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TESTING AND ANALYSIS OF CURVED FRAME SPECIMENS MADE FROM A LONG DISCONTINUOUS FIBER (LDF) MATERIAL

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TESTING AND ANALYSIS OF CURVED FRAME SPECIMENS MADE FROM A LONG DISCONTINUOUS FIBER (LDF) MATERIAL

ABSTRACT

A long discontinuous fiber (LDF) material may be useful for constructing composite parts with complex curvature. Graphite-thermoplastic LDF curved frame specimens were studied to investigate the behavior of curved frame structures made from this material form. Experimental results for three curved frame specimens loaded in a four-point bending configuration and finite-element predictions of strains and displacements are presented.

INTRODUCTION

In the effort to develop a technology to enable the construction of transport fuselage structures with cost-effective composite materials, a material form involving long discontinuous fibers rather than the traditional long continuous fibers has been proposed (refs. 1-3). Graphite fibers in the form of long discontinuous fibers (LDF) within a thermoplastic resin offer advantages in forming curved parts such as frame structures. The advantage of using discontinuous fibers (fibers approximately two inches long) is that, as a flat panel is heated and curved to the desired shape during the manufacturing process, the fibers can slide by one another rather than being stretched or broken. This feature lends itself to the fabrication of structures with complex curvature which could not easily be made with traditional plies of tape with continuous fibers. In this process, any stacking sequence can be used and fiber orientation does not significantly change during the forming process. Flat panels made with discontinuous fibers have been shown to have strength and stiffness properties within 10 percent of those of panels made from continuous fibers (refs. 1 and 2).

A study to investigate the behavior of curved frame structures made from LDF material is presented herein. Experimental results for three curved frame specimens loaded in a four-point bending configuration and finite-element predictions of strains and displacements are presented.

TEST SPECIMENS

Curved frame specimens made from LDF material were manufactured by E. I. DuPont de Nemours Inc. under a subcontract to contract NAS1-189671. Three frames were supplied to NASA Langley Research Center where they were tested. A description of the stretch-forming fabrication process used to fabricate these frames is presented in references 2 and 3. Each specimen was manufactured with AS4 graphite fibers and PEKK thermoplastic resin. The geometry of the frame specimens is shown in figure 1. The curved frame specimens resemble a curved J-stiffener with a 2.7-inch high web, a .89-inch wide flange and a .49-inch wide cap. Each frame specimen had an outer radius of curvature of 40.5 inches and was approximately 16 inches long. Two specimens (identified as specimens A and B) had a laminate with stacking sequence of $[\pm45/0/90/0_2]_s$ and the third specimen (specimen C) had a laminate with a stacking sequence of $[\pm45/90/\pm45/0]_s$. The largest variation in thickness of the web occurred in specimens B. The thickness in this specimen varied from .056 to .062 inches. A photograph of the test specimens prior to instrumentation is shown in figure 2. Prior to testing, tabs were glued to the webs of the specimens at midheight and 1.5 inches from each end, and .5-inch diameter holes were drilled through the tabs and specimens so that pins could be inserted through the holes for support during testing. Strain gages were attached to the specimens in the pattern shown in figure 3.

APPARATUS AND PROCEDURE

Each specimen was loaded in four-point bending using the fixture shown in figure 4. The fixture minimized out-of-plane deformation (perpendicular to the plane of the web) at the support and load introduction locations. The supports were lined with teflon to allow the flange and cap of the frame to move inplane (in the direction of loading) without binding on a metal support. Load was applied at a rate of approximately 1200 lb/min through .5-inch-diameter rollers at two locations on the flange, as shown in figure 4. Strain gage data and deformations (measured by direct current differential transformers) were recorded during the test. Out-of-plane deformation measurements were recorded on the web at three corners (points B, C, and D in figure 3) and near the web-cap intersection at mid-length (point A in figure 3) for all three specimen. In addition, out-of-plane deformation measurements were recorded on the web near the web-flange intersection at mid-length (point E in figure 3) for frame B. The inplane deformation (motion of the rollers) was also measured. Each frame was loaded until audible and visible damage occurred and attempts to increase the applied load resulted in increased deformation but no increased load.

ANALYSIS

The STAGS computer code (ref. 4) was used to conduct a finite-element analysis to predict the strains and deformations of the curved frames during loading. Two frames (B and C) were analyzed since two different stacking sequences were used in the test specimens. The geometry of the two frames, except for web, flange and cap thicknesses, was assumed to be identical. Within each specimen, the entire cap was assumed to have one thickness, the web another, and the flange another. Assumed thicknesses for the web and flange were averages of measured values. A mesh of quadrilateral elements, with .25-inch-long sides, was used to model each part of the structure, as shown in figure 5.

An evenly distributed load totalling 1500 lb was applied. The load was applied over 15 nodes for each loading roller. Since the loading rollers were .5 inches in diameter, the load was applied over a width of .5 inches (3 nodes wide, as shown in the figure). Load was applied to the web and to the flange. In the following discussion, as well as in the figure, displacement u refers to the radial direction of the web, displacement v refers to the circumferential direction of the web and displacement w refers to the out-of-plane direction of the web. No w deformation was permitted at the end of the cap at the support for the pins. No u or w deformations were permitted at the center of the pins. No w deformation was permitted at the flanges at the load locations and no v deformation was permitted at a point at the center of the specimen. Restraint and load introduction locations are shown in figure 5. These restraints were chosen to agree with test conditions as closely as possible. Linear and nonlinear analyses were conducted for specimen B to verify that a linear analysis was adequate to predict deformations and strains. Deformations from linear and nonlinear analyses at a load of 1500 lb differed by less that 1 percent.

The effect of a variation in stiffness of up to 20 percent from the outer radius to the inner radius on the behavior of curved beams loaded in pure bending is considered in reference 3. That study concludes that for $D = (R_i+R_o)/2(R_o-R_i) > 10$, where R_o is the outer radius and R_i is the inner radius, variations in stiffness will not affect the performance of the beams. The beams tested in the present study have $D = 14.5$, so radial variations in stiffness were not considered in the present study.

In the present analysis, the assumption that the LDF material behaves in the same manner as continuous fiber material of the same stacking sequence and thickness is made. Selecting appropriate material properties is not straightforward since a range of values of material stiffness are reported in the literature (refs. 1 and 3). In addition, compressive and tensile modulii are not equal and the frame is subjected to both tensile and compressive stresses in the four-point-loading configuration. Material properties used in the analysis are as follows: longitudinal Young's modulus $E_L = 18$ Msi, transverse Young's modulus $E_t = 1.5$ Msi, shear modulus $G_{lt} = .87$ Msi and Poisson's ratio $\nu_{lt} = .35$. Because of the geometry and stacking sequences of the frames, removing coupons from the failed specimens and testing them in uniaxial loading to determine material properties was considered not to be a viable option.

RESULTS AND DISCUSSION

Experimental and analytical results are presented in this section. Analytical results are discussed for applied loads up to 1500 lb only since the test specimens experience local failures after that load level and the analysis cannot account for local failures.

The deformation δ (movement of the loading rollers) was measured as the load P was applied and this load-displacement relationship is shown in figure 6 for all three specimens. The load-displacement relationship is linear for all three specimens up to a load of at least 1600 lb. This load-displacement relationship is the same for all three specimens, even though specimen C has a different stacking sequence from the other two.

Measured strains and deformations in frame specimens A, B and C at a load of P = 1500 lb are shown in figures 7-9, respectively. The measured circumferential strains on the web from back-to-back gages were averaged at each location and the result is shown. There is little difference in the measurements from the back-to-back gages. The maximum difference between two back-to-back circumferential gages in specimen B is .0004, which is 17 percent of the maximum strain. The deformations and strains in the test data are not symmetric about centerline at $\alpha = 0°$. For example, in frame B, the measured deformation at points C and D in figure 8 are -.00563 and -.0165 for P = 1500 lb. The maximum out-of-plane deformation recorded for each specimen occurred near the web-cap intersection (x = .25 inches) at mid-length (point A in figures 7-9), with this deformation being opposite in sign from those recorded for the three corners (points B, C and D in figures 7-9). The maximum measured circumferential strain occured at x = .25 inches and $\alpha = 3^\circ$. However, the difference in strain between $\alpha = 3^\circ$ and $\alpha = 0^\circ$ is only about 10 percent.

The location of maximum measured circumferential strain for all three specimens was near the web-cap intersection at a point located approximately directly below the load introduction sites, as shown in figures 7-9. The maximum circumferential strain at a load of 1500 lb was about .0022 for frame A, .0024 for frame B and .0029 for frame C. The maximum strains at maximum load were .00338 for frame A, .00359 for frame B and .00588 for frame C.

At a load of 1500 lb, the finite-element analysis indicates that the deformation δ is .0405 inches for specimen B and .046 for specimen C, which are 19 and 5 percent lower than the test data, respectively. For specimen B this difference between the measured and predicted δ is .0094 inches. Since the analysis does not account for any damage or crushing at the point of contact between the rollers and the frame and the load at which the damage occurs is not known, this damage may account for the difference between analysis and test.

Contour plots of deformations and strains predicted by the finite-element analysis differ little for frames B and C so only results for frame B are presented. Out-of-plane deformations and circumferential strains predicted for frame B at a load of 1500 lb are shown in figures 10 and 11, respectively. Little local effect of the load rollers can be seen in the strains or the deformations. A comparison between figure 8 and figure 11 indicates that the maximum strain is at $\alpha = 0°$ for the analysis and is at $\alpha = 3°$ for the test data. Analytical predictions of out-of-plane displacement data for the web at $\alpha = 0°$ are 17 percent higher than the test results for specimen B and 18 percent higher than the test results for specimen C. However, analytical predictions of circumferential strain in the web at $\alpha = 0°$ are 1 percent lower than test data for specimen B and 10 percent higher than test data for specimen C.

Failures were detected during the tests by audible cracking and by discontinuities in the slope of the recorded load-deformation plots. The first audible failures occurred at loads ranging from 1000 to 2000 lb, for the three specimens. Load-deformation plots indicate that failures occurred at load levels between 1600 and 2000 lb. Two types of failures occurred. In all three specimens, the tabs separated from the web and damage to the web in the form of bearing failures occurred at the support-pin holes. A photograph of this type of damage is shown in figure 12(a). In addition, damage occurred at the load introduction sites. In all specimens the flange was damaged at the location of contact between the loading rollers and the flange. In the specimens with stacking sequence $[\pm 45/0/90/0_2]_s$, the web immediately beneath the rollers was also damaged, as shown in figure 12(b). The maximum load level was between 2600 and 3000 lb for the three frame specimens and the maximum applied deformation was between .046 and .050 inches.

CONCLUDING REMARKS

Threee curved frame specimens made from a long-discontinuous-fiber material with AS4 graphite fibers and PEKK thermoplastic resin were tested to failure in a four-point-bending test. Comparison of finite-element results and test data indicates that curved composite frame specimens made from long discontinuous fibers behave in a predictable manner when loaded in four-point bending. Finite-element analysis based on continuous fibers properties accurately describes frame behavior prior to failure. Strains in the webs of the curved frame specimens were as high as .0059 prior to local failures at supports and load application points.

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4. Almroth, B. O.; Brogan, F. A.; and Stanley, G. M.: Structural Analysis of General Shells, Volume II, User Instructions for STAGSC-1. Lockheed Palo Alto Research Laboratory, Palo Alto, CA, Rept. LMSC-D633873, 1981. (Available as NASA CR-165671.)

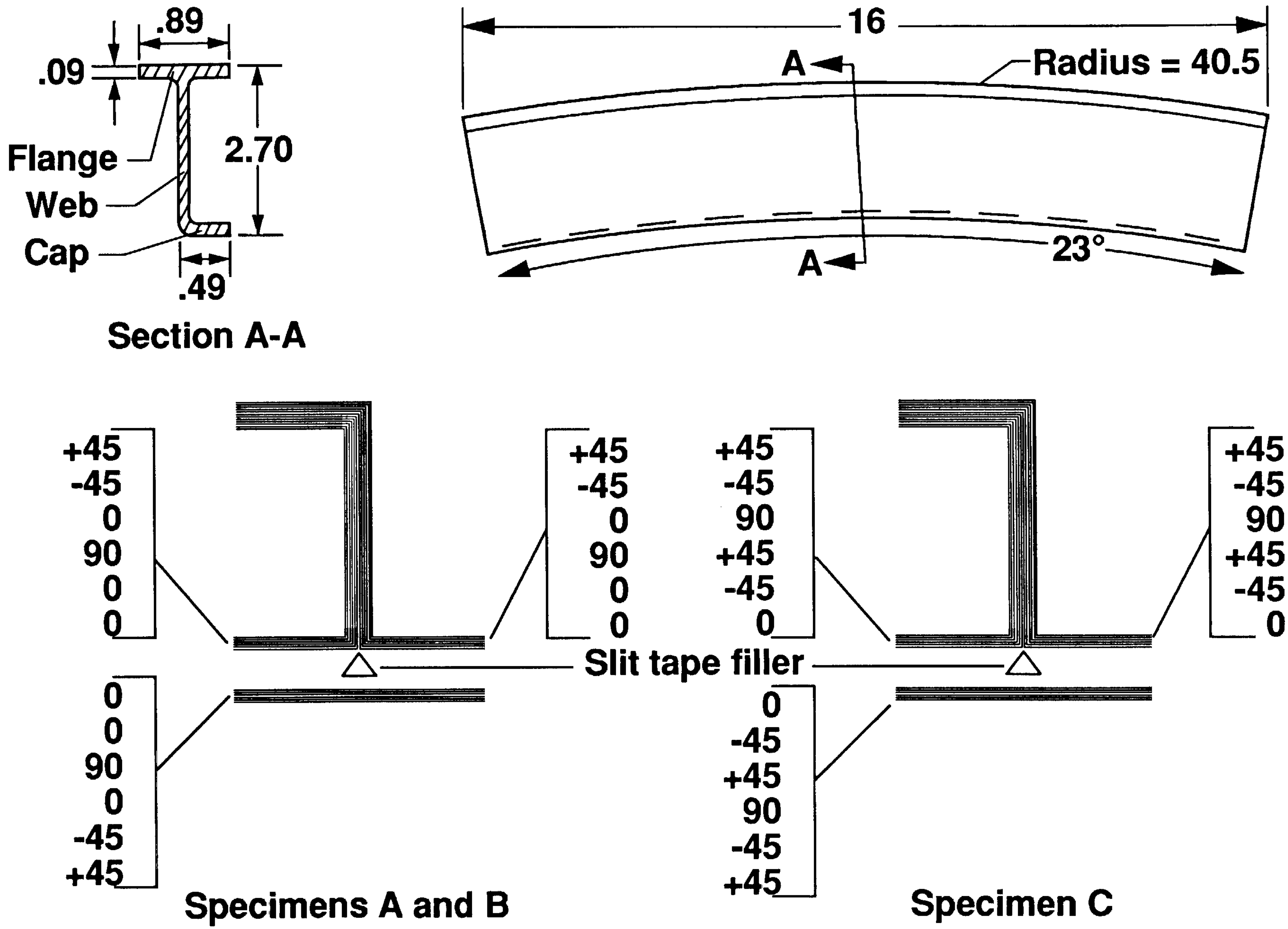


Figure 1. Frame specimen geometry (Dimensions are in inches, ply angles are in degrees).

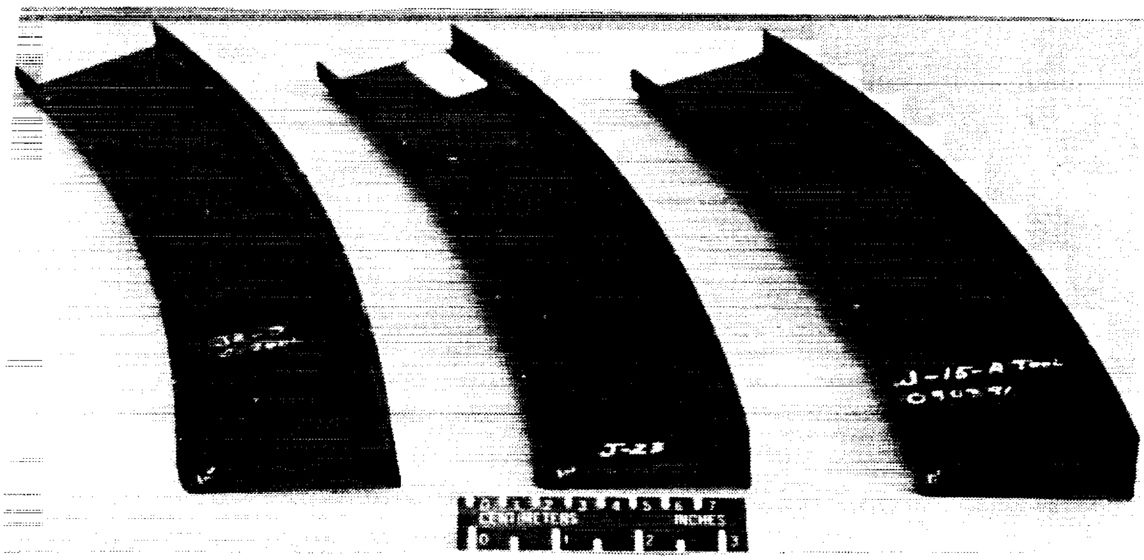


Figure 2. Test specimens.

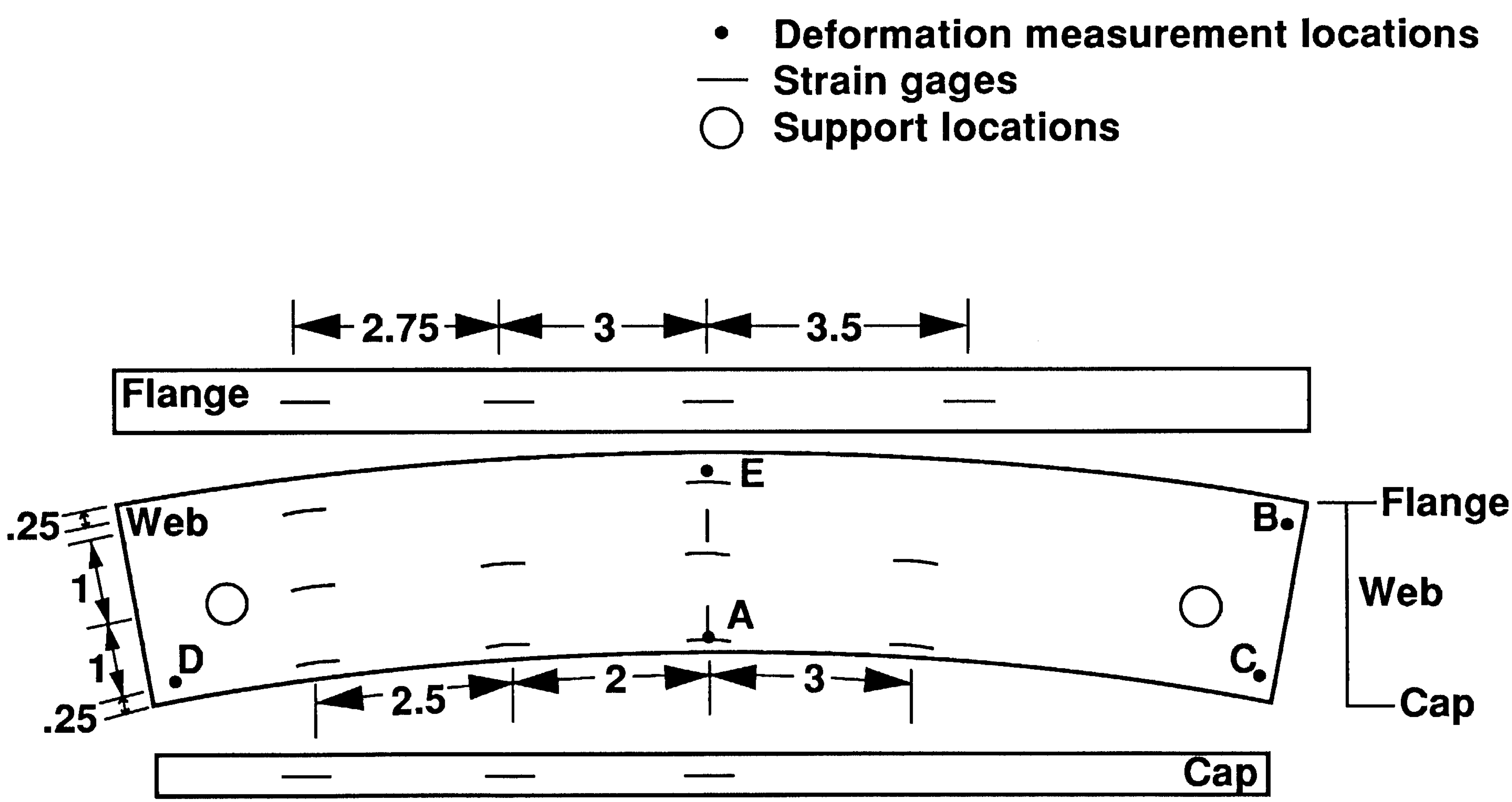


Figure 3. Strain gage and displacement measurement locations (All dimensions are in inches).

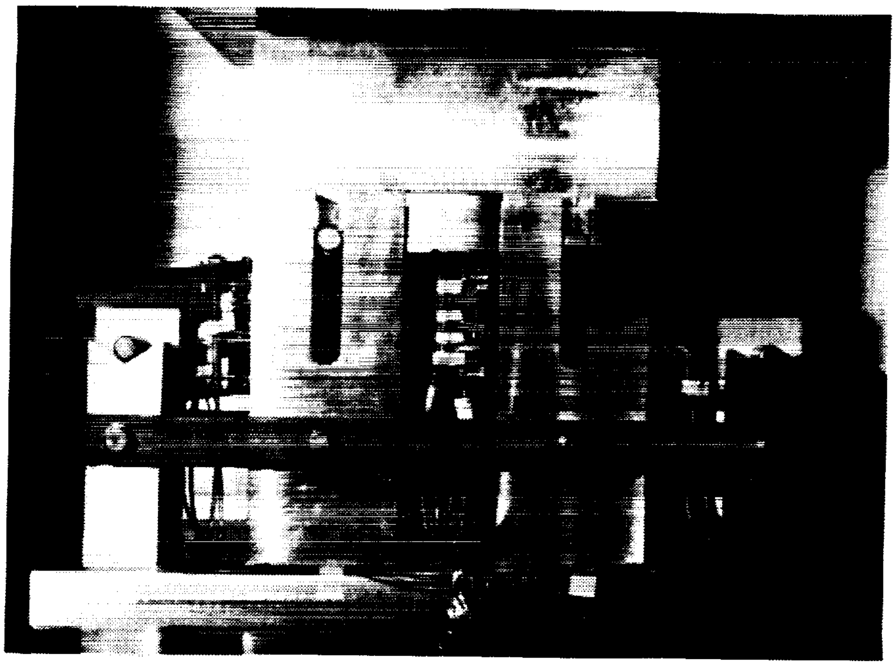


Figure 4. Specimen in test fixture.

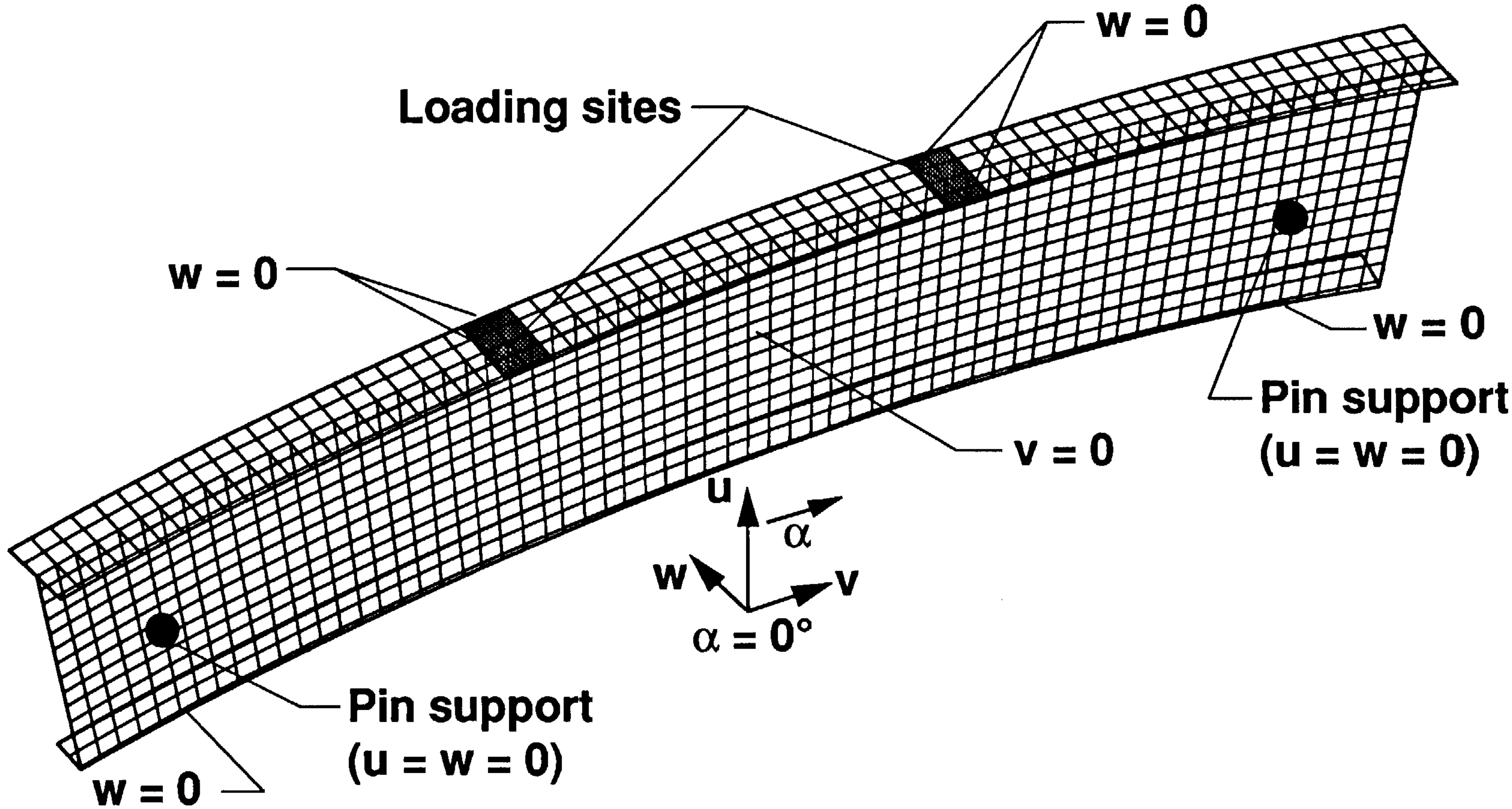


Figure 5. Finite element model of frame specimen.

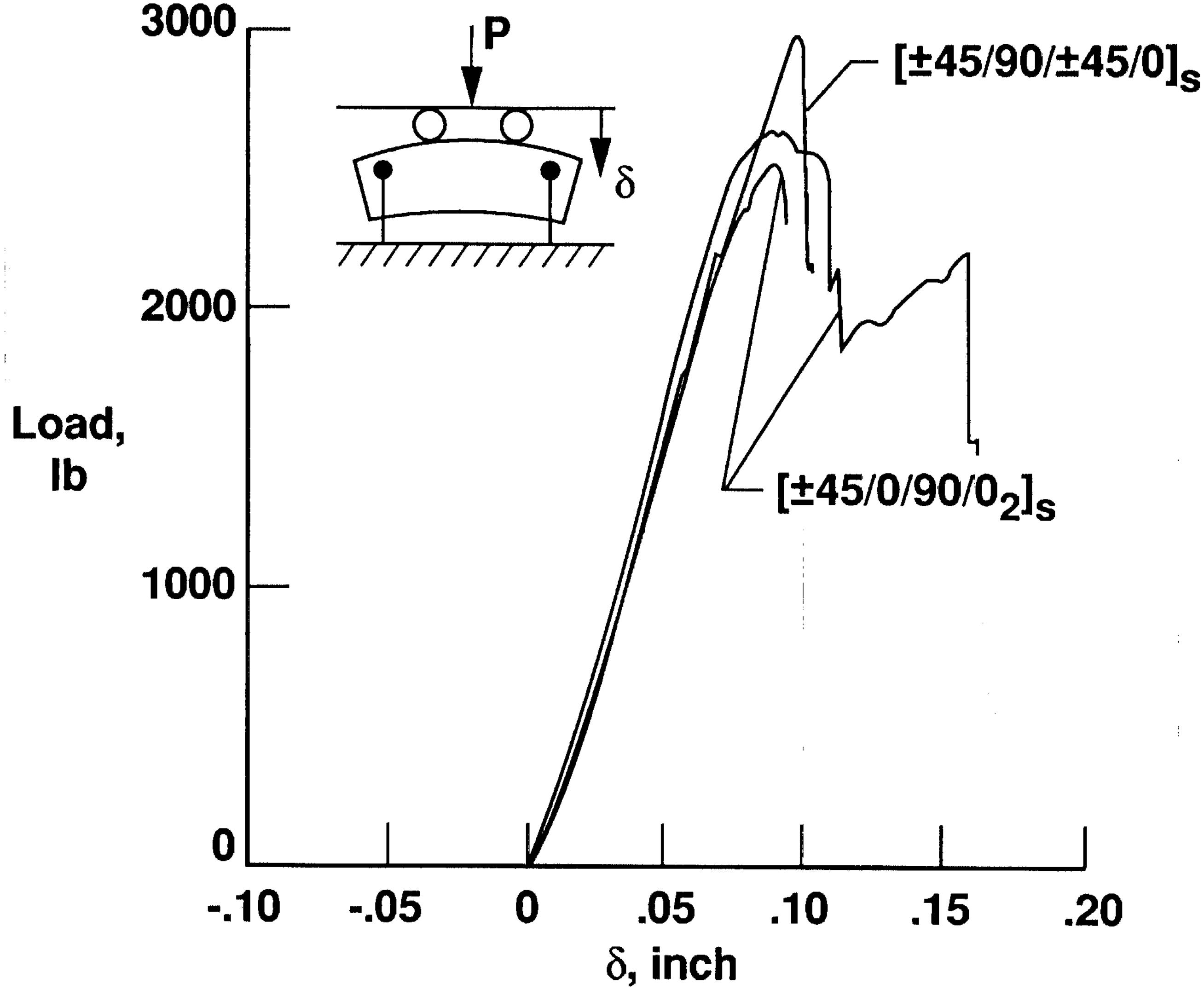


Figure 6. Load versus inplane displacement of test specimens.

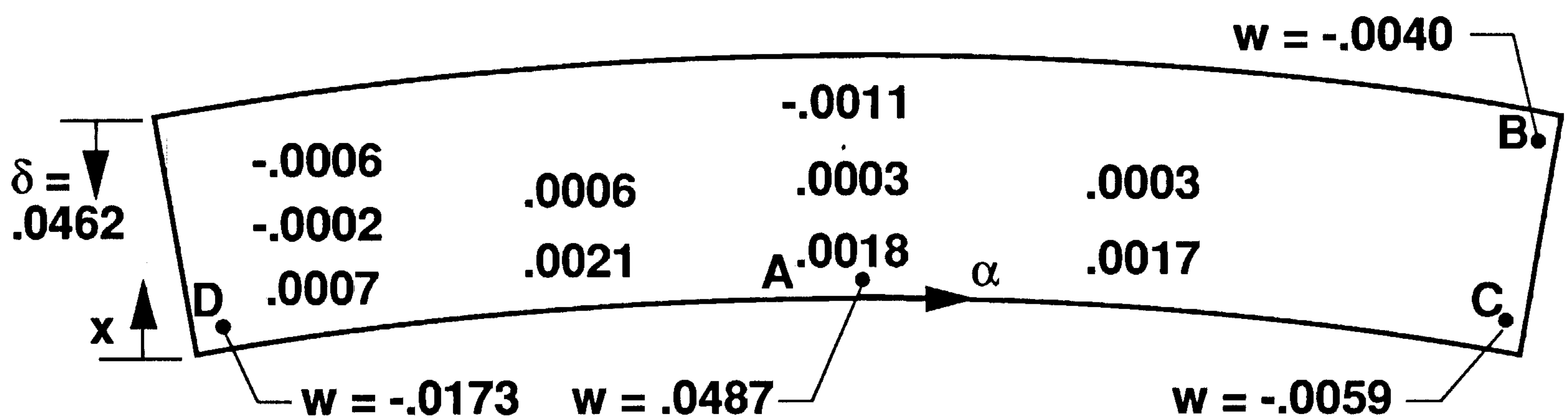


Figure 7. Measured strains and displacements in specimen A at P=1500 lb (Displacements are in inches).

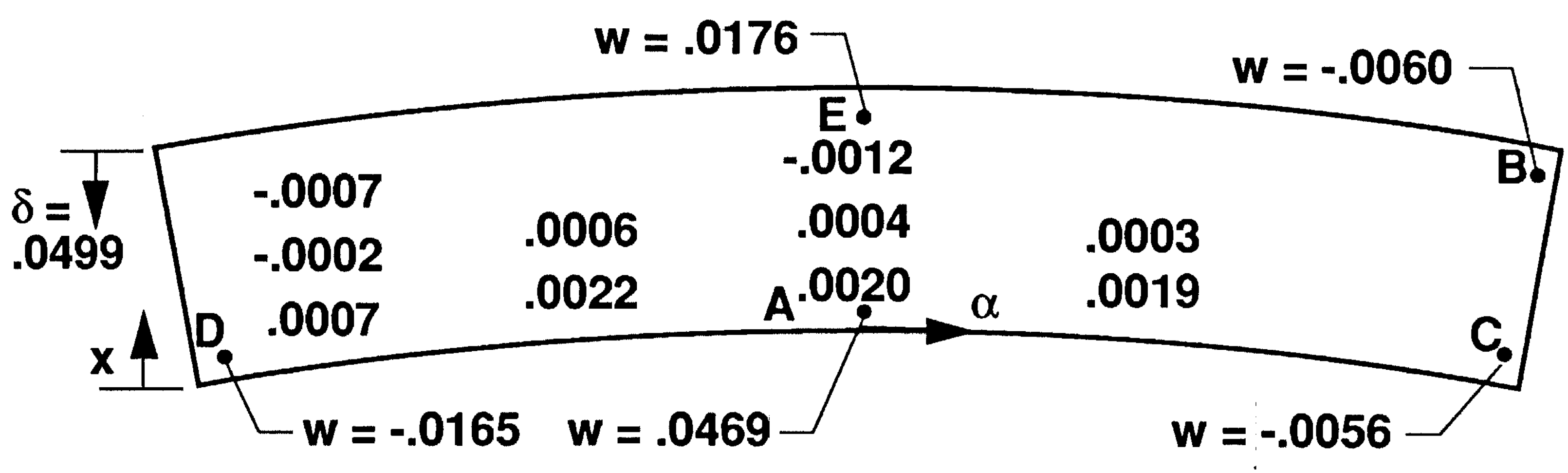


Figure 8. Measured strains and displacements in specimen B at P-1500 lb (Displacements are in inches).

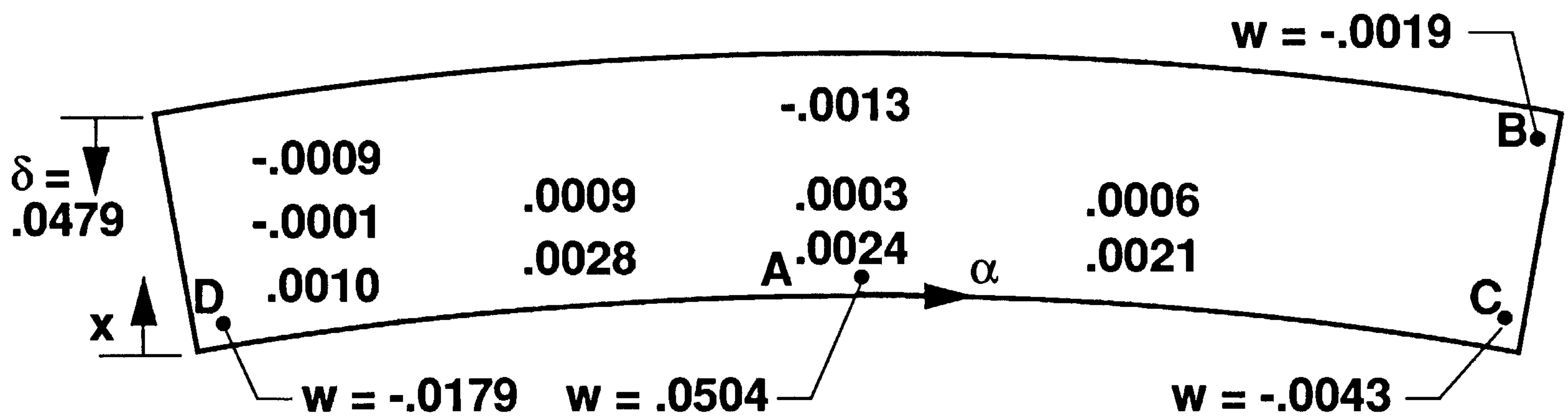


Figure 9. Measured strains and displacements in specimen C at P=1500 lb (Displacements are in inches).

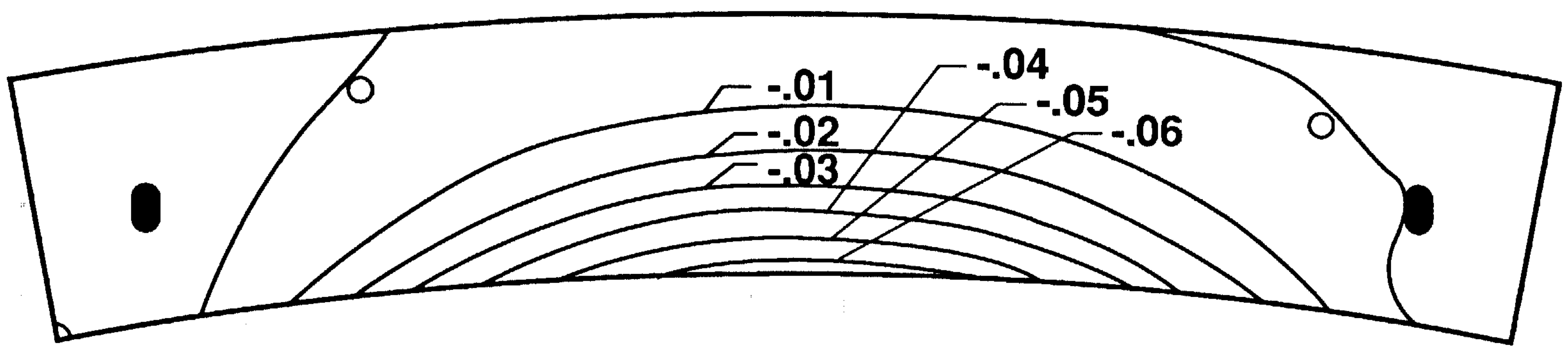


Figure 10. Out-of-plane displacements predicted by finite-element analysis for specimen B at P=1500 lb (Displacements are in inches).

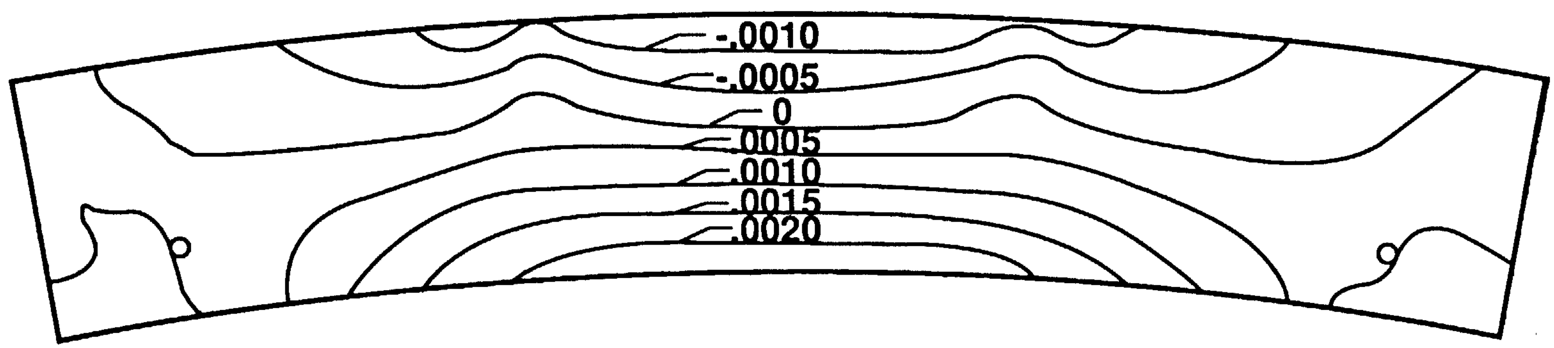
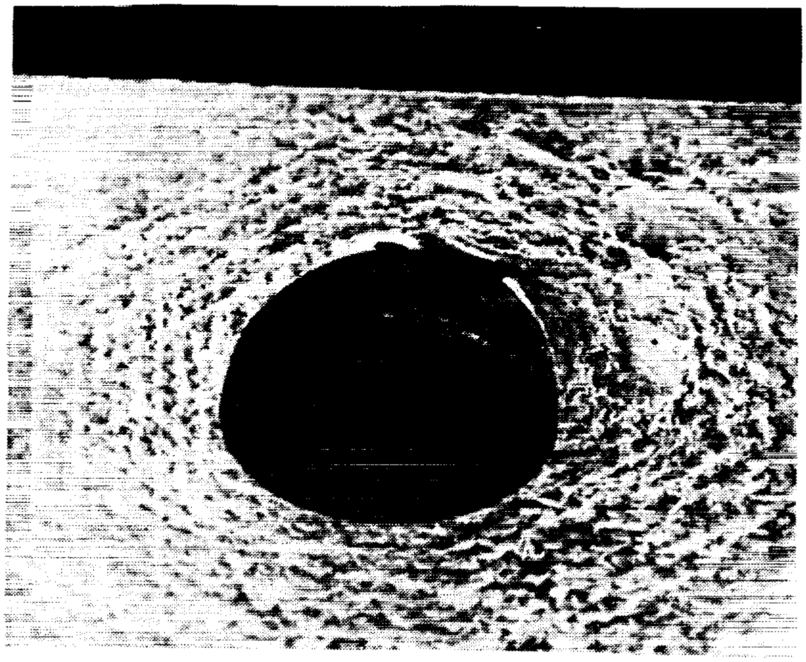
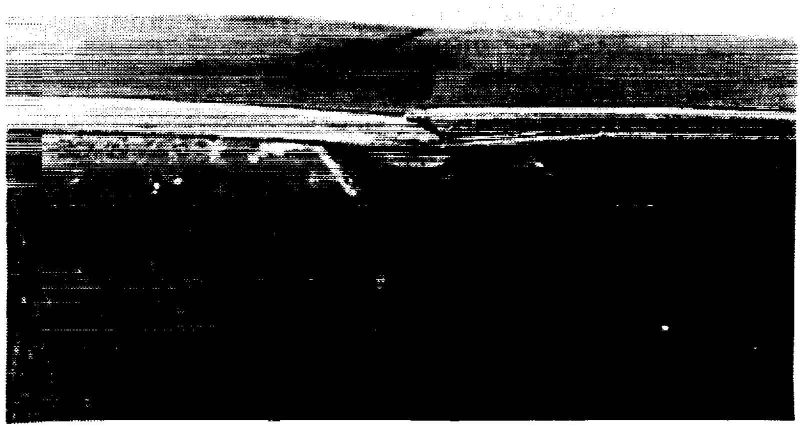


Figure 11. Circumferential strain contours predicted by finite elements analysis for specimen B at P=1500 lb.



(a) Damage to pin-support hole.



(b) Damage to flange and web.

Figure 12. Damage to specimen.

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