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**Scientific and Technical
Information Branch**

INTRODUCTION

Performance improvements for high-altitude high-speed aircraft and spacecraft have motivated the search for minimum-mass fuselage and tank structures. Some fuselage structural concepts for such aircraft have external heat shields that provide an aerodynamically smooth surface. Thus, mass-efficient concepts for the fuselage primary structure which do not have a smooth outer surface can be used to carry the fuselage loads and to support the heat shields. An important limiting load in such aircraft is the compression buckling load in the fuselage wall. A number of structural concepts for compressive loading applications have been investigated (ref. 1 and 2). Of these concepts, the corrugated panel with beaded webs offers a very attractive mass-strength efficiency (ref. 2). Recent advances in the state of the art of superplastic forming and diffusion bonding (SPF/DB) technology (ref. 3) for a limited class of materials provide considerable freedom in the design of structural components. The object of the present study was to investigate the feasibility of fabricating titanium corrugated panels with beaded webs by using superplastic forming and weld-brazing and to demonstrate the structural integrity of the panels. Panels of this unique configuration had not previously been fabricated or tested.

The test panels in this study consisted of superplastically formed (SPF) titanium alloy Ti-6Al-4V (Ti-6-4) half-hat elements (fig. 1) that were joined by weld-brazing (WB) to Ti-6-4 caps to form either single-corrugation compression panels (fig. 2) or multiple-corrugation compression panels (fig. 3). The panels were tested in end compression at room temperature and the results compared with analytical prediction. The processes for panel fabrication, testing, and analysis are discussed in the present paper.

SYMBOLS

A	panel area (width times length), cm^2 (in^2)
$\bar{A}_m$	mass-equivalent cross-sectional area, cm^2 (in^2)
$\bar{A}_s$	stiffness-equivalent cross-sectional area, cm^2 (in^2)
E	material elastic modulus, GPa (lbf/in^2)
$E\bar{A}_s$	panel rigidity, MN (lbf)
L	panel length, cm (in.)
P	applied test load, N (lbf)
w	panel weight, kg (lbm)

$w/\rho AL$	panel mass coefficient
ε	strain
ρ	material density, kg/m^3 (lbm/in^3)
σ_{TY}	material yield strength, MPa (lbf/in^2)

PANEL PROCESSING

The procedure utilized to form the half-hat elements consisted of blowing titanium sheet materials at elevated temperatures into a mold containing a ceramic die using argon gas pressure. Gas pressure was controlled to duplicate previously established strain rates commensurate with good superplastic forming strains. The complete mold assembly is shown in figure 4. The mold and ceramic die tooling of the half-hat configuration evaluated in this study is shown in figure 4(a) and the cover plate in figure 4(b). The unique concept of forming half of a hat over a shallow die was selected to minimize localized thinning of the titanium during SPF which was reported to occur when forming a full-hat element over a deep die (ref. 4). The reduction in thinning was to be accomplished by the orientation of the half-hat die in the mold to reduce the amount of stretching necessary to achieve a fully formed element (fig. 5).

Tooling

The ceramic material used for die tooling in this study was Harbison-Walker Harchrome G, a hydraulic setting refractory cement consisting of a chrome ore based mix, bonded with a high-strength, high-purity calcium aluminate binder. Ceramic tooling was investigated as an alternative to steel tooling used in earlier studies (refs. 4 and 5). Harchrome G was selected for the die material after an evaluation of several ceramic materials. Harchrome G was found to meet the strength and temperature requirements and demonstrated a low interaction with titanium over the temperature range required for SPF.

The fabrication of the ceramic die tooling used in this study consisted of first making a wooden pattern of the desired configuration. Silicone rubber was then poured into a frame around the pattern to produce a rubber mold having an image of the desired shape. A ceramic mixture containing a maximum of 8 percent by weight of water was prepared and was cast into the rubber mold. The exposed surfaces of the ceramic casting were then covered with a sheet of polyethelene at ambient temperature for 24 hours to allow the casting to attain its maximum wet strength. The cast die tool was then removed from the rubber mold and placed in an air oven for drying. The die tool was heated to 93°C (200°F) and held for 8 hr to remove the mechanical water and then heated to 427°C (800°F) and held for 4 hr to remove the chemically combined water. After drying, the die tool was heated in an air furnace to 1093°C (2000°F) and held for 4 hr for the final processing of the ceramic die tool. The ceramic die was now ready for use as a suitable tool for superplastic forming and no additional surface preparation was required prior to use.

Superplastic Forming

The superplastic forming facility (fig. 6) consisted of the ceramic die tooling inserted in a mold with cover plate, ceramic heating platens, mechanical press, and an argon gas purge and pressurizing system. The mold with the ceramic die tooling in place and cover plate was placed between the heating platens that are mounted in the mechanical press. The platens were used to provide the required heat source. Insulation was placed along the perimeter of the mold and platen to reduce heat loss. The mechanical press was used to apply pressure on the mold to maintain a seal between the titanium being formed and the cover plate. The cover plate had a raised bead around the mating surface to form the seal. The press also supplied the reaction force to the argon gas pressure during the SPF process. The argon gas pressurizing system provided the force to SPF the Ti-6-4 sheet.

The superplastic forming procedure consisted of preheating the mold and cover plate to 935°C (1715°F). A 1.27-mm-thick (0.050-in.) sheet of Ti-6-4, which had been chemically cleaned, was sprayed several times with a die release compound containing graphite. With the argon gas purge in operation, the upper head of the mechanical press was raised to lift the upper heating platen and cover plate. The Ti-6-4 sheet was placed on top of the mold and the upper head of the mechanical press lowered. A cross section of the assembled tooling is shown in figure 7. An initial load of 44 480 N (10 kips) was placed on the mold through the mechanical press. To reduce contamination of the titanium sheet during the forming process, the mold and cover plate were purged with argon gas while the Ti-6-4 sheet was heated to 927°C (1700°F). When the Ti-6-4 sheet reached a temperature of approximately 745°C (1375°F), a seal was established as the Ti-6-4 sheet formed around the bead on the cover plate. When the temperature of the mold reached 927°C (1700°F), the argon gas pressure was increased in the cover plate and a pressure of 276 kPa (40 psi) was developed and held for approximately 20 minutes with a flow stress of approximately 20.7 MPa (3 ksi) being generated for SPF. As the argon gas pressure was increased, the load on the mold developed by the mechanical press was increased to 57 824 N (13 kips). The argon gas pressure in the cover plate was increased in 138-kPa (20-psi) increments with 20-min holds until the forming pressure reached 690 kPa (100 psi) at which time the pressure was held for approximately 60 min. In the total forming time of approximately 150 min, the titanium sheet was completely blown into the mold taking the shape of the ceramic die. At the completion of forming, the flow of argon gas was turned off and pressure applied by the press was released. The cover plate was raised above the mold and the SPF element removed from the mold with a special tool (fig. 8) with the mold temperature at 927°C (1700°F). The element was then chemically cleaned and the excess material trimmed away. (See fig. 1.)

Weld-Brazing

Joining of the titanium half-hat into single or multiple corrugation panels consisted of spot-welding two elements to a cap 1.27 mm (0.050 in.) thick and 66.5 mm (2.62 in.) wide to fabricate a single-corrugation panel. The repetitive joining together of single-corrugation panels was the process by which the multiple-corrugation panels were fabricated. (See fig. 3.) Spot-welds were located on 50.8-mm (2.0-in.) centers when connecting each flange to a titanium cap. Spot-weld parameters were developed so that weld nugget expansion established a faying surface gap of 50.8 μm to 76.2 μm (0.002 to 0.003 in.) between the flanges of the half-hat elements and the cap. A 31.7-mm-wide (1.25-in.) titanium cap was then spot-welded to the edge flanges to complete the corrugated panels. (See fig. 2 for single-corrugation panel.) A 3003 aluminum braze alloy (0.406 mm (0.016 in.) thick) was then placed adjacent to the joints to be brazed. Ample braze alloy was used to completely wet and fill the faying surface gap and to produce a generous fillet along the beaded web-cap interface. The panels were then placed in the brazing furnace. The spot-welds were sufficient to maintain alignment and no other tooling was required for brazing of the panels.

Brazing of the panels was accomplished in a vacuum furnace at a pressure of 1.33 mPa (1×10^{-5} torr) and a temperature of 677°C (1250°F). Upon melting, the 3003 aluminum braze alloy was drawn into the faying surface gap by capillary action. The temperature of 677°C (1250°F) was maintained for 5 min. The panel was then allowed to cool to room temperature before being removed from the furnace. A superplastically formed/weld-brazed (SPF/WB) single corrugation panel is shown in figure 9 after completion of the brazing cycle.

SPF/WB Panel

Following brazing, the ends of the SPF/WB panel were potted by using an epoxy potting compound, as shown for a typical multiple-corrugation stiffened panel in figure 10. Potting material was used to facilitate grinding the ends of the panel flat, parallel to each other, and perpendicular to the cap. The finished panel was 254 mm (10.0 in.) long and either 143 mm (5.62 in.) wide for the single-corrugation panel or 449 mm (17.69 in.) wide for the multiple-corrugation panel. The potting also served to prevent premature failure of the panel ends during compression testing. Three single-corrugation panels and three multiple-corrugation panels were fabricated for room temperature compression tests.

TEST PROCEDURE

The SPF/WB single- and multiple-corrugation panels were tested in end compression using a 1.3-MN-capacity (300-kip) hydraulic testing machine. The edges of the specimens were supported with knife edges positioned 6.35 mm (0.25 in.) from the edge (fig. 11). Relative motion between the upper and lower heads of the testing machine was determined by using an average of three linear variable differential transformers (LVDT). Foil strain gages were attached to the flanges and caps and were used to measure local strains. Data were recorded every 2 sec until two-thirds of the predicted failure load was achieved and every second thereafter to maximum load. All tests on single-corrugation panels were tested at an initial load rate of 112 N/s (15 000 lb/min), and multiple-corrugation panels were tested at an initial load rate of 3707 N/s (50 000 lb/min).

RESULTS

Panel Processing

Titanium panel elements were successfully fabricated by SPF by using the shallow half-hat die concept instead of a deep die. A low cost, ceramic material was successfully used to make the die for the SPF process. A minimum of surface interaction on the titanium which occurred during forming was removed by chemical cleaning. Stretching and subsequent thinning of the titanium sheet during SPF was reduced by approximately 35 percent as determined from specimen thinning measurements. The resulting thickness of the SPF half-hat element was uniform with only a 5 percent variation across the beaded web as can be seen in the typical panel cross section shown in figure 12. Half-hat elements were successfully joined by weld-brazing to a titanium cap to form single-corrugation panels. Extending this concept, multiple-corrugation panels were also successfully fabricated, limited in size only by the size of the brazing furnace.

Panel Analysis

To determine the stiffness properties of the test panels, the non-load-carrying beaded-web material and the load-carrying cap material must be considered properly. The intersection line formed by the flange/web material where the flange is bonded to the cap is not straight but has a sine-wave type shape. Thus the load-carrying material in the panel cross section, shown hatched in figure 13, includes all the cap material (width times thickness) but is taken to include only that portion of the flange material encompassing an average width determined from the sine-wave geometry. The sum of these load-carrying areas is the stiffness-equivalent area $\bar{A}_s$, and calculated values of $\bar{A}_s$ are tabulated in table 1. The nominal elastic modulii for the panel material is 113.8 GPa (16 500 ksi) (refs. 4 and 6). Multiplying the calculated stiffness-equivalent area $\bar{A}_s$ times the elastic modulus will give the computed extensional rigidity $E\bar{A}_s$. Values of $E\bar{A}_s$ so calculated are also tabulated in table 1.

Both the computed (elastic) Euler buckling strain for the panels and the computed (elastic) buckling strain for the caps are greater than the nominal yield strain for the material. Thus the panels should be expected to carry a load equivalent to the yield strength of the material multiplied by the stiffness-equivalent area. Multiplying the stiffness-equivalent area $\bar{A}_s$ by the nominal yield strength of 988.0 MPA (143.3 ksi) (refs. 4 and 6) gives an expected failure load of 288.1 kN (64 800 lb) for the single-corrugation panels and 880.9 kN (198 000 lb) for the multiple-corrugation panels.

The mass-equivalent area $\bar{A}_m$ in the cross section includes the load-carrying material $\bar{A}_s$ and the beaded web material. Values of $\bar{A}_m$ computed for the panels are shown in table 1. A nominal density of 4400 kg/m^3 (0.16 lbm/in^3) is used to compute the weight of the panel, and this weight is used to obtain the values of $w/\rho AL$ tabulated in table 1. The parameter $w/\rho AL$ is the familiar equivalent thickness divided by length t/L used in mass strength efficiency studies.

Panel Tests

Typical load-shortening curves for the single-corrugation panels and for the multiple-corrugation panels are shown in figures 14(a) and (b), respectively. The slope of the load-shortening curves is the panel extensional rigidity divided by panel length $E\bar{A}_s/L$. Multiplying the slope by panel length gives the experimental values of $E\bar{A}_s$ given in table 1. Dividing these values by the material elastic modulus of 113.8 GPa (16 500 ksi) gives the values of stiffness-equivalent area $\bar{A}_s$ in table 1. These values agree well with the calculated ones. Failure of the panels occurred at the loads tabulated in table 1 by wrinkling of the caps accompanied with localized separation of the weld-braze joint in the wrinkle (fig. 15). None of the panels tested exhibited catastrophic failure of the weld-braze joint. The failure load values were 96 and 89 percent of the expected failure load values for the single- and multiple-corrugation panels, respectively. The results verify that heavily loaded corrugated panels carrying loads approaching the yield strength of the material can be fabricated by using titanium alloy and the superplastic forming/weld-brazing fabrication process.

The load-strain test results are nondimensionalized by dividing the test loads by the yield strength times stiffness-equivalent area and by dividing the observed strains by the yield strength divided by material modulus. Typical normalized load-strain test results are shown in figure 16. The slope of the normalized test results falls along the diagonal (indicated by the dashed line) of the graph shown in figure 16; this indicates excellent agreement between test and the calculated values for both the single- and multiple-corrugation panels.

To find the experimental mass-equivalent area $\bar{A}_m$, each panel was weighed, and the weight was divided by the nominal material density $\rho = 4400$ kg/m^3 (0.16 lbm/in^3) and the panel length L. The resulting mass-equivalent areas $\bar{A}_m$ are tabulated in table 1. Dividing the panel weight by the density ρ, then by the panel area A (width times length), and then by the length L gives the mass coefficient $w/\rho AL$ also tabulated in table 1. As can be seen in table 1, these values agree well with the analytical values.

CONCLUDING REMARKS

The objective of this study was to investigate the feasibility of superplastically forming corrugated panels with beaded webs and to demonstrate the structural integrity of the concept by testing.

Half-hat beaded-web elements were successfully superplastically formed from titanium Ti-6Al-4V sheet and subsequently weld-brazed with other panel components to produce full-size panels with a unique corrugated design. Both single-corrugation and multiple-corrugation panels were fabricated. Stretching and subsequent thinning of the titanium sheet during superplastic forming was reduced by approximately 35 percent by using the shallow half-hat die concept instead of the deep die concept. This concept also resulted in a more uniform thickness across the beaded webs. The half-hat panel concept allows multiple-corrugation panels to be fabricated by weld-brazing that are limited in size only by the size of the brazing furnace. The use of low cost, ceramic die tooling was demonstrated in the superplastic forming process for titanium with a minimum of surface interaction. The panels were tested in end compression to failure. They failed at compressive loads approaching the yield strength of the titanium material. At maximum load, the caps wrinkled with accompanying localized separation of the weld-braze joint in the wrinkle. None of the panels tested exhibited catastrophic failure of the weld-braze joint. Experimental test results were in good agreement with structural analysis of the panels.

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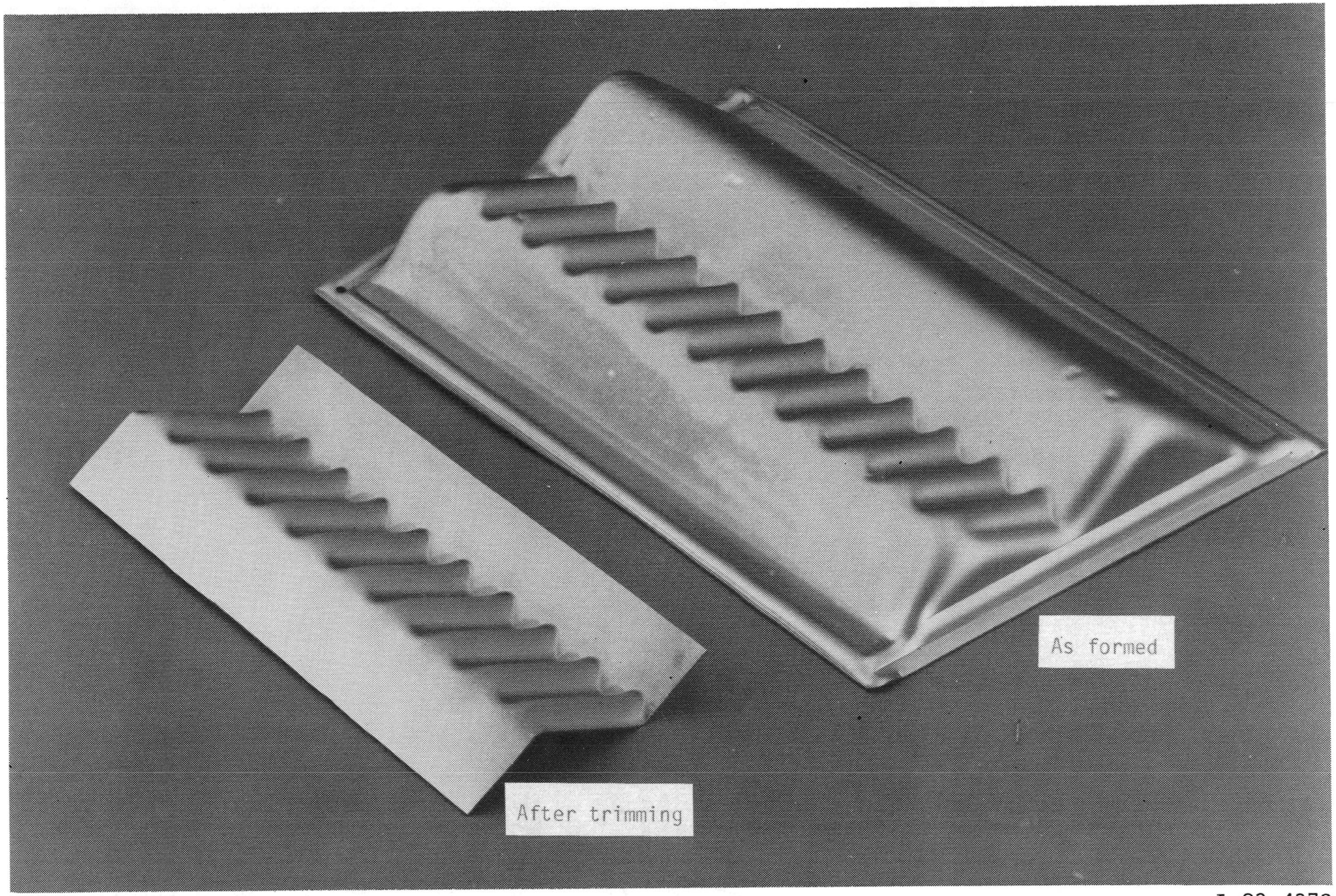
Table 1.- ANALYTICAL AND EXPERIMENTAL RESULTS OF TEST PANELS

(a) U.S. customary units

Panel	Analysis					Test				
	$\bar{A}_m$, in^2	w/ρAL	$\bar{A}_s$, in^2	E$\bar{A}_s$, lbf	Load, lbf	$\bar{A}_m$, in^2	w/ρAL	$\bar{A}_s$, in^2	E$\bar{A}_s$, lbf	Load, lbf
CRPL-1	0.629	0.0112	0.452	7 470 000	64 800	0.599	0.01060	0.447	7 370 000	59 892
CRPL-2	0.629	0.0112	0.452	7 470 000	64 800	0.608	0.01076	0.445	7 350 000	64 078
CRPL-3	0.629	0.0112	0.452	7 470 000	64 800	0.602	0.01065	0.435	7 180 000	62 948
Average	0.629	0.0112	0.452	7 470 000	64 800	0.603	0.01067	0.442	7 300 000	62 306
PNL-1	1.910	0.0108	1.382	22 800 000	198 000	1.790	0.01012	1.499	24 940 000	177 020
PNL-2	1.910	0.0108	1.382	22 800 000	198 000	1.800	0.01017	1.432	23 620 000	176 020
PNL-3	1.910	0.0108	1.382	22 800 000	198 000	1.790	0.01012	1.412	23 300 000	178 150
Average	1.910	0.0108	1.382	22 800 000	198 000	1.793	0.01014	1.448	23 890 000	177 063

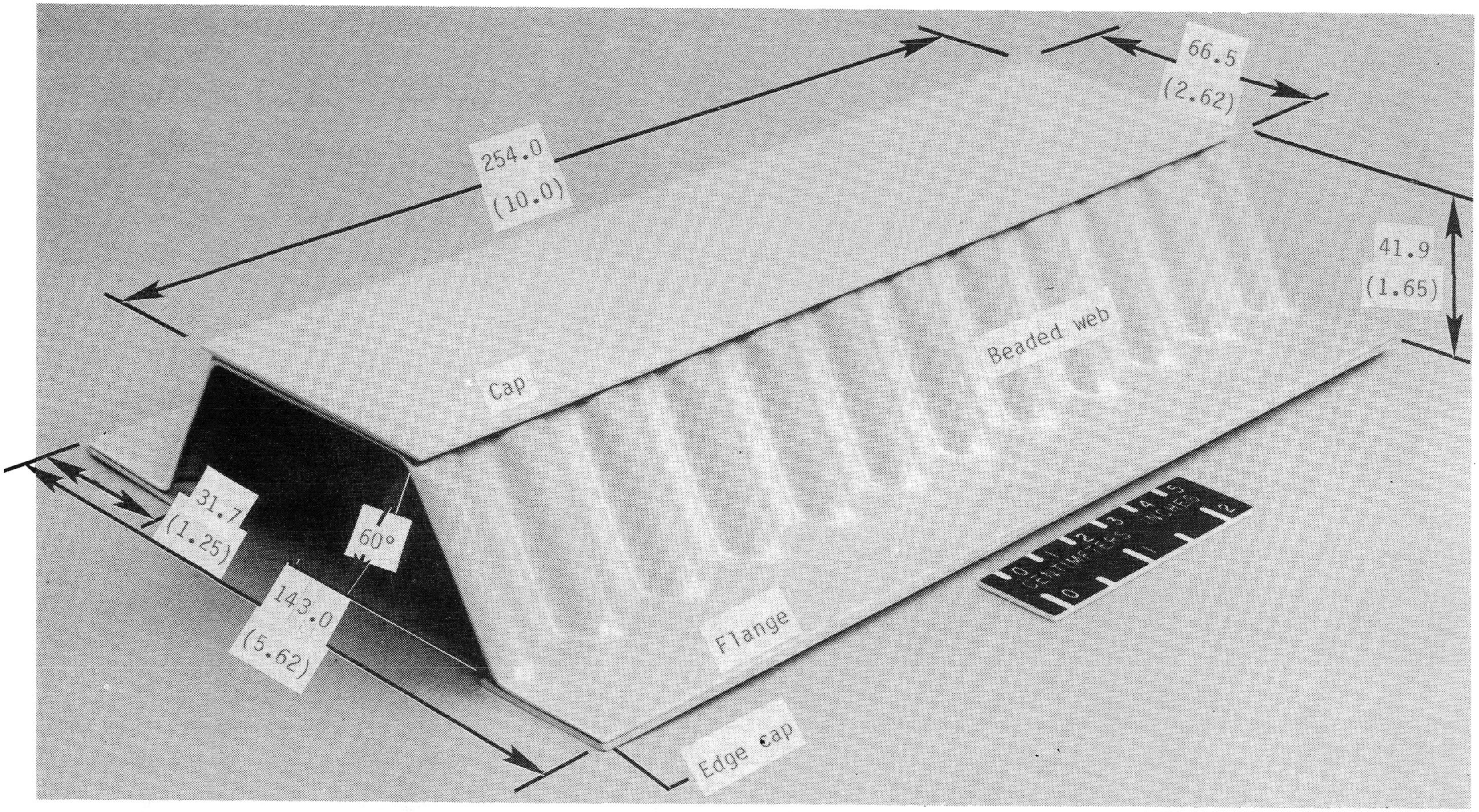
(b) SI units

Panel	Analysis					Test				
	$\bar{A}_m$, in^2	w/ρAL	$\bar{A}_s$, in^2	E$\bar{A}_s$, lbf	Load, lbf	$\bar{A}_m$, in^2	w/ρAL	$\bar{A}_s$, in^2	E$\bar{A}_s$, lbf	Load, lbf
CRPL-1	4.058	0.0112	2.916	33.2	288.1	3.865	0.01060	2.884	32.8	266.4
CRPL-2	4.058	0.0112	2.916	33.2	288.1	3.922	0.01076	2.871	32.7	285.0
CRPL-3	4.058	0.0112	2.916	33.2	288.1	3.884	0.01065	2.806	31.9	280.0
Average	4.058	0.0112	2.916	33.2	288.1	3.890	0.01067	2.854	32.5	277.1
PNL-1	12.32	0.0108	8.916	101.4	880.9	11.548	0.01012	9.671	110.0	787.4
PNL-2	12.32	0.0108	8.916	101.4	880.9	11.613	0.01017	9.239	105.1	782.9
PNL-3	12.32	0.0108	8.916	101.4	880.9	11.548	0.01012	9.110	103.6	792.4
Average	12.32	0.0108	8.916	101.4	880.9	11.570	0.01014	9.340	106.2	787.6


As formed
After trimming

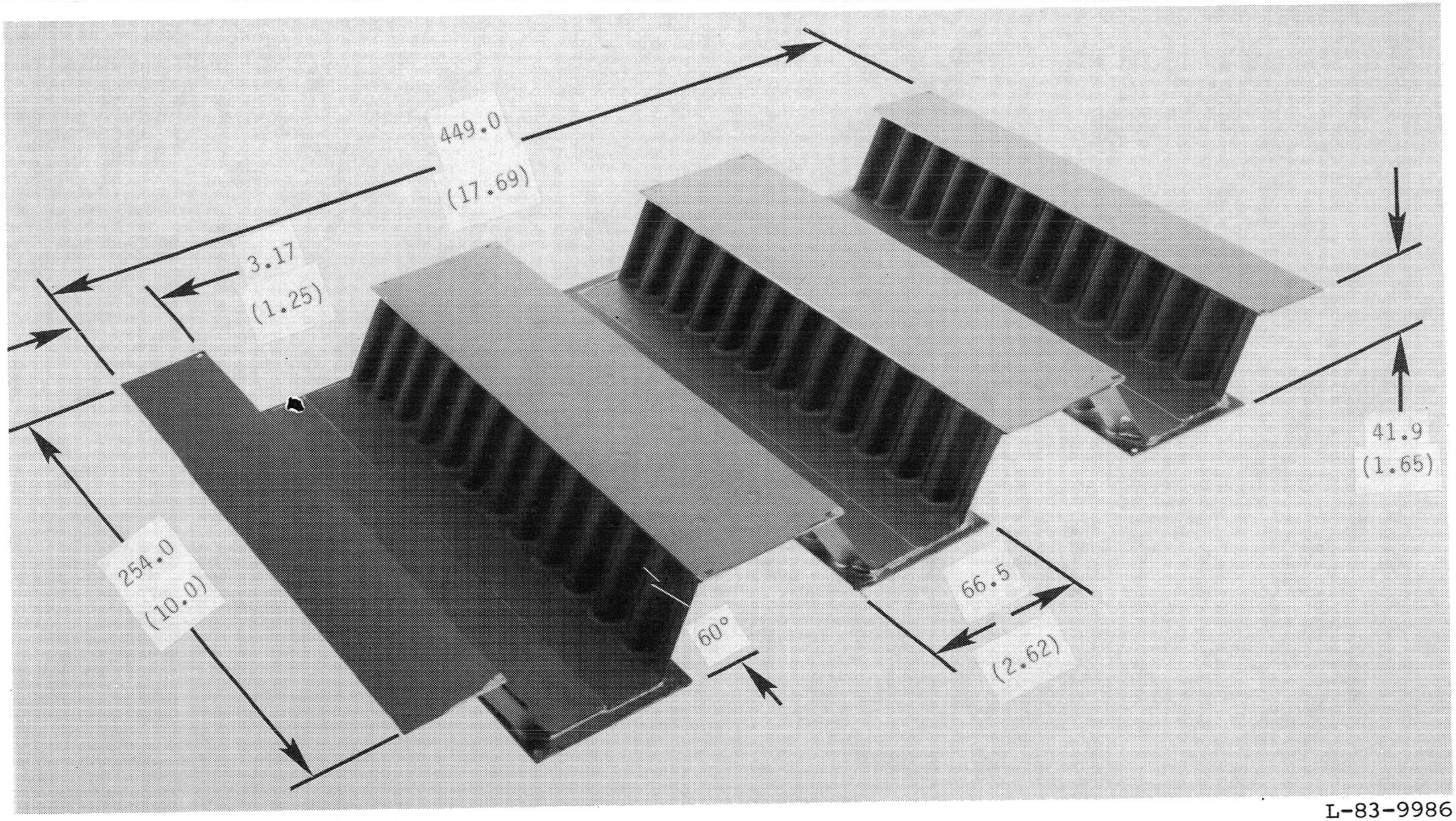
L-83-4372

Figure 1.- Superplastically formed Ti-6Al-4V titanium alloy half-hat element.


254.0
(10.0)
66.5
(2.62)
41.9
(1.65)
Cap
Beaded web
31.7
(1.25)
60°
143.0
(5.62)
Flange
Edge cap
CENTIMETERS
0 1 2 3 4 5
INCHES
0 1 2

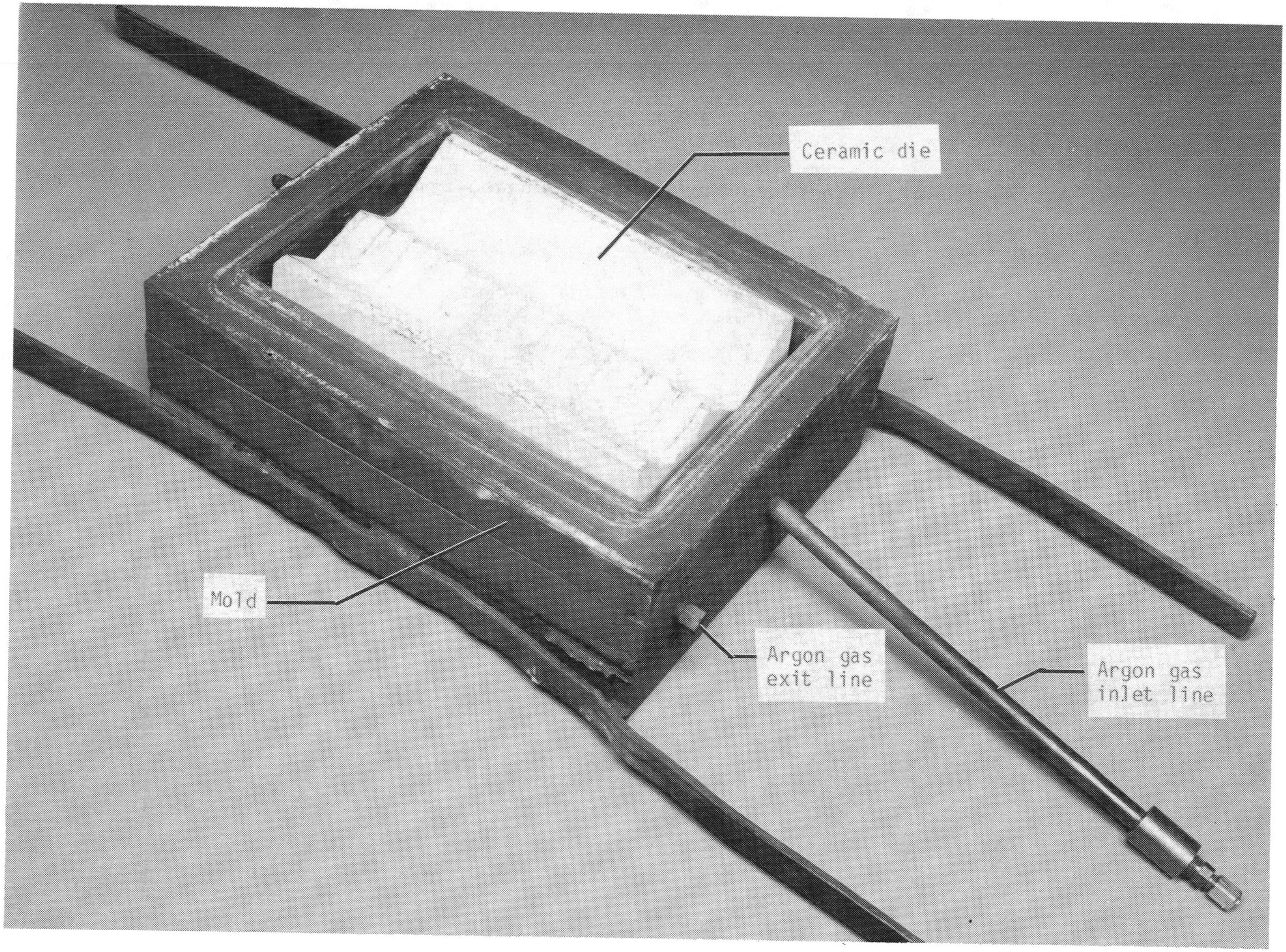
L-84-331

Figure 2.- Single-corrugation compression panel. Dimensions are in millimeters (inches).


449.0
(17.69)
3.17
(1.25)
254.0
(10.0)
60°
66.5
(2.62)
41.9
(1.65)

L-83-9986

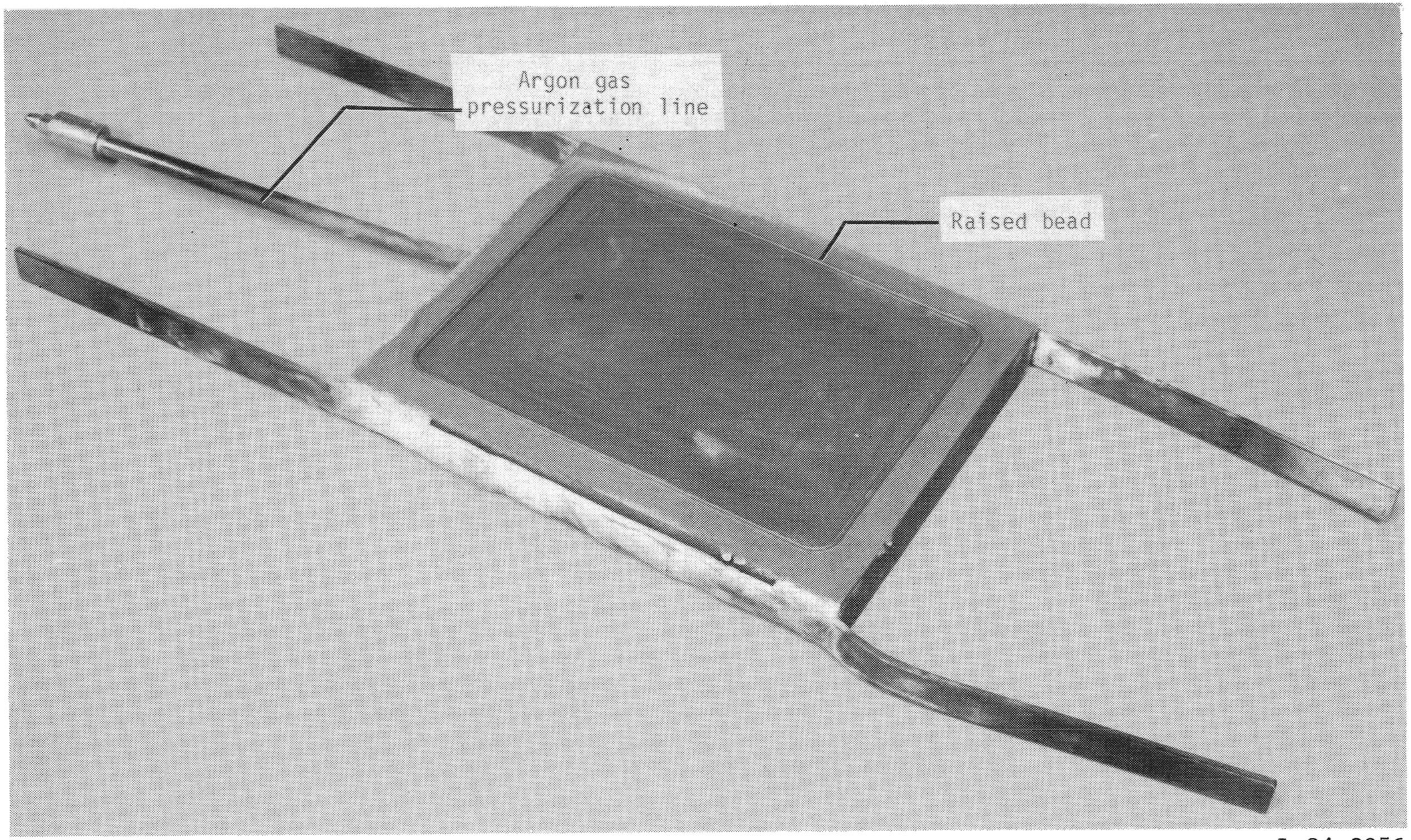
Figure 3.- Multiple-corrugation compression panel. Dimensions are in millimeters (inches).


Ceramic die
Mold
Argon gas exit line
Argon gas inlet line

L-84-3349

(a) Mold and ceramic die.

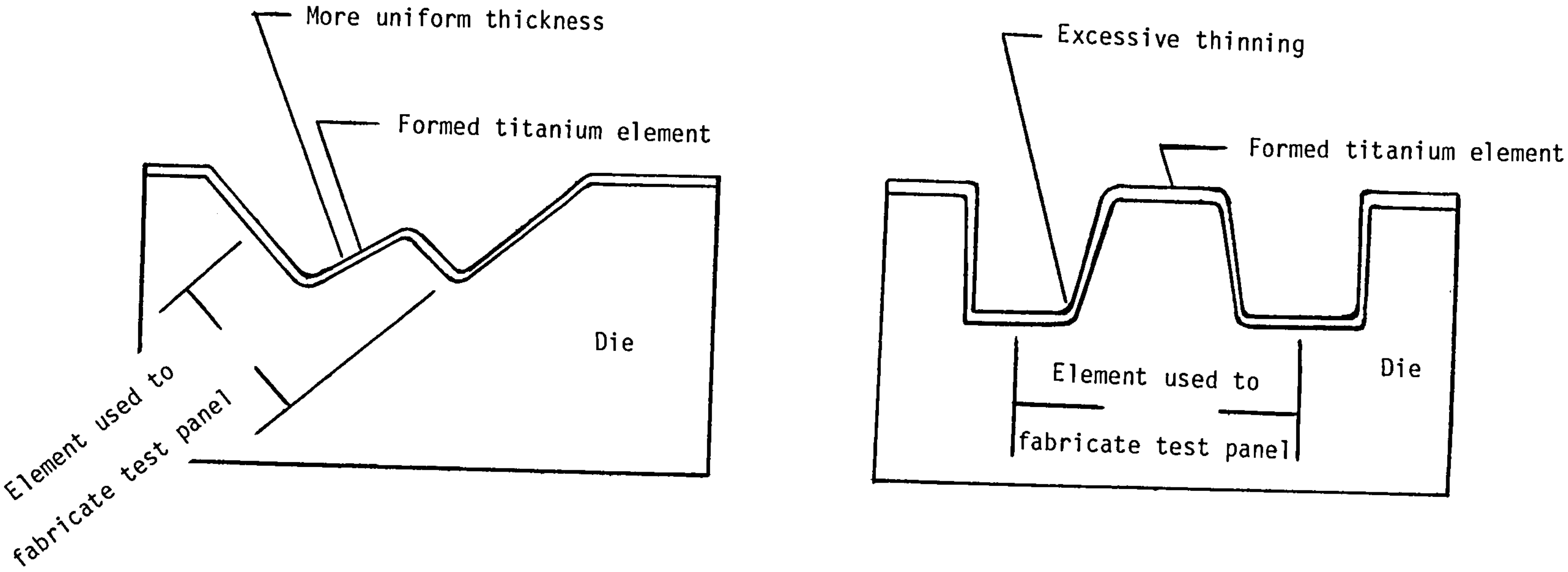
Figure 4.- Tooling for superplastic forming of half-hat element.


Argon gas pressurization line
Raised bead

L-84-3356

(b) Cover plate.

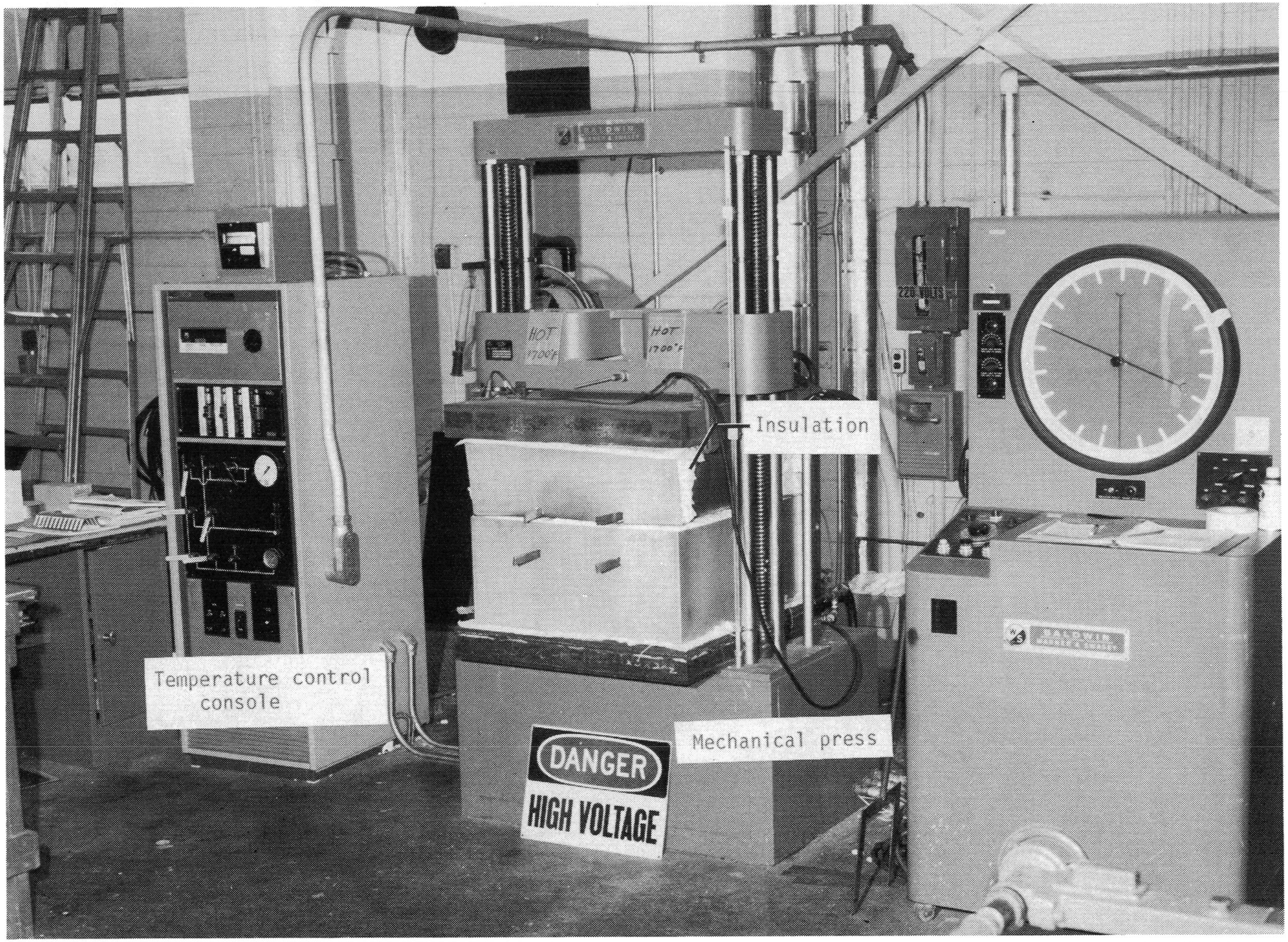
Figure 4.- Concluded.


More uniform thickness
Formed titanium element
Die
Element used to
fabricate test panel
Excessive thinning
Formed titanium element
Die
Element used to
fabricate test panel

Shallow half-hat die

Deep full-hat die

Figure 5.- Cross sections of tooling configurations for superplastic forming hat-shaped elements.


Insulation
Temperature control console
Mechanical press
DANGER
HIGH VOLTAGE
HOT 1700°F
HOT 1700°F
220 VOLTS

L-83-11,148

Figure 6.- Superplastic forming equipment to form half-hat elements.

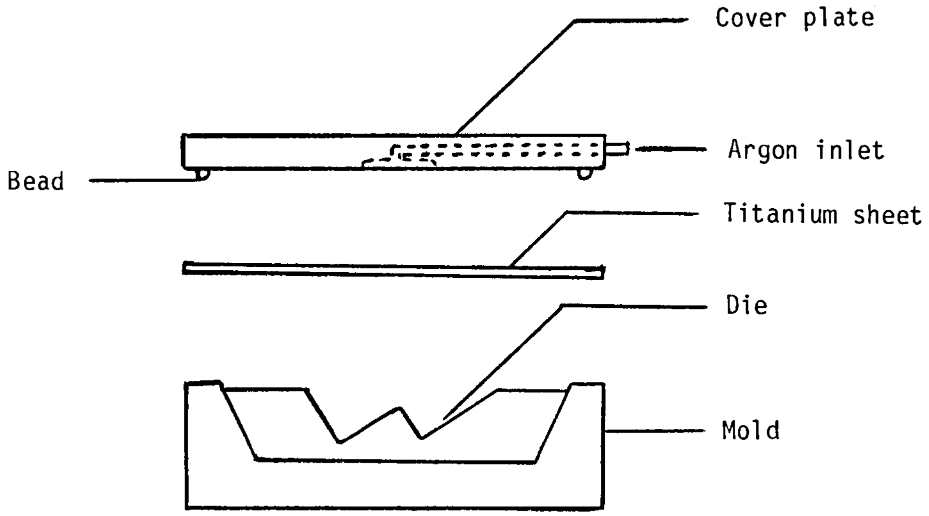
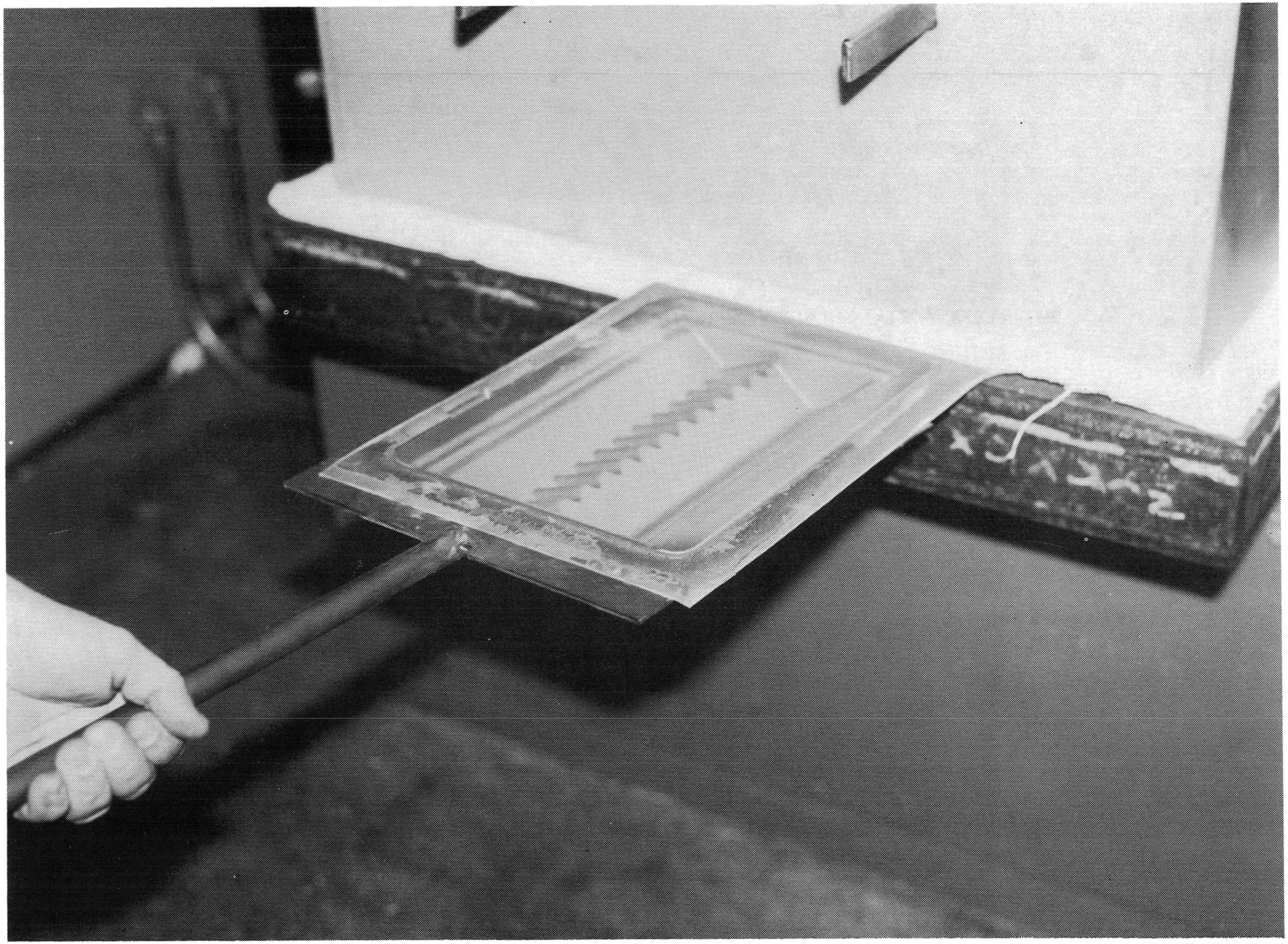
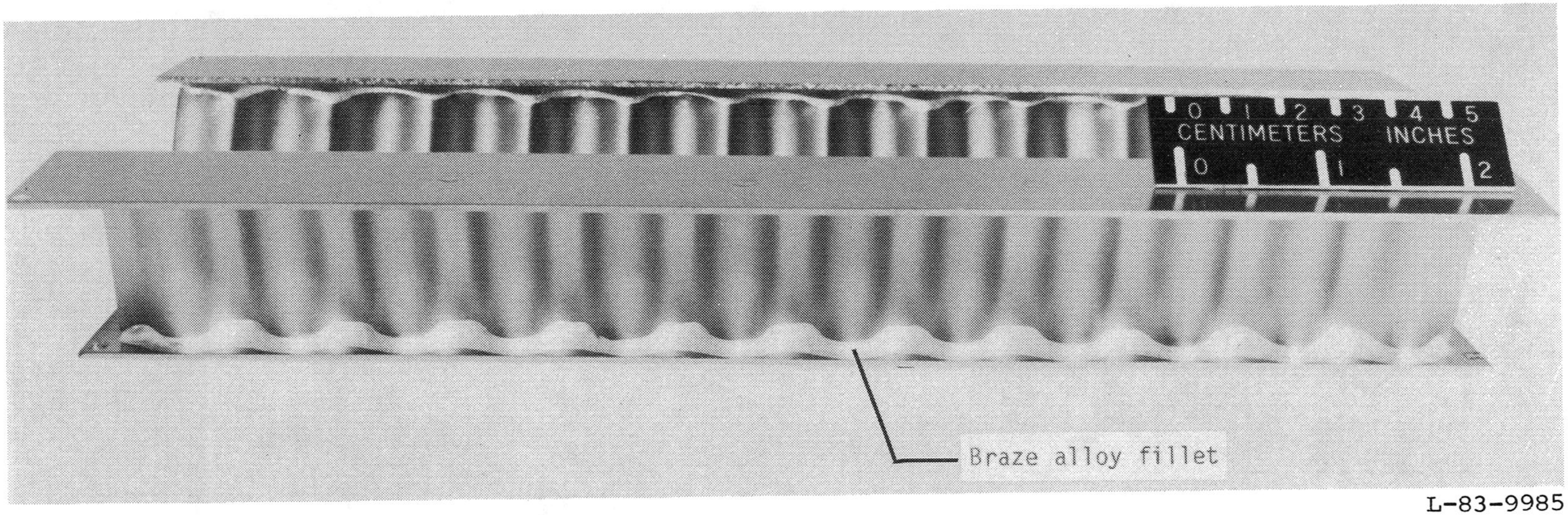

Cover plate
Argon inlet
Bead
Titanium sheet
Die
Mold

Figure 7.- Cross section of assembled tooling.



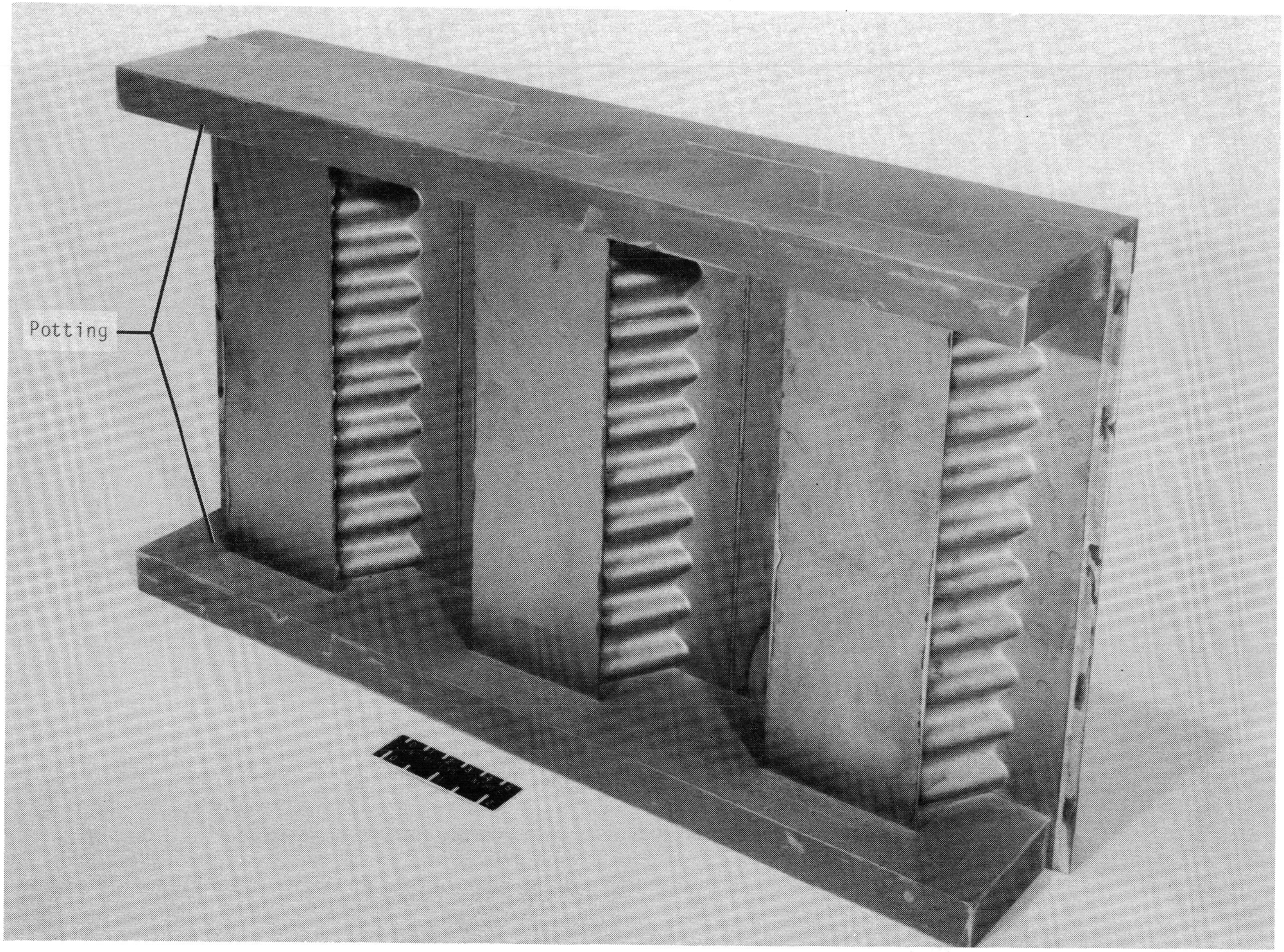
L-83-11,147

Figure 8.- Superplastically formed element being removed from mold.


0 1 2 3 4 5
CENTIMETERS
INCHES
0 1 2
Braze alloy fillet

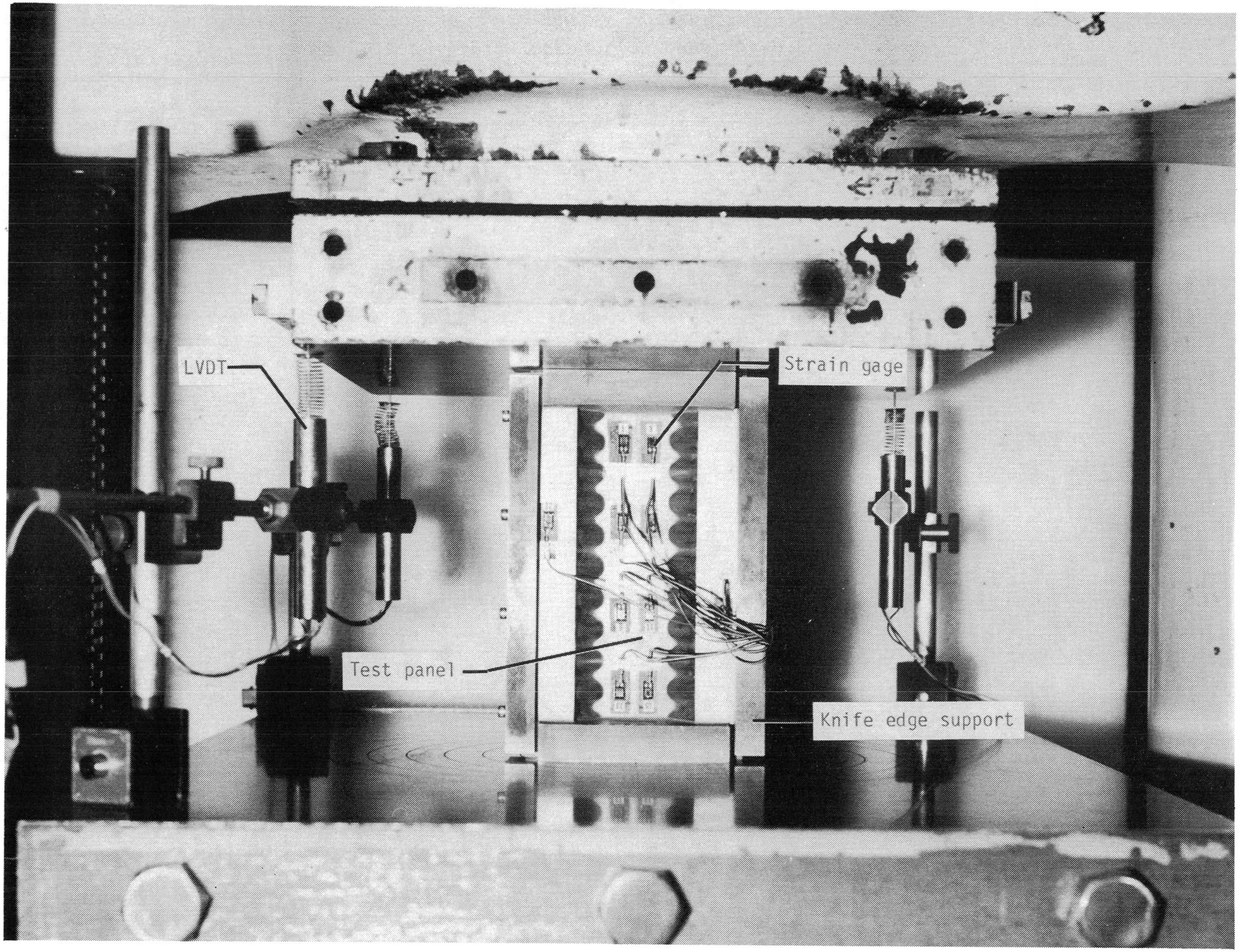
L-83-9985

Figure 9.- Single-corrugation panel showing braze alloy filleting.



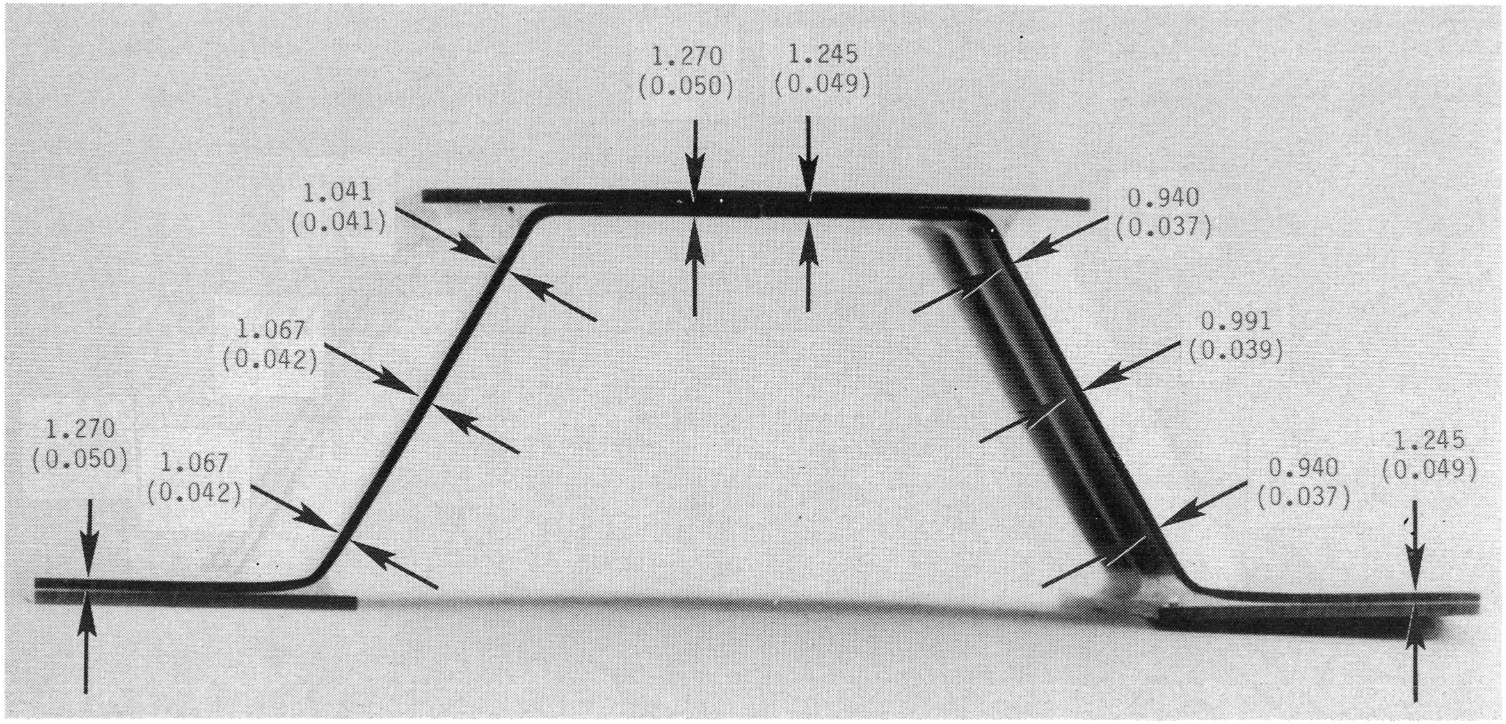
L-84-332

Figure 10.- Multiple-corrugation panel with potted ends.


LVDT
Strain gage
Test panel
Knife edge support

L-85-141

Figure 11.- Test setup for single-corrugation panel.


1.270
(0.050)
1.245
(0.049)
1.041
(0.041)
0.940
(0.037)
1.067
(0.042)
0.991
(0.039)
1.270
(0.050)
1.067
(0.042)
0.940
(0.037)
1.245
(0.049)

L-84-5536

Figure 12.- Uniformity of thickness of a superplastic formed single-corrugation panel. Dimensions are in millimeters (inches).

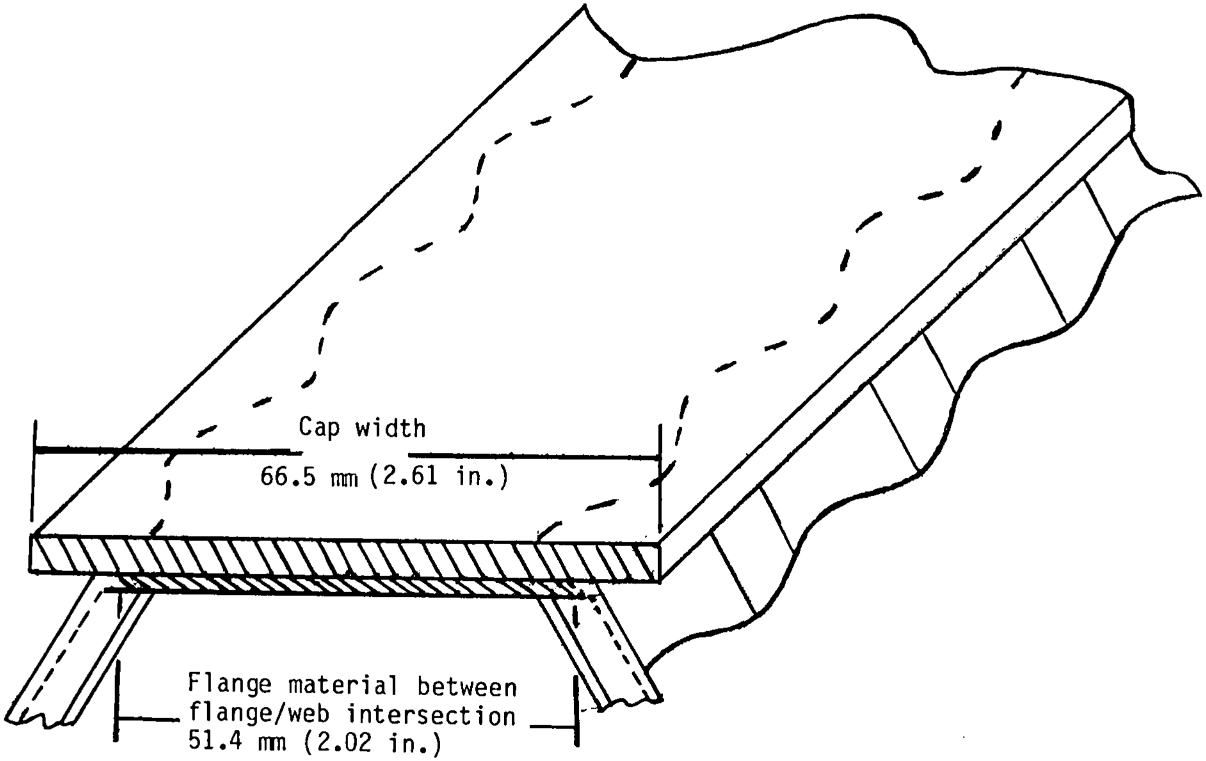
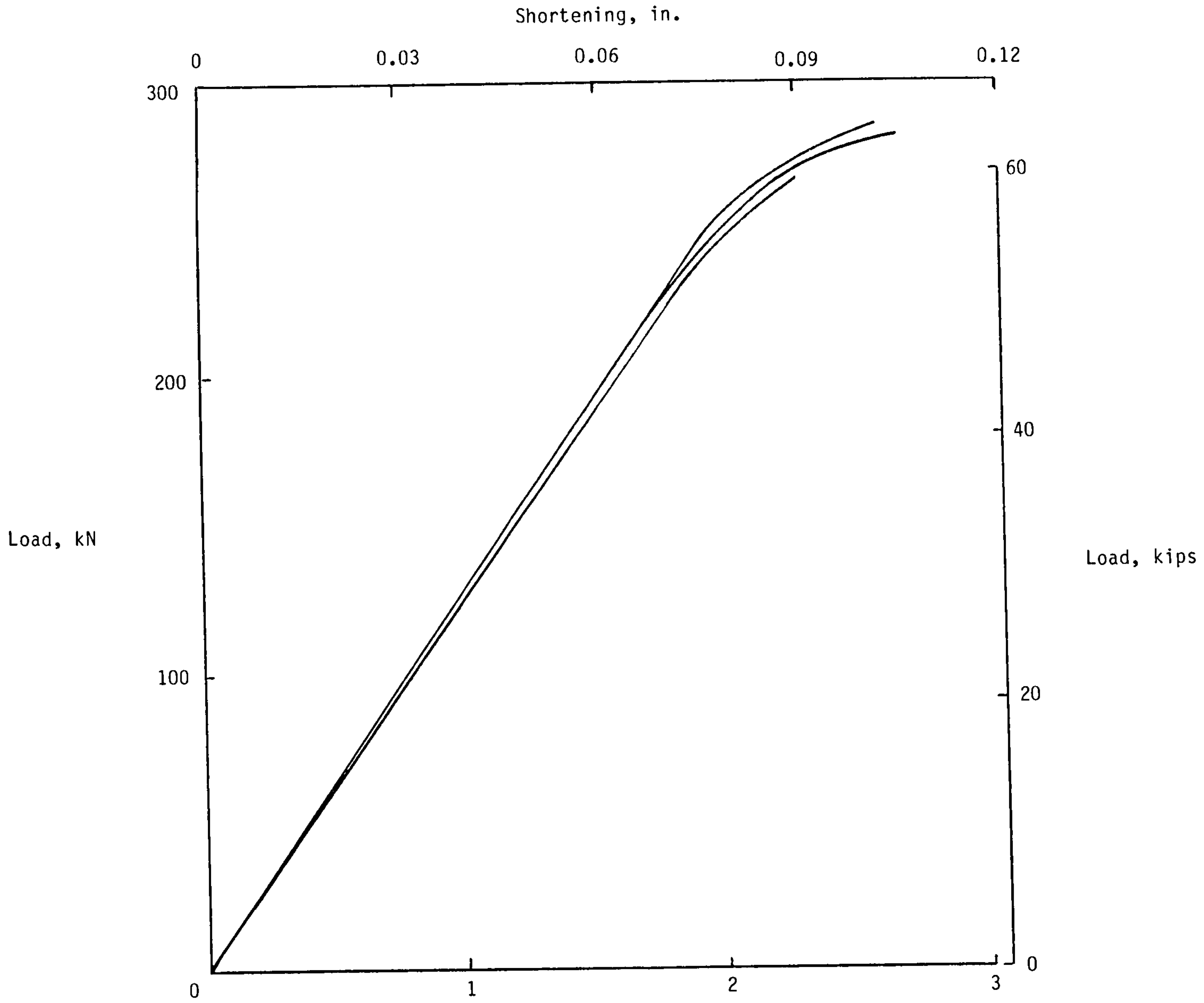
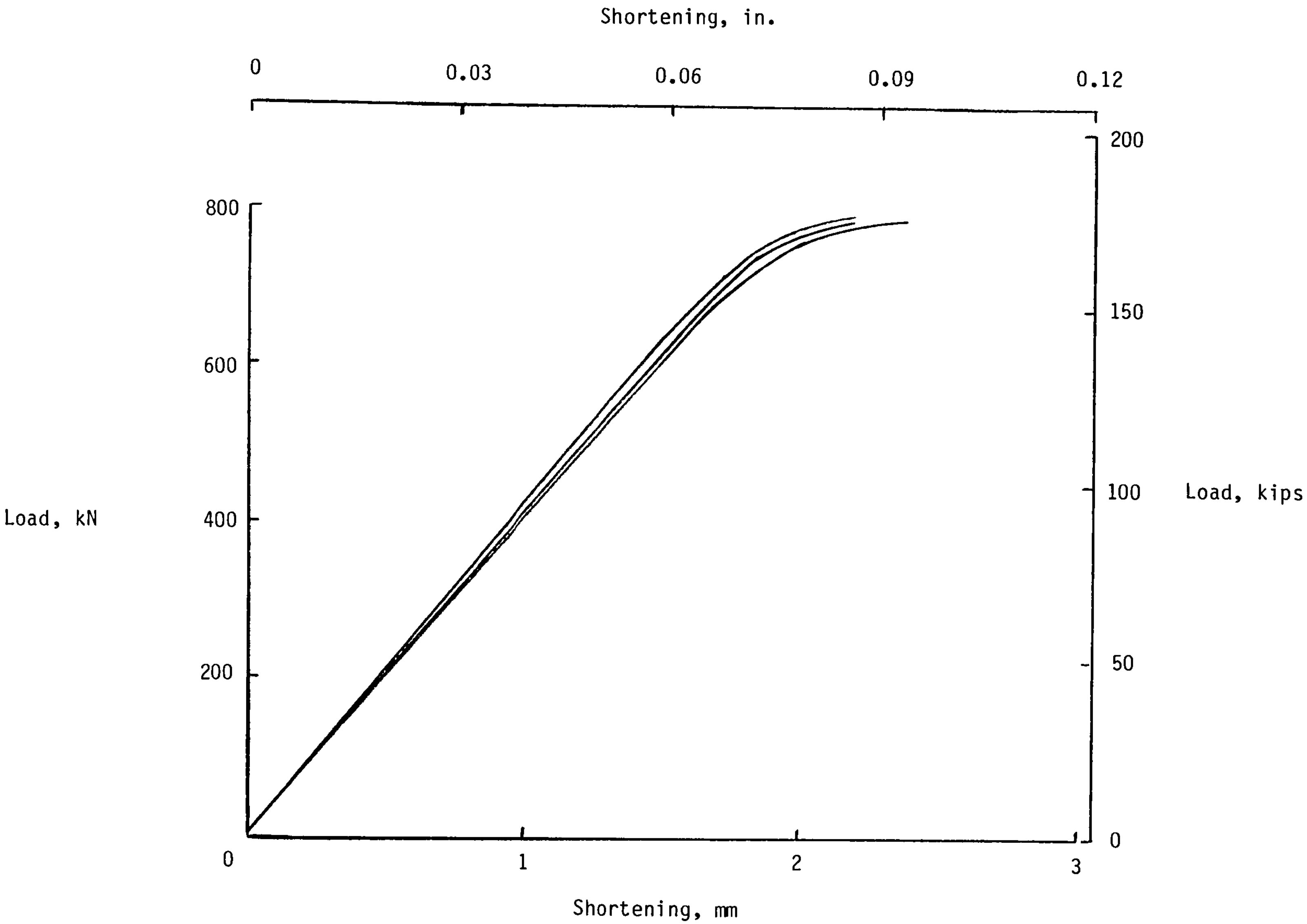

Cap width
66.5 mm (2.61 in.)
Flange material between
flange/web intersection
51.4 mm (2.02 in.)

Figure 13.- Schematic of cap/flange cross-sectional area showing load-carrying material (hatched).



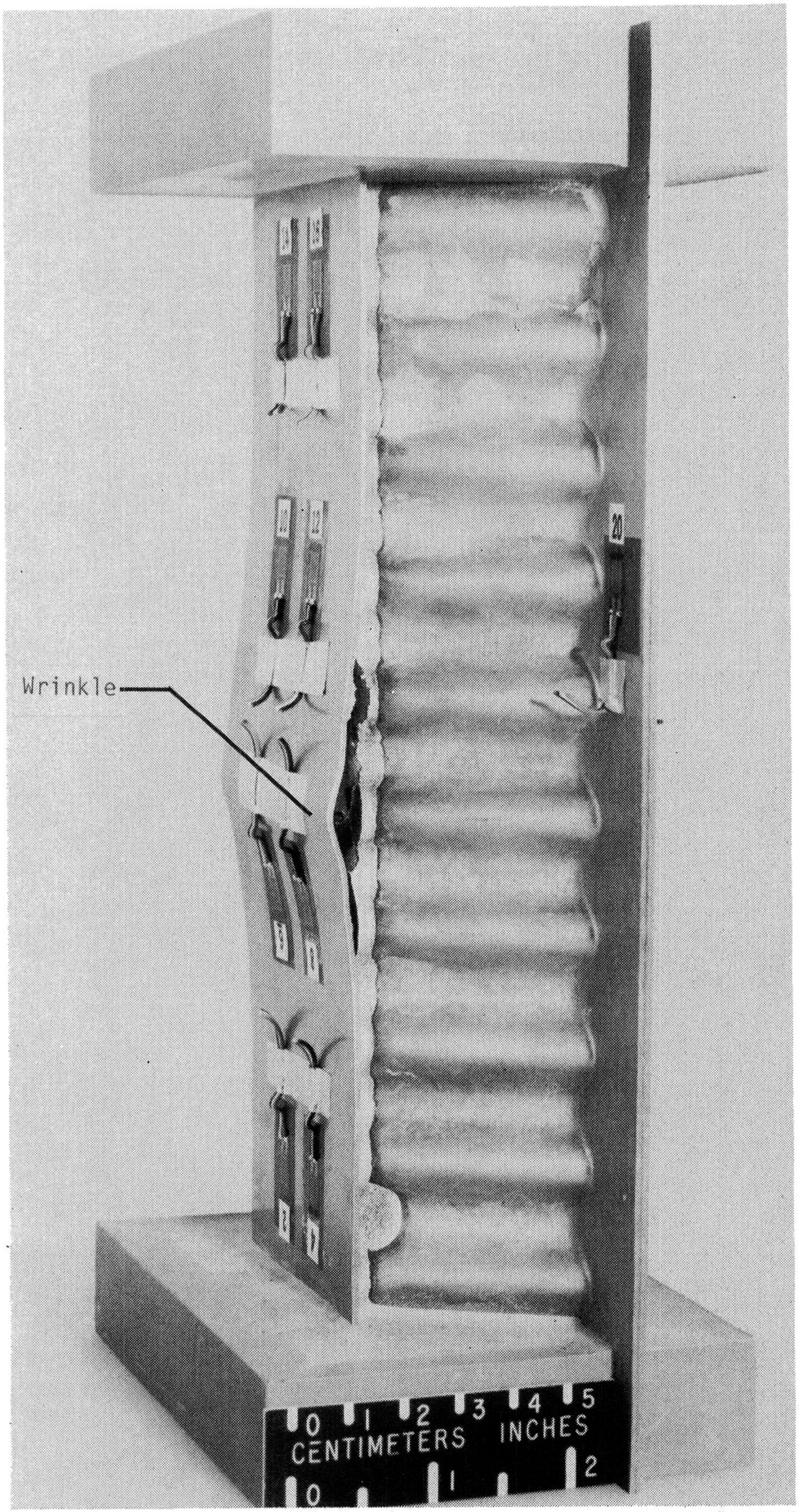
(a) Single corrugation.

Figure 14.- Load-shortening curves for compression panels.



(b) Multiple corrugation.

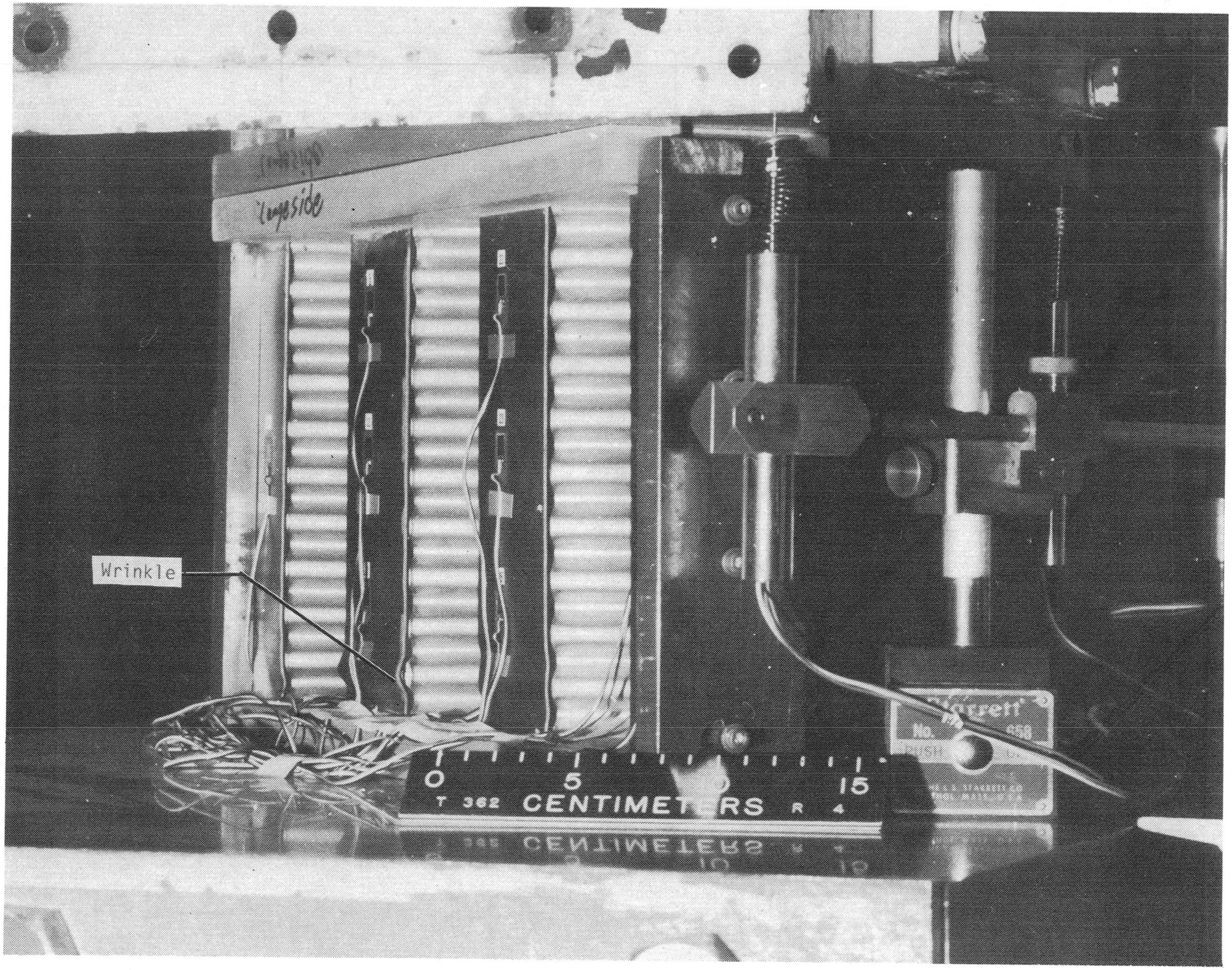
Figure 14.- Concluded.


Wrinkle
20
0 1 2 3 4 5
CENTIMETERS INCHES
0 1 2

L-83-11,986

(a) Single corrugation.

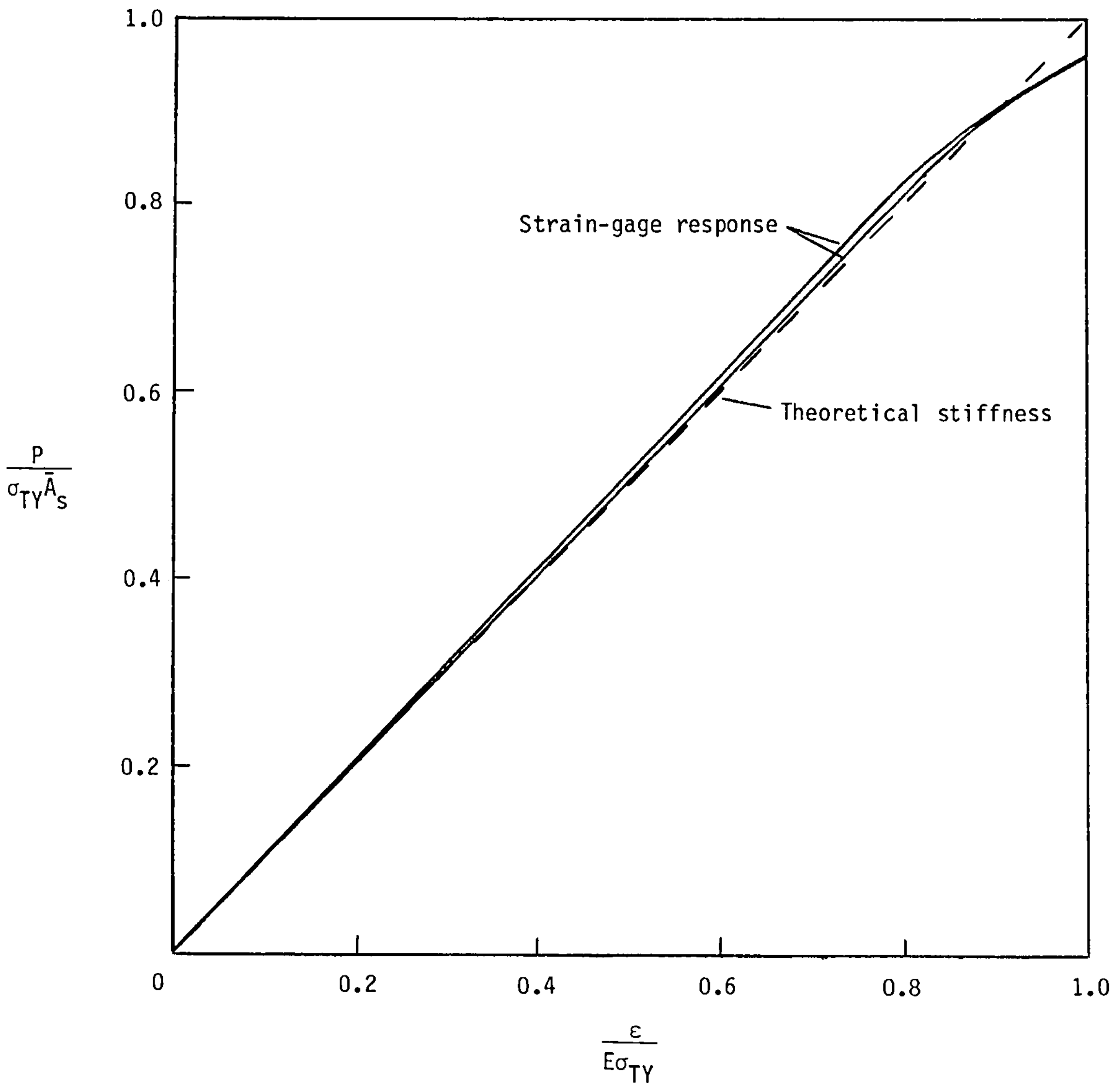
Figure 15.- Typical failure for compression panels.


Wrinkle
0
5
15
T 362
CENTIMETERS
R 4

L-85-142

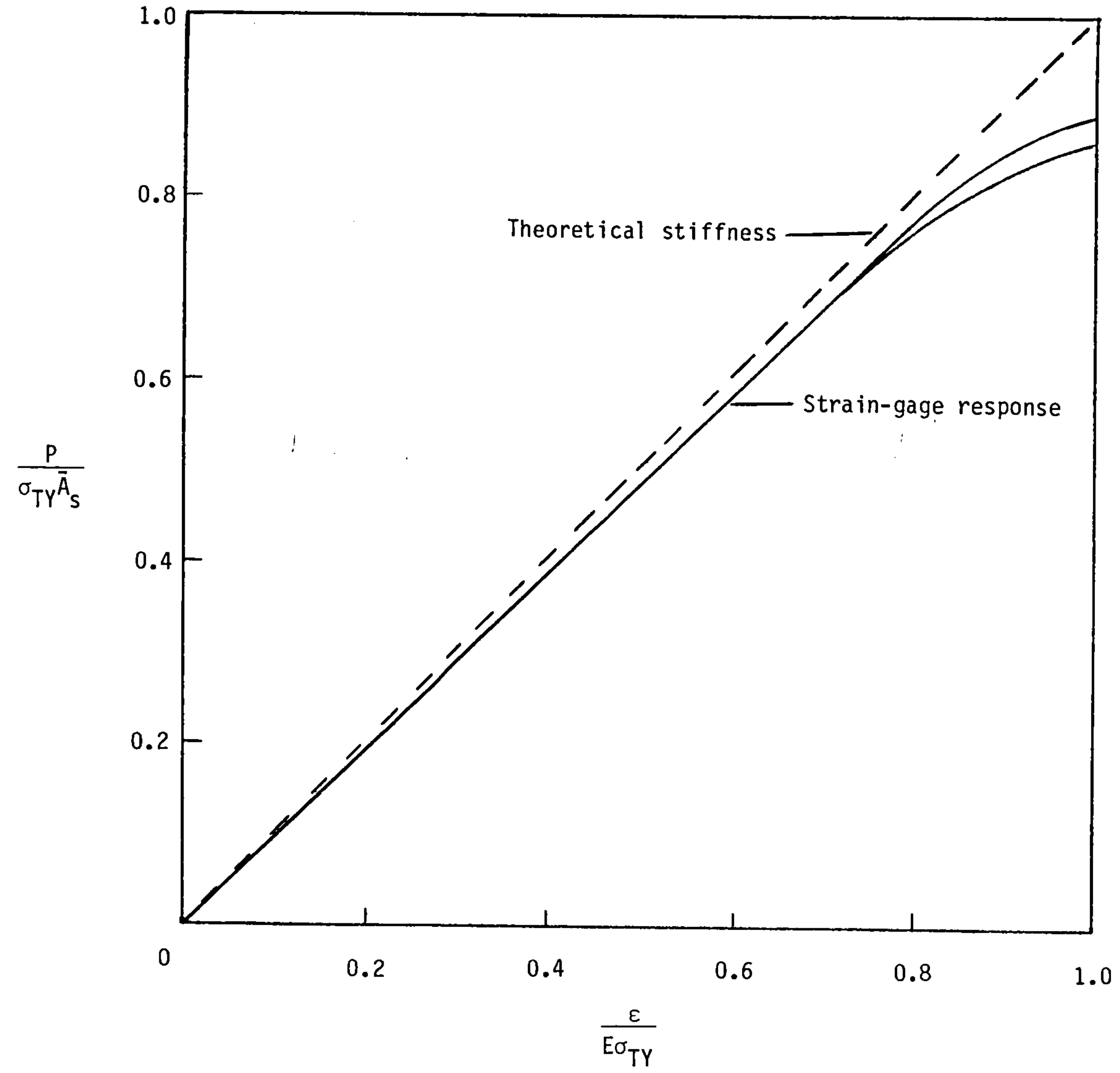
(b) Multiple corrugation.

Figure 15.- Concluded.



(a) Single corrugation.

Figure 16.- Sample back-to-back load-strain response for cap of stiffened panels.



(b) Multiple corrugation.

Figure 16.- Concluded.

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16. Abstract

A study was made to investigate the feasibility of superplastically forming corrugated panels with beaded webs and to demonstrate the structural integrity of these panels by testing. The test panels in the study consisted of superplastically formed titanium alloy Ti-6Al-4V half-hat elements that were joined by weld-brazing to titanium alloy Ti-6Al-4V caps to form either single-corrugation compression panels or multiple-corrugation compression panels. Stretching and subsequent thinning of the titanium sheet during superplastic forming was reduced by approximately 35 percent with a shallow half-hat die concept instead of a deep die concept and resulted in a more uniform thickness across the beaded webs. The completed panels were tested in end compression at room temperature and the results compared with analysis. The heavily loaded panels failed at loads approaching the yield strength of the titanium material. At maximum load, the caps wrinkled locally accompanied with separation of the weld-braze joint in the wrinkle. None of the panels tested, however, failed catastrophically in the weld-braze joint. Experimental test results were in good agreement with structural analysis of the panels.

17. Key Words (Suggested by Authors(s))
- Titanium
- Superplastic forming
- Weld-brazing
- Compression panels
- Experimental and predicted panel behavior

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