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Abstract

Four hat stiffened titanium panels with two different stiffener configurations were fabricated by superplastic forming/weld brazing and tested under a moderately heavy compressive load. The panels had the same overall dimensions but differed in the shape of the hat stiffener webs; three panels had stiffeners with flat webs and the other panel had stiffeners with beaded webs. Analysis indicated that the local buckling strain of the flat stiffener web was considerably lower than the general panel buckling strain or cap buckling strain. The analysis also showed that beading the webs of the hat stiffeners removed them as the critical element for local buckling and improved the buckling strain of the panels. The analytical extensional stiffness and failure loads compared very well with experimental results.

Introduction

Recent advances in the state of the art of superplastic forming (SPF) of certain metals[1-7] have made it possible to fabricate design shapes that depart from past experience. With the SPF process the designer has considerably more freedom to design mass efficient structures. Parts with intersecting compound contour surfaces can be made that would be impossible to fabricate with more conventional methods.

The hat stiffened panel, shown in figure 1, is a typical construction for aircraft structure. The superplastic forming/weld brazing (SPF/WB) fabrication process has been explored for this type of geometry in titanium[6,7]. The primary function of the material in the webs of the hat stiffener is to support the load carrying caps. For this purpose the webs should be made as thin as possible yet have enough bending stiffness to provide adequate support for the caps[5]. For a panel with stiffener caps and webs fabricated from a single sheet of material, the requirement for thin webs conflicts with the requirement for a cap with high local buckling strain.

Beads in the stiffener webs (see figure 2) increase their transverse bending stiffness to provide more cap support and produce a web with a high local buckling strain. Thus if the panel configurations were optimized the beaded webs would allow for a deeper stiffener that would increase the general panel buckling strain. However, because of the fabrication constraints of this study (discussed below) such an optimization was not carried out. The geometry shown offered a simple test specimen that could be formed by SPF/WB to check out fabrication process details. Titanium sheet material 0.050 inch thick was used because it was readily available.

For this study, two hat-stiffened panel geometries were fabricated using the SPF/WB process. The only fabrication variable available for change was the geometry of the stiffener. Three panels were fabricated with flat webs and one panel was fabricated with beaded webs. The two geometries used the same basic mold and started with the same nominal gage sheet material. The panel length was sufficiently low to preclude general panel buckling. The purpose of this report is to present the results of the analytical and experimental investigation of the effect of beading the webs on the buckling strain for hat-stiffened panels.

Analysis

The analytical local buckling strain of any flat element depends on a boundary condition factor times the square of the ratio of the element thickness to width. If all of the elements in the cross-section have a similar boundary condition factor, then their local buckling strains can be ordered by comparing their ratio of thickness to width. Using this criteria, the local buckling strain of the flat stiffener webs (figure 1) is lower than the other elements in the cross-section. The skin under the caps has the next lowest local buckling strain. The caps have a local buckling strain less than the double layer skin between stiffeners which has the highest local buckling strain of all of the elements.

Beading provides a web with low extensional stiffness and with extra transverse bending stiffness so that, based on the ratio of thickness to width, the skin under the stiffeners now has the lowest local buckling strain of the remaining elements. Thus beading the stiffener webs will raise the strain level needed to cause local buckling in the panel cross-section. However, the webs are no longer load carrying elements of the panel and the net effect on the total load the panel could carry must be considered.

A PASCO[8] analysis of a model of the conventional hat stiffened panel cross-section verified the order of the local buckling strains among the elements given by the thickness to width analysis and showed that they were all below the critical strain for a general panel buckling mode. The PASCO code uses compatibility between elements of the cross-section and does not have to assume a boundary condition factor for the elements, thereby giving an accurate computed element buckling strain. However, the program cannot account for loss of panel stiffness when an element buckles, therefore the code cannot be used to find the higher buckling loads or the maximum load for the panel.

The panels are made from two sheets of 0.05 inch material. Regardless of reshaping by the SPF process, the cross-sectional area, mass and extensional stiffness (EA) of the panels have values equal to those of two sheets 0.05 inch thick. Using a nominal modulus of 17,000,000 psi, the computed extensional stiffness (EA) is 54,000,000 lbs. Using this value of extensional stiffness and the computed local buckling strains for the flat webs, the stiffener webs are calculated to buckle at a panel load of 200,000 lbs. To compute a maximum load for the panel, the stiffener webs and the skin under the stiffeners are assumed to be buckled and their effective widths are reduced to one half. Using this criteria for the reduced load carrying area and a yield stress of 133,800 psi, the maximum load computed for the conventional hat stiffened panel is 340,000 lbs.

A PASCO analysis of the beaded hat stiffened panel shown in figure 2 is not so straight forward as the conventional hat-stiffened panel. The PASCO code is a linked strip analysis and requires that the geometry of the strips be uniform along the panel length. Therefore, stiffness properties of a uniform strip equivalent to the beaded webs had to be generated. To this end, the beaded web geometry was analysed as a separate model on PASCO to determine the web overall bending and extensional stiffnesses. Then using the computed bending and extensional stiffnesses the geometry and modulii of an equivalent element were determined[5].

Beading the sides of the stiffeners reduces the computed EA by 11% to 48,300,000 lbs. Based on this analytical EA and the computed local buckling strains, the skin under the stiffeners is calculated to buckle at about 212,500 lbs. This implies a 6% improvement in the lowest local buckle load over the conventional hat stiffened panel. Assuming the skin buckles under the stiffener leaving an effective width of one half, the beaded hat stiffened panel is calculated to carry a maximum load at yield of 316,600 lbs. This implies a 7% reduction in maximum load capacity for the beaded hat stiffened panel compared with the conventional hat stiffened panel.

Panel Fabrication

The panels were SPF Ti-6Al-4V alloy multistiffener sheets joined to a Ti-6Al-4V alloy skin. The multi-stiffeners were SPF from one 0.05 inch thick sheet in a single forming operation. Prior to SPF, the sheet was chemically cleaned, sprayed with a die release compound and placed between the cover plate and mold as indicated in figure 3. The mold assembly was positioned between resistance heated ceramic platens which were mounted in a hydraulic press. The mold assembly was heated to the forming temperature of 1700°F by means of the resistance heaters in the ceramic platens. After heating, a load was applied to the platens to establish a gas-tight seal between the titanium sheet material, the upper cover plate, and the mold. Argon gas was then injected between the upper surface of the titanium sheet and the cover plate. The argon gas pressure was then increased to approximately 100 psi to superplastically form the sheet. The applied load of the hydraulic press was increased to react the forming pressure. At 100 psi gas pressure, the forming time required to SPF a multiple stiffener sheet was approximately 60 minutes.

The configuration of the two male die inserts for the panels is shown in figure 4. The conventional hat stiffener dies were machined from 17-4 stainless steel bar stock. The beaded hat stiffened die inserts were cast to shape using 17-4 stainless steel. The conventional hat and beaded hat dies were interchangeable and fastened by screws to the retainer plate.

Following removal from the mold and chemical cleaning, the SPF multiple stiffener sheets were joined to the Ti-6Al-4V panel skin sheets by two rows of eight spot welds between each stiffener. The spot welds were sufficient to maintain alignment and no additional tooling was required. Strips of 0.016 inch thick 3003 aluminum braze alloy were placed adjacent to the joints. The assemblage was first placed in a vacuum brazing furnace, heated to 1250°F and held for 5 minutes to complete the brazing, and finally furnace cooled. At the brazing temperature, the molten braze alloy was drawn into the faying surfaces of the joints by capillary action.

Test Procedure

The panel ends were potted and machined flat and parallel to each other. A machined steel bar was placed between each end of the panel and faces of the test machine platens. Feeler gage measurements were used to fit shims between the steel bars and the platens to ensure bending-free contact with the panels. Resting against the steel bars, the flat panel ends offered considerable restraint against panel end rotation. The panel edges were mounted in knife edge supports to simulate simply supported edges.

The specimens were loaded to failure in compression between the displacement controlled platens of a one million pound test machine at the rate of 60,000 pounds per minute. The panels were instrumented with electrical resistance strain gages. Platen displacements were monitored with linear voltage displacement transducers (LVDT). The load, strain gage responses and displacements were monitored by a data acquisition system that recorded the data on a digital computer tape.

Three of the failed panels (panels designated 2, 3 and 4 in Table 1) were cut up to make material coupon test specimens. The coupon specimens were marked with uniform lines across the test section and instrumented with electric resistance strain gages. The coupons were pulled to fracture in a tensile test machine. Uniform elongations were measured from marked gage lines over a 1 inch section of the specimen away from the fracture zone. Elongations across the fracture were measured from marked gage lines over a 2 inch section across the fracture zone after the specimen had been put back together.

Results and Discussions

Tensile property data from the coupon tests are given in tables 2, 3 and 4. The average modulus was 17,000 ksi and the average material yield stress was 133,800 psi. Comparing the average coupon data obtained from the cap and skin areas, indicate that the fabrication process had little or no effect on the basic material properties.

Conventional Hat Stiffened Panels

Local thinning of the cross section by the SPF process must be taken into account to properly interpret the experimental results. The titanium sheet prior to forming rests on top of the male die insert in the mold cavity. The SPF forming pressure stretches the sheet over the male die insert. The sheet material lying on top of the die insert undergoes very little stretching and becomes the stiffener cap. As the sheet superplastically forms into the mold, it stretches and makes contact with the sides of the die insert and forms the webs of the stiffeners. As the sheet progressively forms into the mold, the stretching causes the stiffener webs to be progressively thinner toward the bottom of the mold cavity. The resulting stiffener cross-section has a cap with a thickness nearly equal to the original sheet thickness and webs with a tapering thickness (see figure 5).

As the titanium sheet forms into the mold cavity, at the ends of the die insert, it not only stretches transverse to the stiffener as it contacts the sides of the die insert, but it also stretches along the stiffener as it contacts the side of the mold between the dies. This bi-directional stretching causes greater thinning to occur in the sheet near the bottom of the mold. As a result there is more thinning of the stiffener webs and of the skin section between stiffeners near the panel ends than in the middle of the panel.

This additional thinning causes the position of the neutral surface of the panel to vary along the panel length. Its position is closer to the skin near the ends than in the middle of the panel. This variation in position of the neutral surface produces an offset load path for the axial load that causes the panel to bend. This could be prevented by cutting off more of the ends of the panels. The offset load path explains why the strain gage response data for the conventional stiffened panels showed that the panels were bending from the onset of loading, with the skin side bowing inward (see figure 6).

The experimental extensional stiffness values (from load displacement plots such as in figure 7) for the conventional hat stiffened panels averagedout to 51,400,000 lbs(see table 1). This value is 5% lower than the computed extensional stiffness value. Since coupon tests determined that the material modulus was close to the nominal value used for the computations, the slightly lower than expected value of EA is attributed to the greater thinning near the panel ends.

The stiffener caps in all three conventional hat stiffened panels buckled near the potted ends. Because the potted ends of the panel prevent rotation as the panel begins to bend, the stiffener caps near the ends were subjected to an additional compressive component due to the end moment required to prevent rotation. Thus these cap buckles were caused by increased compression strains combined with thinner webs near the ends. Conventional hat stiffened panels 1 and 2 had no strain gages located near the panel ends. However, several gages were placed on the stiffener caps 1.5 inch above the potting material on panel 3. The response curves from these strain gages, for two different stiffeners, are shown in figure 8. One gage was nearly centered on a local cap buckle and the other was just outside the local cap buckle. These strain gages showed that strain reversal occurred near the panel ends before any reversal occurred near the middle of the panel (compare figures 8 and 9). The lowest strain reversal in panel 3 occurred in the caps at the panel ends at a load of 193,000 lbs. This is slightly lower than the 200,000 lb. computed panel load based on local buckling strain in the stiffener webs. The buckling analysis, however, did not include any of the bending effects that appeared in the experimental buckling results. It can only be be assumed that panels 1 and 2 also had reversals at lower loads near the panel ends as found in panel 3. Since panel 3 was the only conventional hat stiffened panel with gages at the panel ends, for comparative purposes, the initial strain reversal data shown in Table 1 are from gages located near the panel midsections. The average of these loads is 19% higher than the computed local buckling load based on the analytical buckling strain in the stiffener webs.

Local buckles in the caps near the ends of the panels increase the bending moment at the panel midsection because of the additional shift in the location of the neutral surface. At the midsection the bending strains were reversed from those at the panel ends. Strain gage response data showed that the compressive bending strains combined with the axial compressive strain to cause a higher strain in the panel skin than in the caps. As can be seen by the strain gage response curves shown in figure 10, the skin in the panel midsection buckles before the caps.

At failure, a catastrophic collapse occurred that produced permanent buckles in the caps and webs near the panel ends and in the skin at the panel midsections (see figures 11 and 12). None of the weld braze joints in the panels failed during the test. The corresponding maximum or collapse loads recorded from the panel tests are shown in Table 1. The 296,870 lb average for these loads agrees within 13% of the computed 340,000 lb maximum load.

Beaded Hat Stiffened Panel

The neutral axis location for the beaded hat stiffened panel does not depend on the beaded stiffener webs because the webs are not load carrying. Thus greater thinning of the beaded webs near the panel ends has little effect on the location of the neutral surface panels. Hence the beaded hat stiffened panel has less bending than the conventional hat stiffened panel. This explains strain gage response data from the beaded hat stiffened panels showing much less bending in the panel with loading compared to the conventional hat stiffened panels (see figure 13).

The experimental results from LVDT data show that the beaded hat stiffened panel EA stiffness (Table 1) was 11% lower than the EA for the conventional hat stiffened panel. This compares very well with the 11% reduction expected based on the computed EA values for the two types of panels.

The experimental EA value for the beaded hat stiffened panel was 5% lower than the computed value. Since the nominal modulus value used in the computations was close to the experimental value obtained from coupon tests, the slightly lower panel EA stiffness value from test is attributed to more thinning of the sheet material between stiffeners near the ends due to bi-directional stretching.

Since the bending occurring near the ends of the beaded hat stiffened panel was slight based on strain gage response data (see figure 14), the caps near the ends did not buckle early as was observed in the conventional hat stiffened panels. As the panel strain level approached material yield, the skin under the stiffeners at the panel midsection began to buckle (see figure 13) causing the panel skin side to bow inward. This induced local buckles in the skin which began to occur at a load of 268,500 lbs. The experimental local buckling load for the beaded hat stiffened panel was 13% higher than the corresponding load for the conventional hat stiffened panel. This is more of an increase in buckling strain between the two types of panels than was expected, based on computations for beading the sides. However, most of this additional improvement is attributed to less bending in the beaded hat stiffened panel compared to the conventional hat stiffened panel.

The local buckles in the panel skin resulted in a pronounced inward bowing of the panel skin and a subsequent catastrophic collapse of the beaded hat stiffened panel across the midsection. The resulting collapse at 280,000 lbs (see table 1) caused fractures to occur at the midsection and produced deep buckles with fractures near the panel ends (see figures 15 and 16). There were no separations in the weld brazed joints observed in the test. The failure load was 11% below the computed maximum load. The maximum load for the beaded hat stiffened panel was 6% below the average failure load for the conventional hat stiffened panel which agrees well with the 7% computed reduction.

Conclusions

Four titanium multi-stiffener panels were successfully fabricated using the SPF/WB technique. Three panels had conventional hat stiffeners (flat webs) and one panel had hat stiffeners with beaded webs. The panels were tested to failure in axial compression. None of the weld braze joints in the panels failed or separated during the tests.

Analyses were made for both types of panels. According to analysis, the local buckling strain of the flat webs is lower than the buckling strain of the other elements in the cross section. Analysis showed that beading the webs of the hat stiffeners raised the buckling strain of the panel by 6%. However it also removed 11% of the load carrying material from the cross section. This reduction in extensional stiffness reduced the computed maximum load by 7%.

Test results for the conventional hat stiffened panels showed bending occurred in the panels under an axial load. The bending is attributed to variation in the position of the non-uniform neutral surface, caused by differential thinning of material along the panel length. This could be prevented by cutting off more of the ends of the panels. At the panel ends this bending combined with the axial load causing a higher strain in the stiffener caps than in the skin. Thus the caps of the conventional hat stiffeners buckle locally near the ends of the panels. The location of the neutral surface along the length of the beaded hat stiffened panel is not affected as much by SPF thinning as the conventional hat stiffened panel. Hence the experimental results for the beaded hat stiffened panel showed very little bending. Consequently the beaded hat stiffened panel did not buckle near the ends as did the conventional hat stiffened panels.

The experimental extensional stiffness (EA or ratio of load to strain) values were only 5% lower than calculated presumably due to more thinning in the stiffener sheets near the ends of the stiffeners. Both the computed and the experimental results for the beaded hat stiffened panel showed a 11% reduction in the EA stiffness value compared to the conventional hat stiffened panel.

The buckling loads from the tests showed the beaded hat stiffened panel had an increase of 13% in local buckling load over the conventional hat stiffened panel. This is higher than the 6% calculated increase for the beaded hat stiffened panel buckling load and is attributed to a combination of decreased bending as well as to beading of the stiffener sides. The bending observed in the experimental results was not included in the analysis. Maximum loads for the panels were governed by yield and differed only slightly between the beaded and conventional hat stiffened panels. Experimental maximum load for the beaded panel was 6% lower than the average of the conventional panel maximum loads compared to a computed 7% reduction.

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Table 1. Experimental and analytical results

Panel	Extensional stiffness, EA lbs × 10^6	Computed extensional stiffness, EA lbs × 10^6	Weight lbs	Reversal load lbs	Maximum load lbs	Computed max load lbs
Conventional						
1	53.3	54.1	10.96	219,764	304,130	340,000
2	54.6	54.1	NA*	273,660	319,134	340,000
3	46.2	54.1	10.71	217,000	267,360	340,000
Beaded						
4	45.6	48.3	10.20	268,500	280,000	316,600

* Not available

Table 2. Material property coupon test results for panel #2, conventional hat.

Location-specimen	Area in^2	Max load lbs	Yield stress Kpsi	Ultimate stress Kpsi	E modulus psi × 10^6	Uniform elongation (1 inch) %	Elongation across fracture (2 inch) %
1-1	.0443	6400	135.3	144.5	17.5	6	12
1-2	.0436	6490	138.8	148.9	18.1	8	13
Avg 1	.0440	6445	137.0	146.7	17.8	7	12.5
2-1	.0238	3300	127.9	138.7	17.6	9	13.5
2-2	.0232	3200	126.5	137.9	17.4	6	10
Avg 2	.0235	3250	127.2	138.3	17.5	7.5	11.8
3-1	.0271	4150	143.0	153.0	18.2	6	11
3-2	.0259	4020	145.6	155.2	18.7	9	12
Avg 3	.0265	4085	144.3	154.1	18.4	7.5	11.5

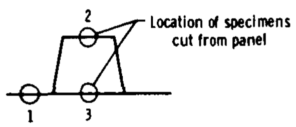


Table 3. Material property coupon test results for panel #3, conventional hat.

Location-specimen	Area in^2	Max load lbs	Yield stress Kpsi	Ultimate stress Kpsi	E modulus psi × 10^6	Uniform elongation (1 inch) %	Elongation across fracture (2 inch) %
1-1	.0430	6090	132.0	141.6	16.5	7	11.5
1-2	.0432	6050	130.7	140.0	16.7	8	10.5
1-3	.0436	6100	130.7	139.9	16.8	7	9
Avg 1	.0433	6080	131.1	140.5	16.7	7.3	10.3
2-1	.0246	3295	126.8	133.9	17.4	3	3
2-2	.0232	3260	130.4	140.5	17.9	5	10.5
2-3	.0224	3150	130.8	140.6	18.0	8	9
Avg 2	.0234	3235	129.3	138.3	17.7	5.3	7.5
3-1	.0246	3575	135.7	145.3	16.6	6	10
3-2	.0247	3575	134.8	144.7	16.6	6	11
3-3	.0224	3580	136.1	146.7	16.8	5	11
Avg 3	.0239	3577	135.5	145.6	16.7	5.7	10.7

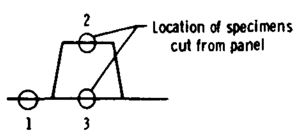
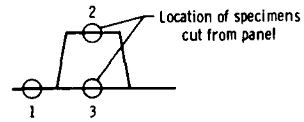


Table 4. Material property coupon test results for panel #4.

Location-specimen	Area in^2	Max load lbs	Yield stress Kpsi	Ultimate stress Kpsi	E modulus psi × 10^6	Uniform elongation (1 inch) %	Elongation across fracture (2 inch) %
1-1	.0451	6300	131.9	139.6	17.2	8	12
1-2	.0468	6620	133.0	141.1	17.3	11	11.5
1-3	.0460	6500	133.6	141.3	17.3	4	6.5
Avg 1	.0460	6473	132.8	140.7	17.3	7.7	10
2-1	.0253	3590	133.0	141.9	19.0	4	10
2-2	.0253	3600	132.4	142.3	18.8	4	9
2-3	.0250	3560	134.8	142.4	18.9	2.5	4
Avg 2	.0252	3583	133.4	142.2	18.9	3.5	7.7
3-1	.0277	3950	134.8	142.6	17.0	6	10
3-2	.0284	4055	134.5	142.8	16.7	8	9.5
3-3	.0288	4090	133.5	142.0	16.5	8	10.5
Avg 3	.0283	4032	134.3	142.5	16.7	7.3	10



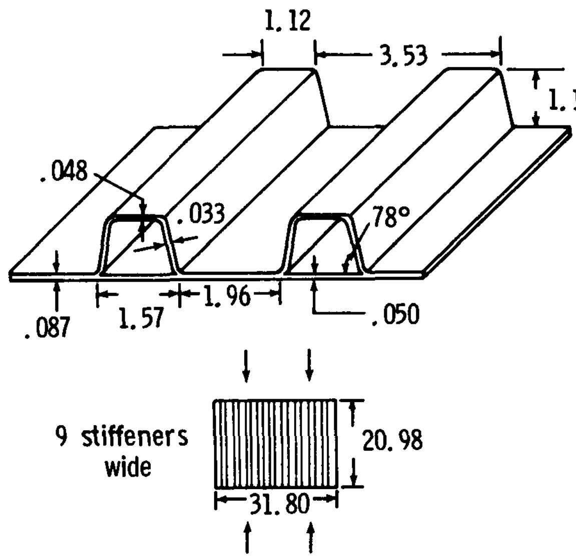


Fig. 1 Geometric details of conventional hat stiffened panels (dimensions are in inches).

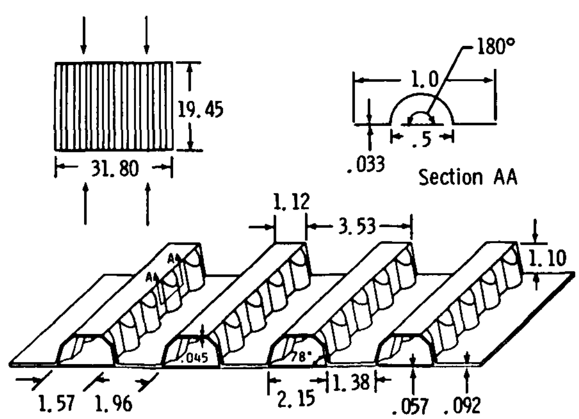


Fig. 2 Geometric details of the beaded hat stiffened panel (dimensions are in inches).

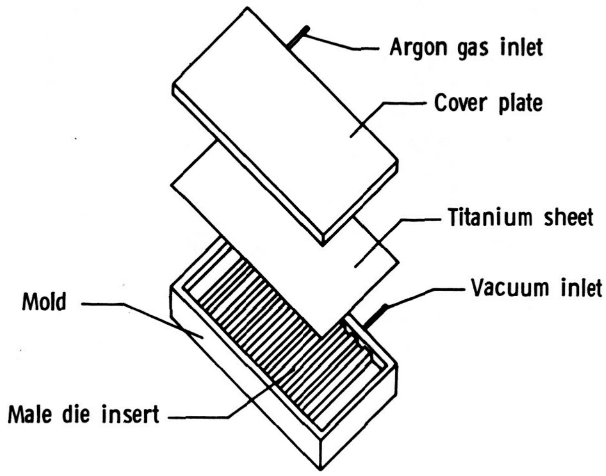


Fig. 3 Schematic of tooling for superplastic forming of the hat stiffeners.

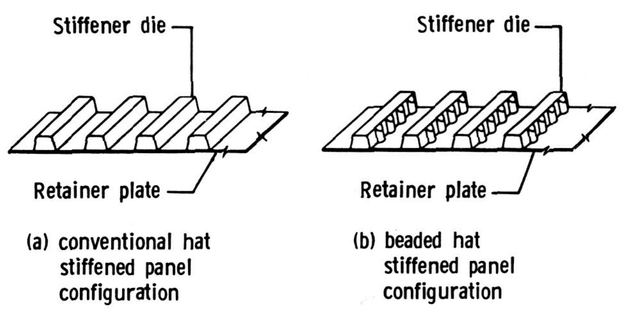


Fig. 4 Configurations of die inserts.

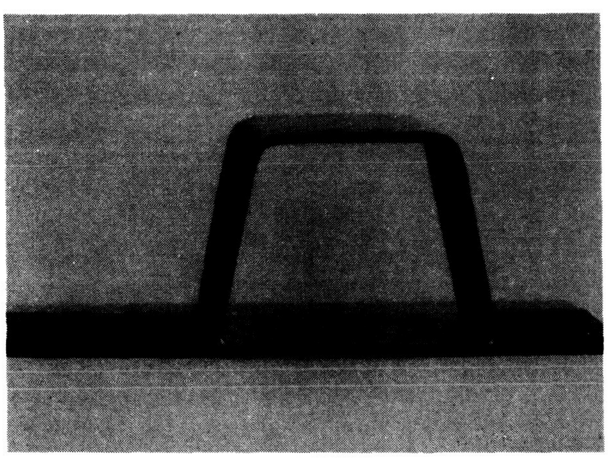


Fig. 5 Photograph of a section through the conventional hat stiffened panel showing effect of SPF thinning on the thickness.

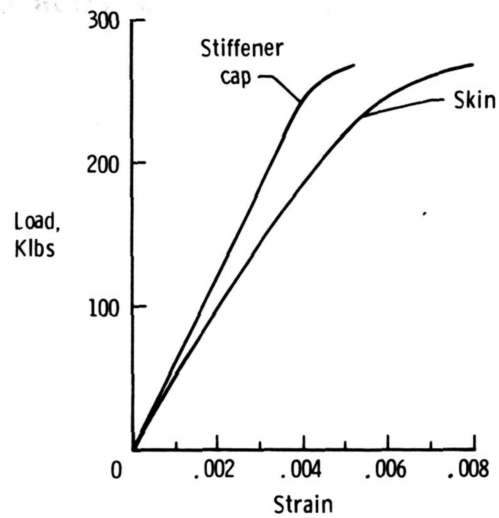


Fig. 6 Midsection back-to-back strain gage response curves for the conventional hat stiffened Panel 3.

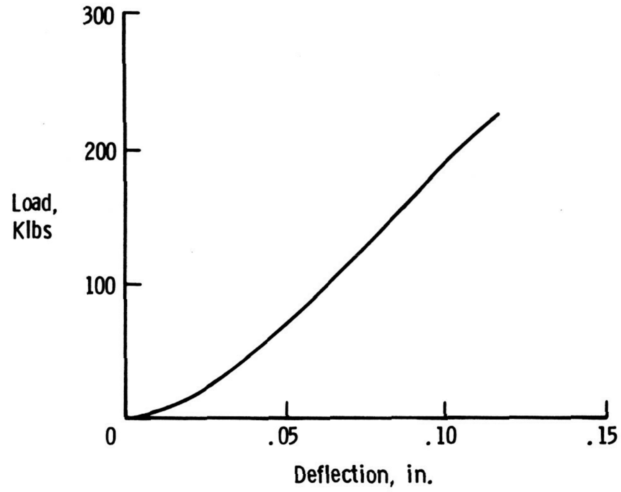


Fig. 7 Typical load-deflection response curve from LVDT placed between test machine platens (from Panel 3).

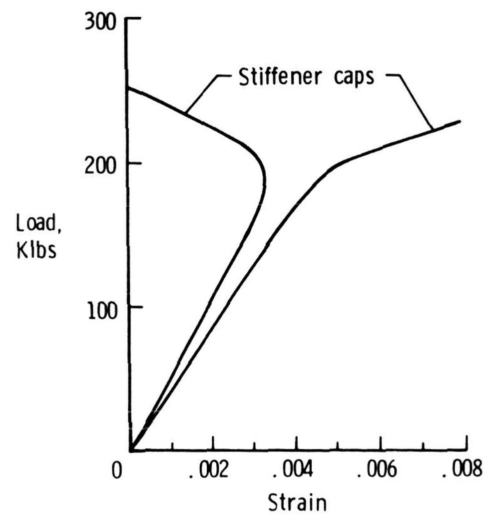


Fig. 8 Typical strain gage response curves from two stiffener caps near the end of the conventional hat stiffened Panel 3.

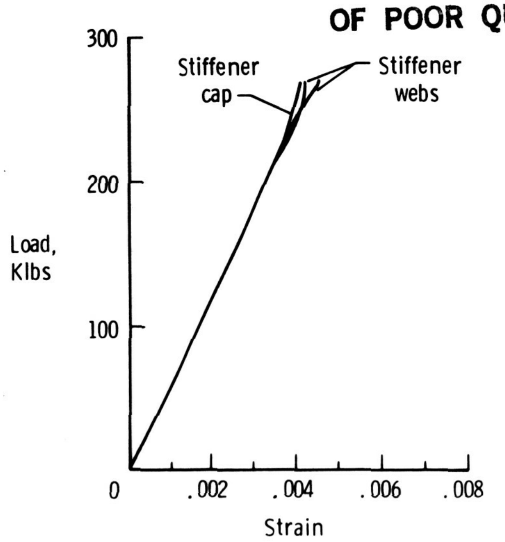


Fig. 9 Strain gage response curves from a stiffener at the middle of a conventional hat stiffened panel.

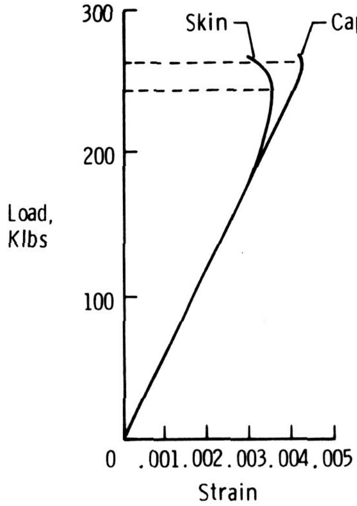


Fig. 10 Midsection strain gage response curves from back-to-back gages that show skin strain reversal occurring before the cap strain reversal.

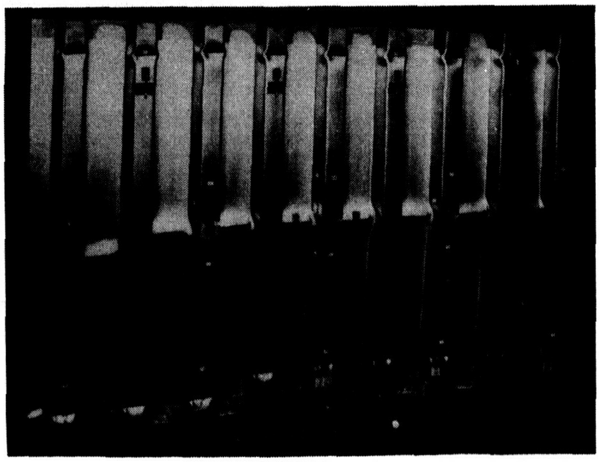


Fig. 11 Conventional hat stiffened panel showing stiffeners after collapse.

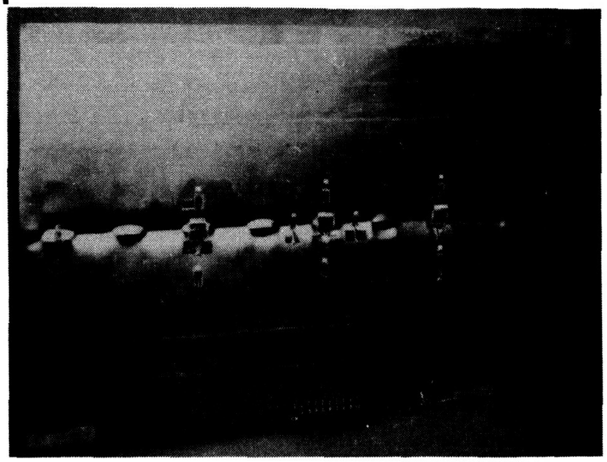


Fig. 12 Conventional hat stiffened panel showing buckles across skin side after collapse.

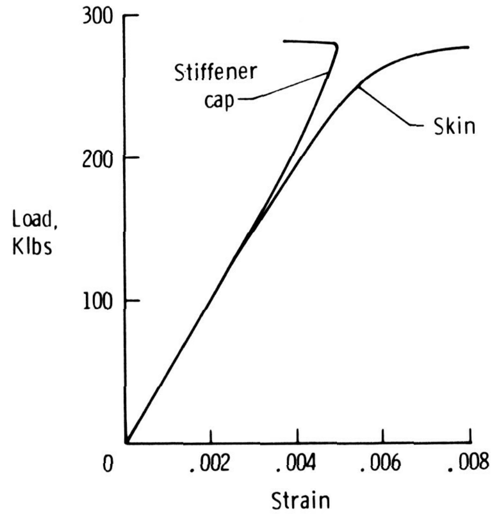


Fig. 13 Typical back-to-back strain gage response curves from midsection of beaded hat stiffened panel.

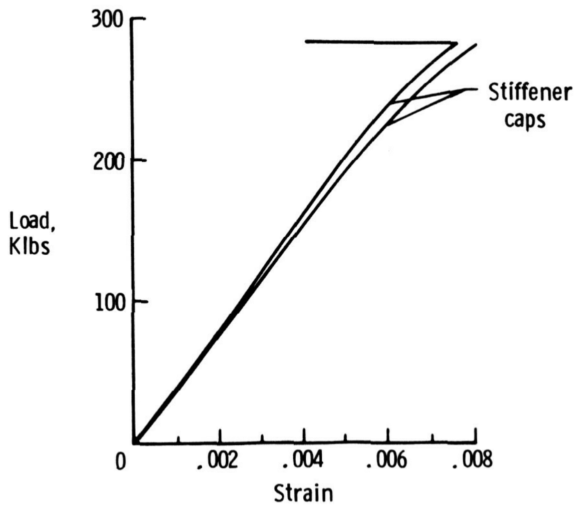


Fig. 14 Typical strain gage response curves from caps of beaded hat stiffeners near the ends of the panel.

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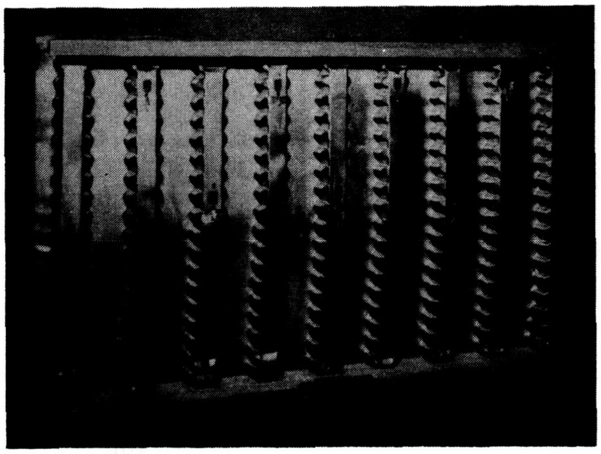

Fig. 15 Beaded hat stiffened panel showing damaged stiffeners after collapse.

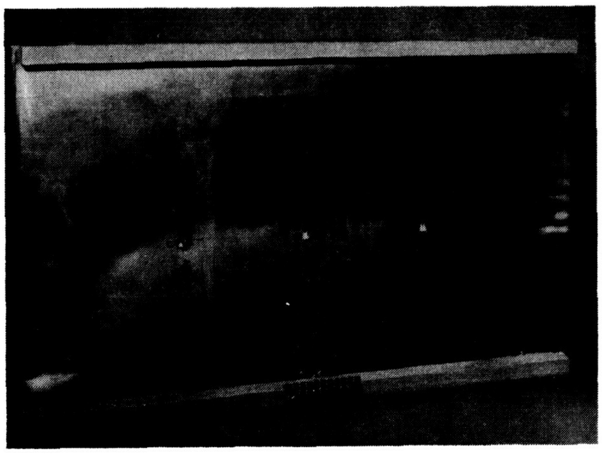

Fig. 16 Beaded hat stiffened panel showing skin side after collapse.

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16. Abstract Four hat-stiffened titanium panels with two different stiffener configurations were fabricated by superplastic forming/weld brazing and tested under a moderately heavy compressive load. The panels had the same overall dimensions but differed in the shape of the hat-stiffener webs; three panels had stiffeners with flat webs and the other panel had stiffeners with beaded webs. Analysis indicated that the local buckling strain of the flat stiffener web was considerably lower than the general panel buckling strain or cap buckling strain. The analysis also showed that beading the webs of the hat stiffeners removed them as the critical element for local buckling and improved the buckling strain of the panels. The analytical extensional stiffness and failure loads compared very well with experimental results.

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