants from a nonlinear analysis of the skin bay without a crack are shown in figure 9 for 8 psi of internal pressure. The corresponding results for the skin bay with a 1-inch-long and a 2-inch-long mid-bay skin crack are shown in figure 10. The distribution of the hoop and axial stress resultants near the crack tip indicates large increases in stresses near the crack discontinuity. The mid-bay radial displacements for the skin without a crack and with 1-inch-long and 2-inch-long cracks are shown in figure 11. The circles represent the results for the skin without a crack and the triangles and squares represent the skin with the 1-inch-long and 2-inch-long cracks, respectively. These results indicate that increasing the crack length from 1 inch to 2 inches causes a significant growth in the radial displacements near the skin crack.

Planned Experimental Facilities

Experiments are planned at NASA Langley Research Center to verify the structural analysis methodology being developed and to identify critical behavioral characteristics that must be understood. The experiments will be conducted on curved stiffened panels and stiffened shells representative of current transport aircraft fuselage structures. The planned experimental program will include specimens that will be subjected to combinations of internal pressure and mechanical loads and different damage conditions.

Two types of test fixtures are being developed for the NASA Langley Research Center structural test program and these test fixtures are shown schematically in figure 12. A pressure box fixture will be used to test curved stiffened panels that are subjected to internal pressure and biaxial hoop and axial loads. Hoop stress resultants N_θ and frame forces P_F will be generated as reactions to the applied internal pressure p. Axial stress resultants N_x and stringer forces P_s will be generated by hydraulic jacks. A closed-cell combined-load test fixture will be used to test curved stiffened panels and stiffened shells that require internal pressure, bending M, and torsion T loads. This fixture will allow hoop and axial stress resultants and shear stress resultants $N_{x\theta}$ to be applied to the specimen as well as internal pressure. Hydraulic jacks will be used to generate the mechanical loads for the combined-load test fixture.

Test Results

A NASA-owned 737 transport fuselage was instrumented and pressurized to 6 psi internal pressure to determine the strains and radial displacements near a longitudinal lap joint in the fuselage skin. The results of this test are presented in reference 2 and the radial displacements of the skin along the circumference midway between a frame and a tear strap are shown in figure 13. Eleven differential voltage displacement transducers were used to make these measurements. The results in figure 13 show the radial displacements in two skin bays located between three adjacent stringers. The stringers are 9.5 inches apart and the lap joint is at the middle stringer. The results indicate that relatively large displacements occur in the skin between these stringers and noticeable bending gradients are present in the skin. The maximum relative displacement is on the order of the skin thickness which indicates that geometric nonlinearities should be included in the corresponding shell analysis.

Concluding Remarks

A verified structural analysis methodology for stiffened fuselage shells with damage is being developed at NASA Langley Research Center. This structural analysis methodology is intended to represent the nonlinear behavior of damaged stiffened shells with combined internal pressure and mechanical loads. Crack growth and residual strength analysis capabilities are being added to a nonlinear structural analysis code for general shell structures. A hierarchical global-local modeling strategy is being developed to represent accurately the nonlinear global response of a stiffened shell subjected to combined loads and the local stress and displacement gradients in shells with propagating cracks. Analytical studies of stiffened shells with cracks and with combined internal pressure and mechanical loads are being conducted to determine the effects of varying structural and crack parameters on the behavior of stiffened fuselage shells with damage. The structural analysis methodology will be verified by experiments on curved stiffened panels and stiffened shells subjected to internal pressure and mechanical loads. Tests and facilities are planned for investigating the behavior of stiffened panels and shells with damage and combinations of internal pressure, bending, and torsional loads that generate the inplane normal stress resultants and shear stress resultants representative of transport fuselage loading conditions.

References

1. Almroth, B. O.; and Brogan, F. A.: The STAGS Computer Code. NASA CR-2950, 1980.

2. Phillips, Edward P.; and Britt, Vicki O.: Measurements of Fuselage Skin Strains and Displacements Near a Longitudinal Lap Joint in a Pressurized Aircraft. NASA TM 104163, October 1991.

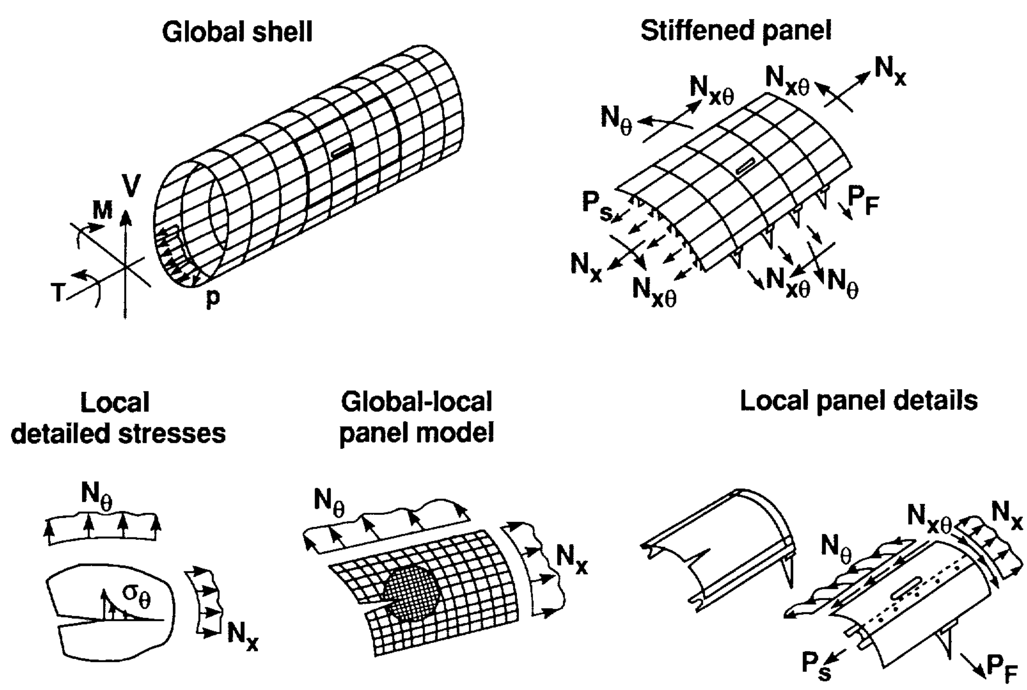

Figure 1. Hierarchical nonlinear stiffened shell models.

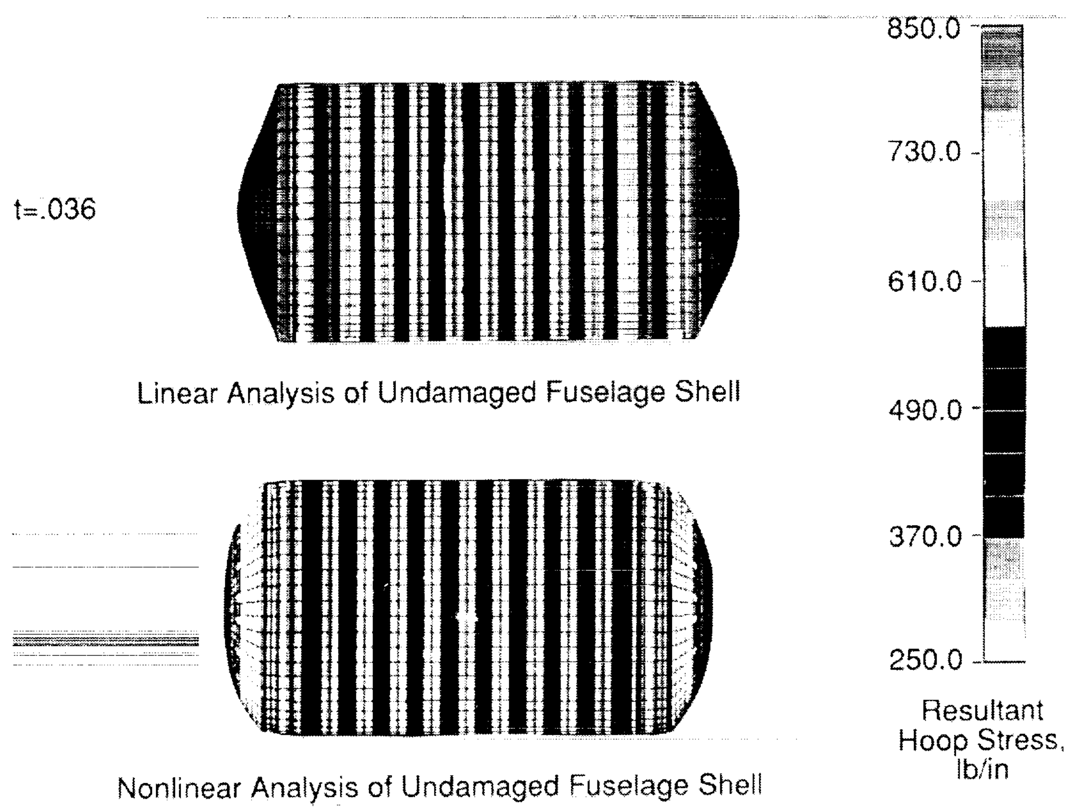

Figure 2. Hoop stress resultant distribution for a stiffened shell with 8 psi of internal pressure.

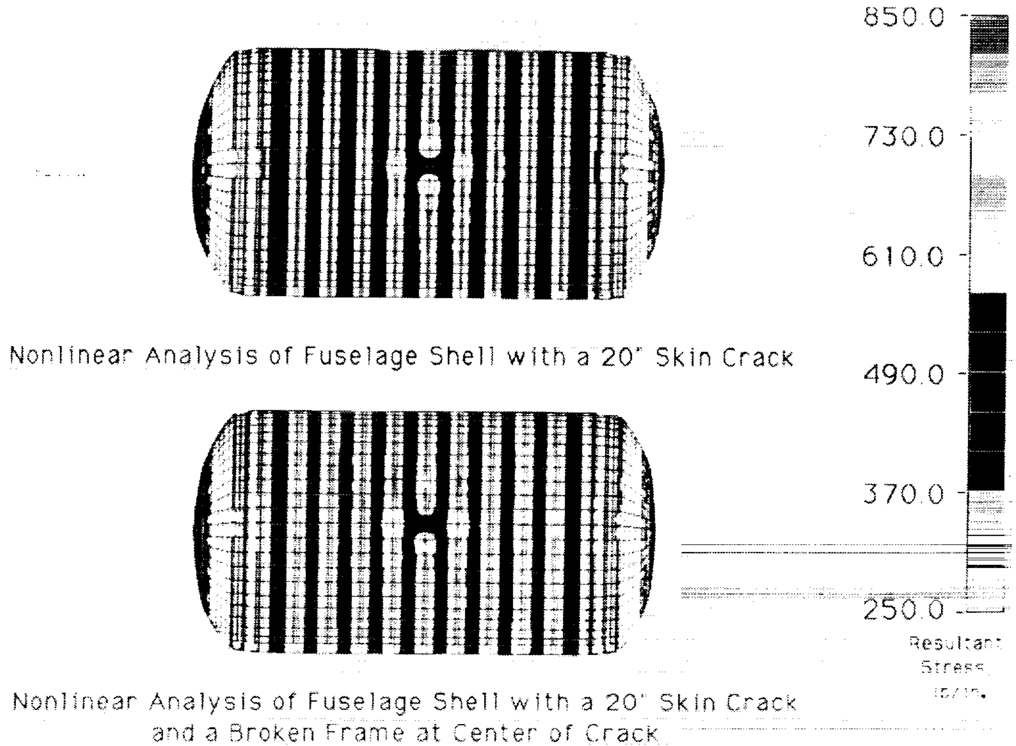

Figure 3. Hoop stress resultant distribution for a stiffened shell with 8 psi of internal pressure and a 20-inch-long longitudinal skin crack, with and without a broken frame.

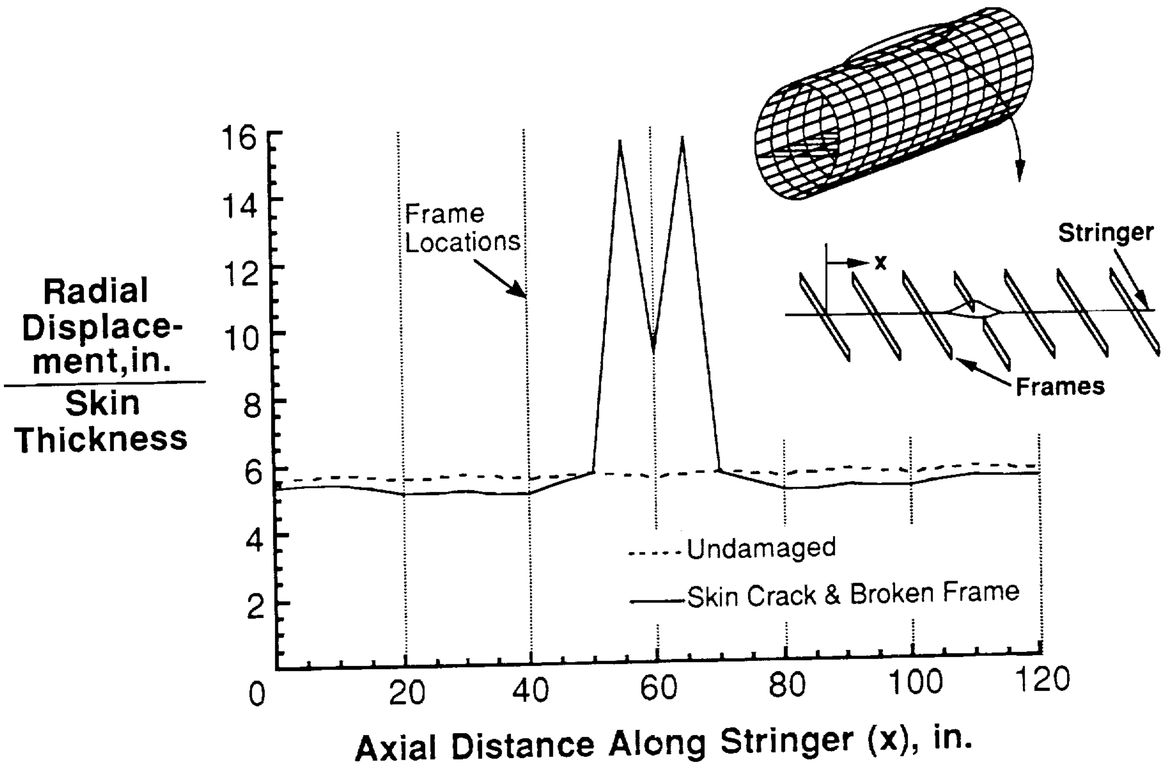

Figure 4. Radial displacements of the skin along a stringer near a skin crack and a broken frame in a stiffened fuselage shell structure. Results are from a nonlinear analysis with 8 psi of internal pressure.

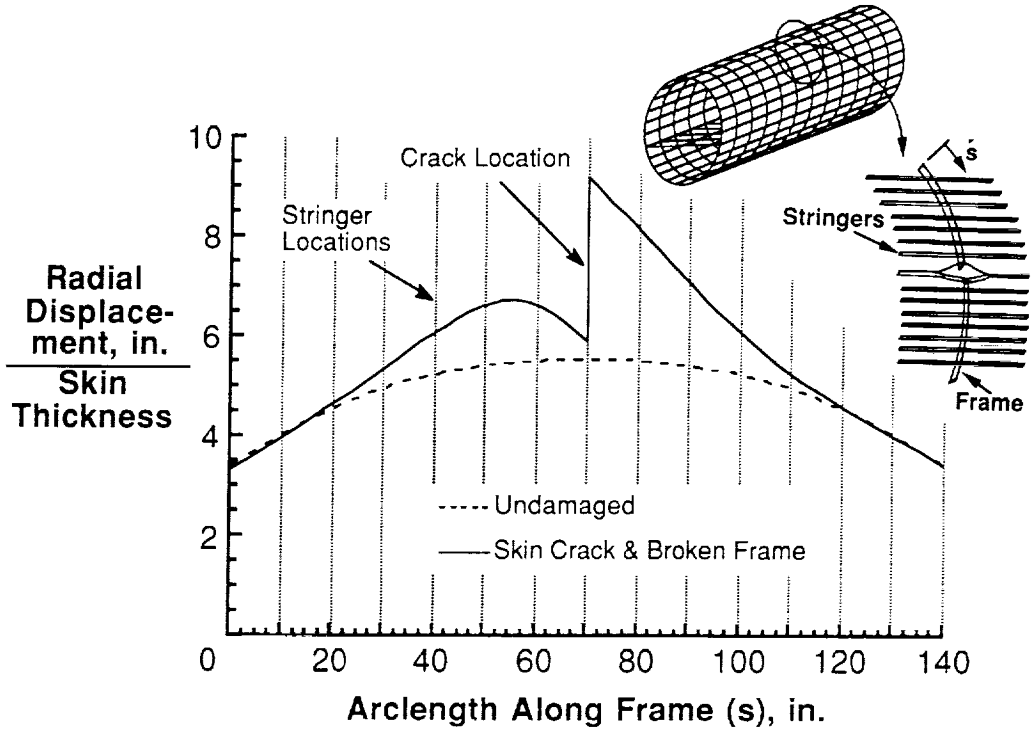

Figure 5. Radial displacements of the skin along a broken frame in a stiffened fuselage shell structure. Results are from a nonlinear analysis with 8 psi of internal pressure.

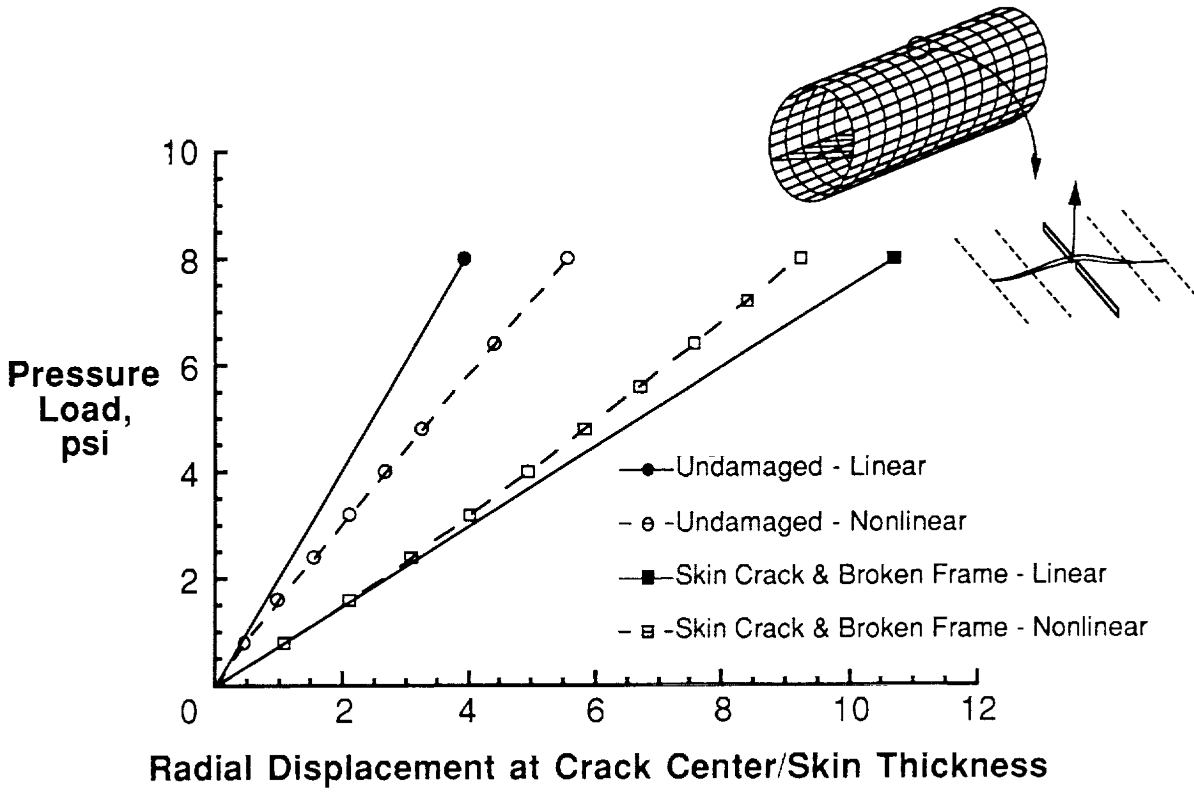

Figure 6. Effect of increasing internal pressure on the radial displacements of a fuselage skin at a frame.

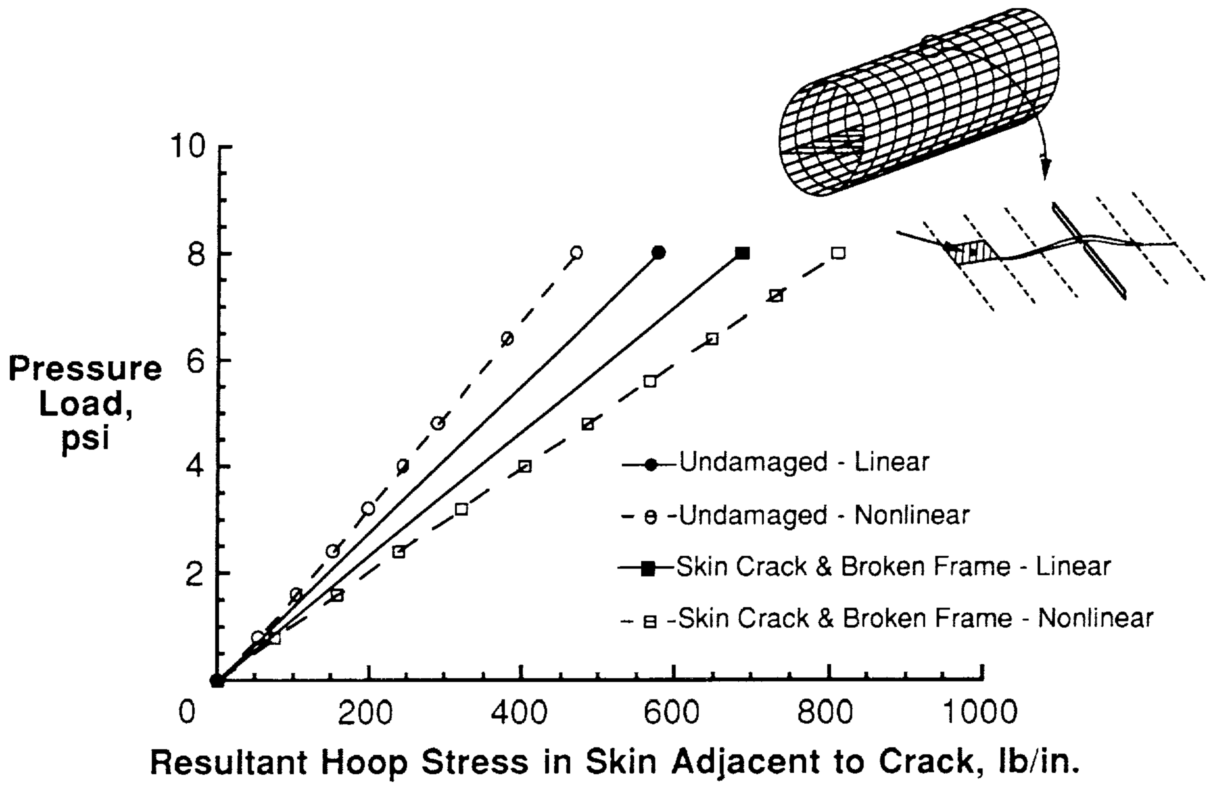

Figure 7. Effect of increasing internal pressure on the hoop stress resultant in a fuselage skin near a crack tip.

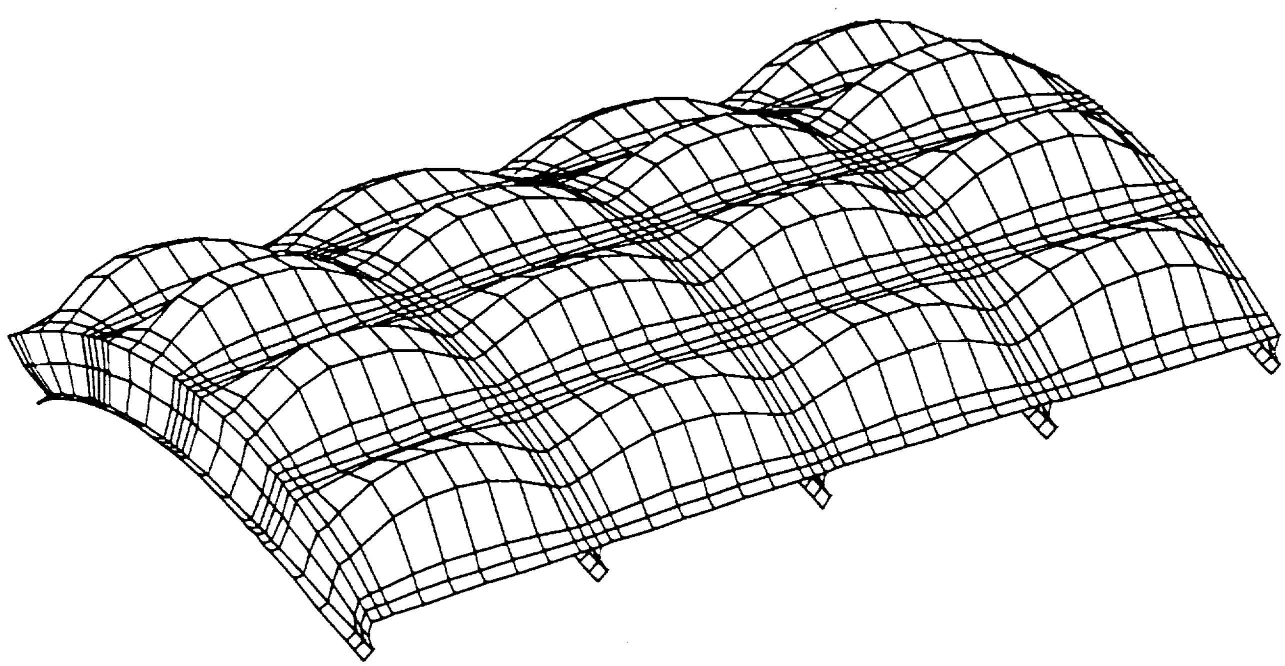

Figure 8. Radial displacements in a stiffened panel with 8 psi of internal pressure.

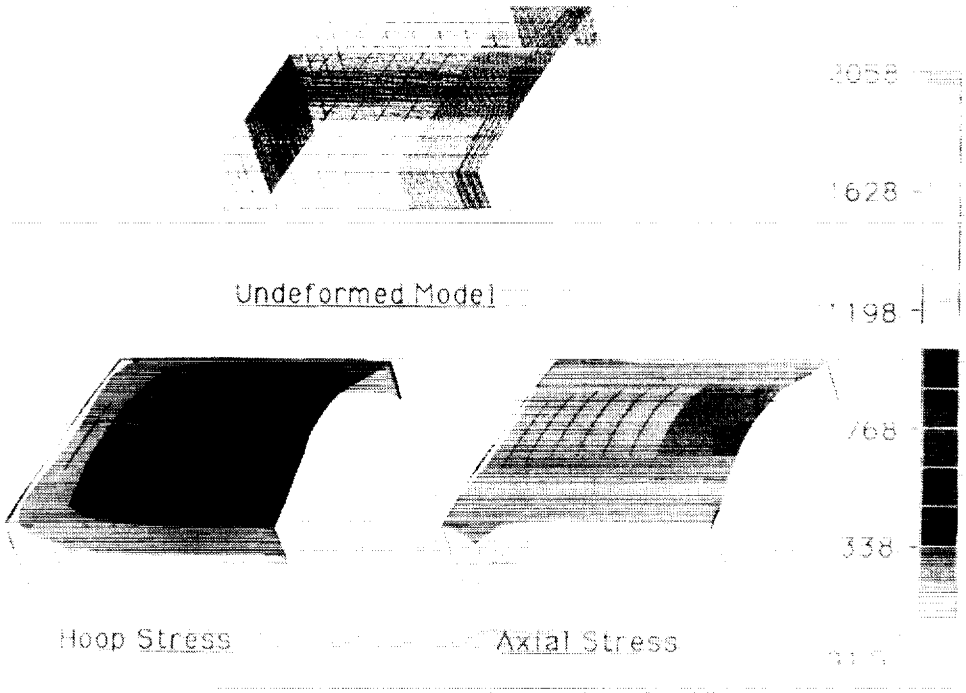

Figure 9. Undeformed model and hoop and axial stress resultants in an undamaged skin bay of a stiffened fuselage shell.

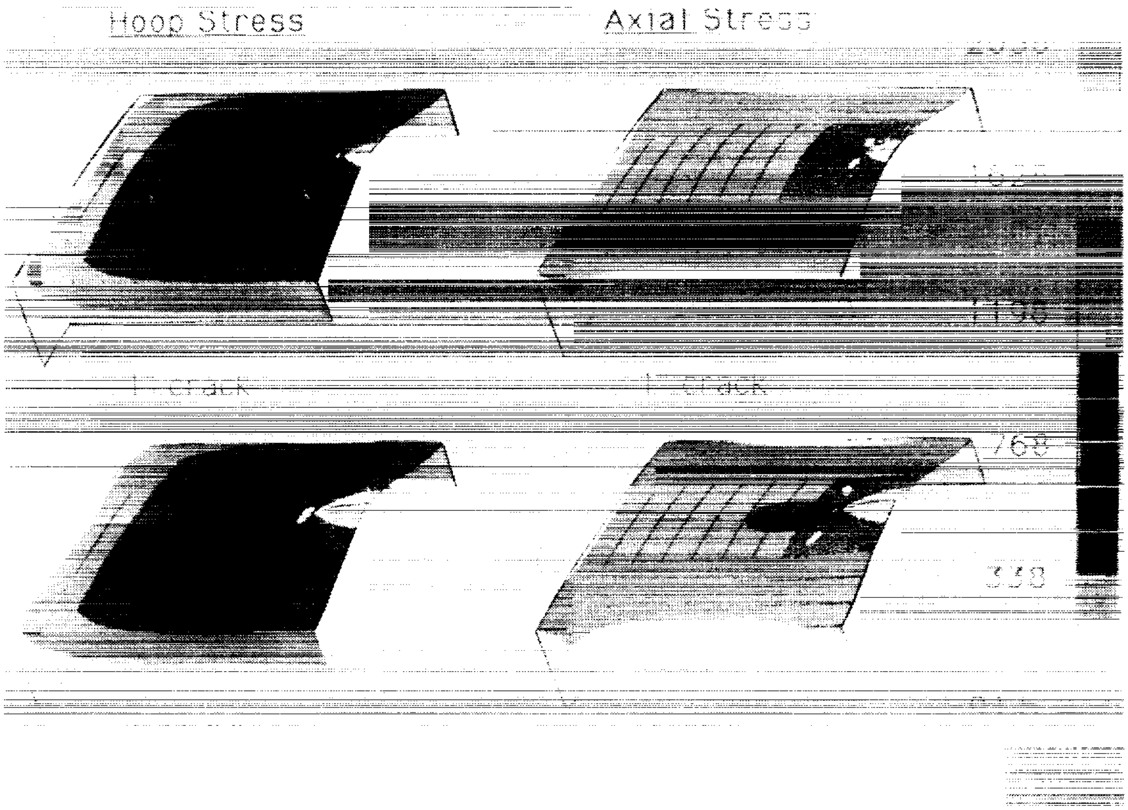

Figure 10. Effect of increasing crack length on the hoop and axial stress resultants in a skin bay of a fuselage shell with mid-bay skin cracks.

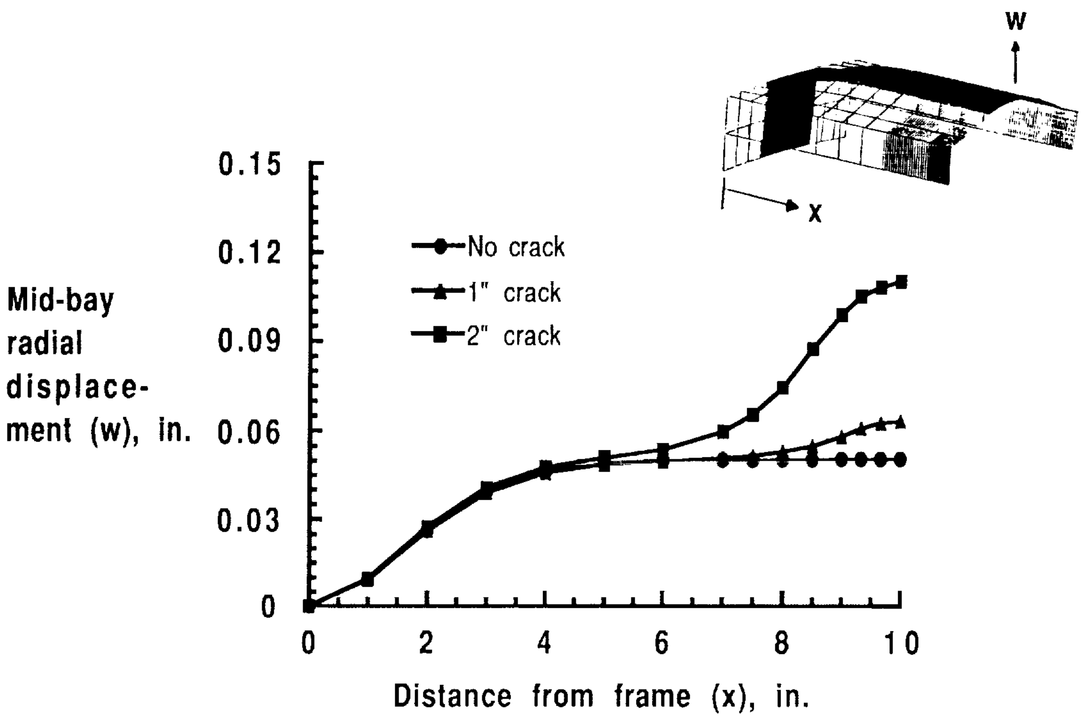

Figure 11. Longitudinal radial displacement distribution along the mid-bay of the skin of a stiffened fuselage shell with and without skin cracks.

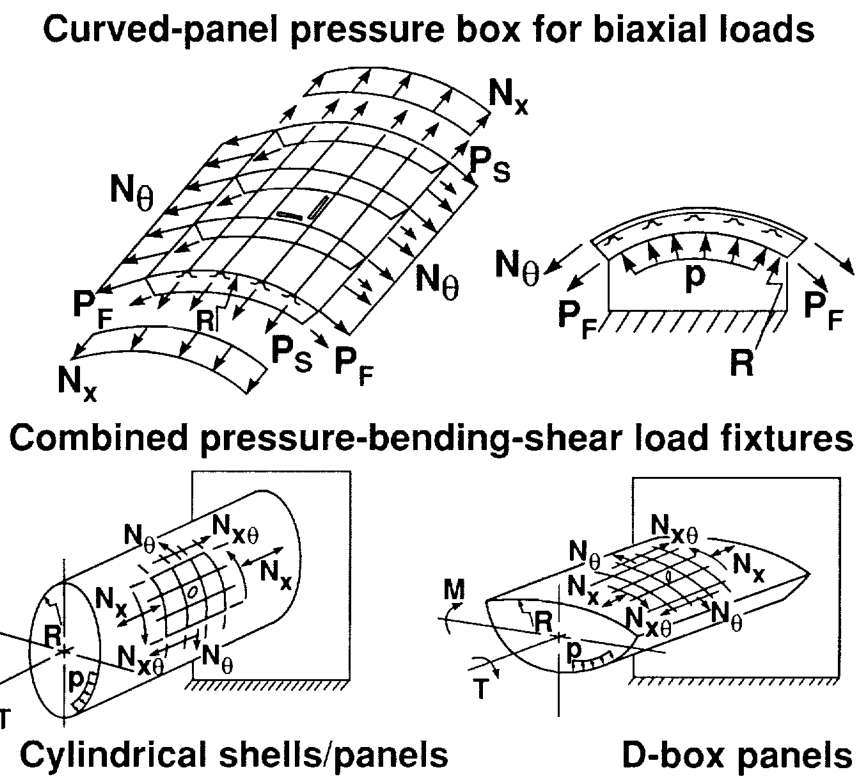

Figure 12. Curved stiffened panel and stiffened shell test fixtures.

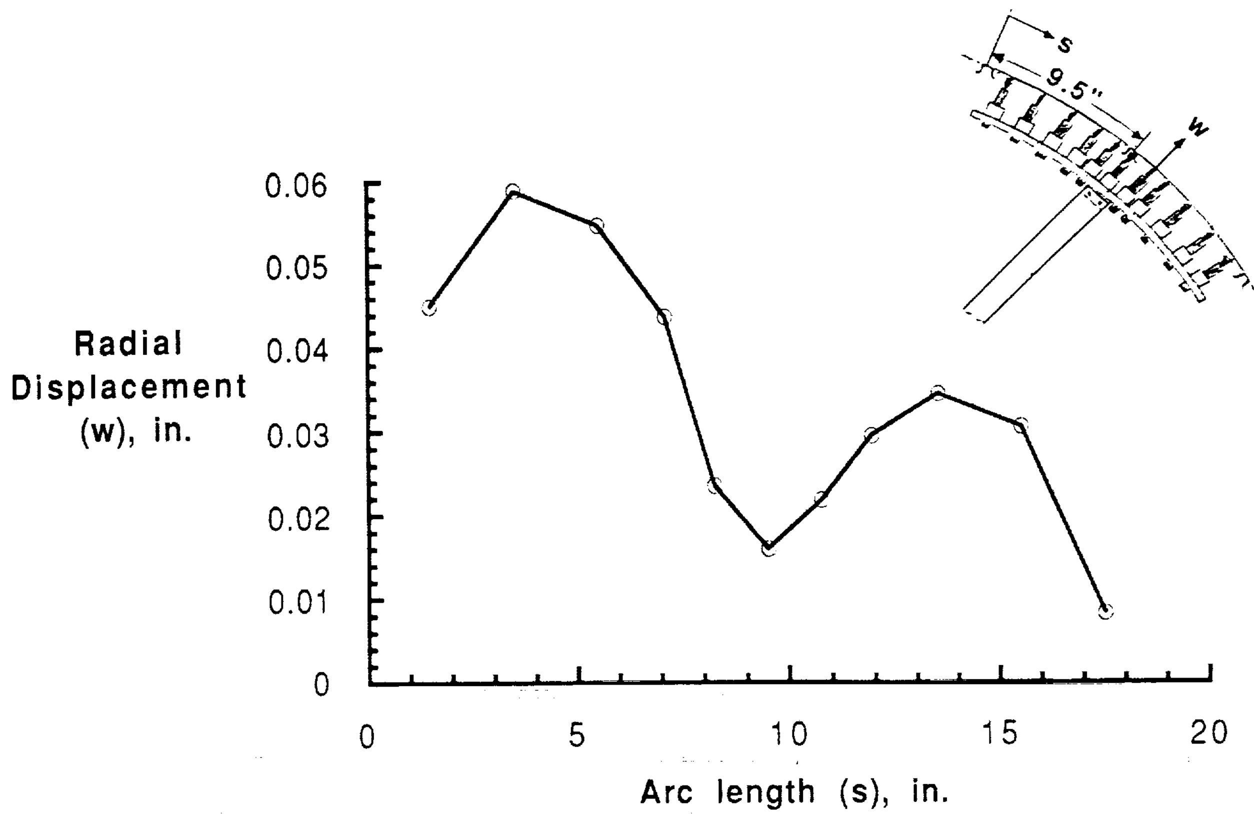

Figure 13. Measured radial displacement in the skin of a stiffened fuselage shell with a longitudinal lap splice and with 6 psi of internal pressure.