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**Scientific and Technical
Information Branch**

INTRODUCTION

Recent studies have shown that titanium can be very readily formed at elevated temperatures by using superplastic forming and successfully joined by either codiffusion bonding just prior to or subsequent to superplastic forming or by a postforming process such as welding or weld-brazing (refs. 1 through 4). The study in reference 1 reports the development of the superplastic forming and diffusion bonding (SPF/DB) process to fabricate expanded sandwich structures and also shows that combining the two processes could be beneficial since the temperatures for superplastic forming and diffusion bonding titanium were the same. The study in reference 2 demonstrated the intricate detail that can be incorporated in the design of structural panels by spot-welding or roll-welding the panel parts together prior to superplastic forming. One advantage of the processes developed in references 1 and 2 is that several sheets of titanium can be readily joined and formed in one operation. In reference 3, superplastic forming and weld-brazing were successfully combined to fabricate 18 titanium skin-stiffened structural panels having six different stiffener configurations. The compressive strength of these panels was evaluated at room temperature and the data showed that the panels having advanced shaped stiffeners developed from 20 to 58 percent higher local buckling strengths than panels with conventionally shaped stiffeners. Fabrication of the advanced shaped stiffeners was made possible by the increased formability afforded by the superplasticity characteristics of the titanium alloy Ti-6Al-4V.

The objective of the research reported herein was to evaluate the 316°C (600°F) performance of the compression panel designs reported in reference 3. The test temperature of 316°C (600°F) was selected as being representative of the upper use temperature for Ti-6Al-4V alloy on future supersonic cruise aircraft. Stiffeners having configurations of a conventional hat, beaded web, modified beaded web, ribbed web, or stepped web were investigated. The data from the panel tests including load-shortening curves, local buckling strengths, and failure loads are compared with data from the panels tested at room temperature and reported in reference 3.

SPECIMEN FABRICATION

The specimens in this study were compression panels consisting of a superplastically formed (SPF) Ti-6Al-4V stiffener joined by weld-brazing (WB) to a Ti-6Al-4V alloy skin. Fabrication details are reported in reference 3 and are summarized briefly herein. Fabrication of the stiffeners was initiated by placing a sheet of 1.27-mm (0.050-in.) thick titanium between the cover plate and the female mold as indicated in figure 1. The female mold had a raised bead around the perimeter that the titanium sheet contacted to make a seal for pressurizing with argon gas or pumping a vacuum. The assembled tooling was placed between ceramic platens mounted in a press. Internal heater elements in the platens were used to provide the required heat source. External pressure was applied by the press to maintain a seal between the cover plate, titanium sheet, and female mold as well as to react the forming pressure provided by the argon gas. The platens were heated until the mold and titanium reached 927°C (1700°F) at which time a vacuum was pulled on the female mold. Argon gas pressure up to 862 kPa (125 psi) was incrementally applied through the cover plate to form the titanium stiffeners. The total time at 927°C (1700°F) during stiffener forming was 70 min.

The female mold and several of the male die inserts for the stiffener configurations evaluated in this study are shown in figures 2 and 3. One die insert was used to form a conventional hat stiffener. The remaining die inserts were used to form advanced shaped stiffeners having either a beaded web, a modified beaded web, a ribbed web, or a stepped web. The advanced shaped stiffeners are either difficult to form or cannot be formed by conventional titanium fabrication methods. The shapes of the advanced stiffeners were selected on the basis of improving buckling strength and to accentuate the characteristic advantages of superplastic forming of titanium. A typical SPF stiffener is shown in figure 4 after being removed from the mold, cleaned, and trimmed.

Each stiffener was joined to a 1.27-mm (0.050-in.) thick titanium skin using the weld-brazing process. The components and the 0.406-mm (0.016-in.) thick 3003 aluminum braze alloy are shown in figure 5. Following chemical cleaning, two rows of four spot-welds were used to attach each flange of the stiffener to the skin. Braze alloy strips were placed adjacent to the joints to be brazed and the assembly was then placed in the brazing furnace. Fixturing provided by the spot-welds was sufficient to maintain alinement and, therefore, no tooling was required. Brazing was accomplished in a vacuum furnace at a temperature of 677°C (1250°F) over a time period of 5 min. Upon melting, the braze alloy was drawn into the faying surface between the stiffener and skin by capillary action and produced a hermetically sealed, high strength joint. Using the superplastic forming/weld-brazing (SPF/WB) process, 14 compression panels were fabricated for testing at 316°C (600°F).

The SPF/WB panels were trimmed on the edges and ends, and the ends of the panels were potted using an elevated temperature epoxy potting compound (Epoxylite #813-9) that was cast around titanium clips spot-welded to the panel ends. The clips were used to prevent separation of the epoxy from the panels during cure of the epoxy or testing at 316°C (600°F) due to differences in thermal expansion between the titanium and the epoxy. The potting material was used to facilitate grinding the ends of the panels flat, parallel to each other, and perpendicular to the skin. The potting also served to prevent premature failure of the ends of the panels during compression testing. A typical finished test panel shown in figure 6 was 254 mm (10 in.) long and 121 mm (4.75 in.) wide.

TEST PROCEDURE

The SPF/WB skin-stiffened structural panels were loaded in end compression at test temperature by using a 1.3-MN-capacity (300-kip) hydraulic testing machine. The unloaded edges of the specimens were supported with knife edge fixtures positioned 6.35 mm (0.25 in.) from the edge as shown in figure 7. Relative motion between the upper and lower heads of the testing machine was measured with linear variable differential transformers (LVDT). Foil strain gages were attached to the stiffener and skin as shown in figure 7 and were used to measure load-strain response in the panel. The panels were heated by quartz lamps with gold-plated reflectors which have been removed for the photographs in figure 7. Both the skin and stiffener sides of the panels were heated to the test temperature of 316°C (600°F). A temperature survey on a representative panel was used to determine uniformity of heating. The survey indicated a temperature range of +28°C to -28°C (+50°F to -50°F) over the entire panel and a temperature range of +5°C to -5°C (+10°F to -10°F) in the strain-gage area. Panels were heated at a rate of 0.5°C/s (50°F/min) and held at temperature for 20 min prior to loading. The strain gages were balanced, the heads of the test machine were brought into contact with the panels, and the tests were conducted at a load rate of

890 N/s (1200 lb/min) until maximum load was achieved. Data were recorded every 2 s prior to local instability and every second from there to maximum load.

RESULTS

Specimen Fabrication

Stiffeners with either a conventional shape or advanced shapes formed superplastically to the desired configurations required no additional sizing or shaping following removal from the mold. Typical thinning of the titanium sheet resulting from SPF a stiffener is shown in figure 8. The thinning of the titanium on the crown of the stiffener is minimal and is an advantage of the female mold/male die insert forming concept. The weld-brazing process by which the stiffeners were attached to the skins utilized spot-welds to maintain alinement and no additional tooling was required for brazing. A photomicrograph of a typical weld-braze joint cross section is shown in figure 9. The 3003 aluminum braze alloy melted and flowed through the faying surface gap and completely surrounded the spot-weld nugget. Also shown in the figure is the grain growth in the titanium associated with SPF a stiffener as compared with the small grains of the as-received titanium represented by the skin material.

Specimen Tests

Load shortening.- Typical panel load-shortening data obtained from the LVDT's for each of the stiffener configurations tested at 316°C (600°F) are shown in figure 10. For ease of comparison, the load-shortening curves from reference 3 for similar panels tested at room temperature are also shown in figure 10. The load-shortening curves for all panels tested at 316°C (600°F) show that the initial stiffness (see fig. 10 for stiffness values) was 10 to 17 percent lower than the initial stiffness of the panels having the same stiffener configurations and tested at room temperature. This reduction in initial stiffness was expected and is explained by material property data from reference 5, which show an 18-percent reduction in the modulus of elasticity of Ti-6Al-4V from room temperature to 316°C (600°F). Deviation from linearity of load-shortening curves indicates the initiation of buckling of the panel.

Loading of the panels continued until instantaneous crippling of the skin and stiffener occurred. This load was defined as the maximum load carried by the panel and is represented by termination of the load-shortening curves in figure 10 and is tabulated in table I. None of the panels tested exhibited a separation failure of the weld-braze joint (see fig. 11). The additional load the panels carried from buckling to the maximum load ranged from 8 to 41 percent. By comparison, the room temperature panels of reference 3 carried a maximum load ranging from 15 to 74 percent higher than buckling. (See table II.) The difference in maximum load at room temperature and elevated temperature is to be expected since the data in reference 5 show a 35-percent difference in compression yield strength for Ti-6Al-4V alloy at room temperature and 316°C (600°F).

Buckling load.- The average buckling load for each panel configuration is shown in figure 12. The buckling load is defined as the load where the load-strain response curves reversed as indicated by the strain gages on the panels and is tabulated in table I for each panel tested at 316°C (600°F). The panels with the conventional hat stiffener developed an average buckling load at 316°C (600°F) of

121 kN (27 170 lbf). The panels with beaded web and modified beaded web stiffeners developed average buckling loads at 316°C (600°F) of 114 kN (25 734 lbf) and 114 kN (25 696 lbf), respectively. The highest average buckling loads achieved at 316°C (600°F) were with the panels having ribbed web and stepped web stiffeners, 151 kN (33 974 lbf) and 154 kN (34 610 lbf), respectively. This is a 25- and 27-percent increase in buckling load at 316°C (600°F), respectively, over the panels with the conventional hat shaped stiffener. The higher buckling loads of these panels over the panels with the conventional hat stiffener were obtained at no increase in panel weight and thus were due strictly to the structural shapes that can be fabricated by the SPF process.

The average buckling loads for the panels tested at 316°C (600°F) are compared with the average buckling loads from panels tested at room temperature in figure 12. A comparison of the data revealed that the average buckling load at 316°C (600°F) for the panels with the conventional hat stiffener is 11 percent less than the average buckling load at room temperature. However, the panels having stiffeners with the beaded web, modified beaded web, ribbed web, or stepped web configuration exhibited average buckling loads at 316°C (600°F) that are 30, 40, 26, and 28 percent less than the respective buckling loads at room temperature.

These buckling load differences can be explained by the tensile stress-strain data tabulated in table III and represented graphically in figure 13. The data are from titanium sheet material used to fabricate the stiffeners and skins of the panels in the current study. Prior to testing, the tensile specimens were thermally exposed to simulate the temperatures and times associated with an SPF/WB cycle. The data show that yield strength at 316°C (600°F) is 35 percent less than the value measured at room temperature and modulus of elasticity at 316°C (600°F) is 10 percent less than the value measured at room temperature. This agrees well with titanium material property data from reference 5, which show a 32-percent reduction in compression yield strength between room temperature and 316°C (600°F) and an 18-percent reduction in modulus of elasticity between room temperature and 316°C (600°F). For each panel tested, the average strain at the buckling load was computed from the load-shortening data and tabulated in tables I and II. The stress-strain curves in figure 13 in conjunction with the average strain at the buckling load for the panels with the conventional hat stiffener tested at room temperature and 316°C (600°F) show that these panels buckled in the elastic region of the stress-strain curves and an approximate 10-percent reduction in material properties would be expected. The panels with the advanced shaped stiffeners developed average strains at buckling that were higher than the proportional limit of the stress-strain curves and material property reductions of approximately 35 percent would be expected.

CONCLUDING REMARKS

Two titanium processing procedures, superplastic forming and weld-brazing, were successfully combined to fabricate compression panels with advanced shaped stiffeners that exhibited higher buckling loads at 316°C (600°F) than panels with conventional hat shaped stiffeners. The panels having stiffeners with the ribbed web or stepped web configurations exhibited buckling loads that were 25 and 27 percent higher, respectively, than panels with conventional hat shaped stiffeners. After buckling, all panels continued to carry additional load up to the maximum load where instantaneous crippling of the skin and stiffener occurred. None of the panels exhibited a separation failure of the weld-braze joint.

The buckling loads at 316°C (600°F) for panels having stiffeners of the conventional hat, beaded web, modified beaded web, ribbed web, or stepped web configurations were 11, 30, 40, 26, and 28 percent lower, respectively, than the buckling loads for the same panel configurations tested at room temperature. The reductions can be predicted based on the reduction in material properties for titanium at 316°C (600°F) compared with values at room temperature.

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January 31, 1983

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TABLE I.- SUPERPLASTICALLY FORMED/WELD-BRAZED COMPRESSION PANEL DATA

[316°C (600°F) tests]

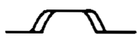
Stiffener configuration		Buckling load, kN	Buckling load, lbf	Average strain at buckling, in/in.	Maximum load, kN	Maximum load, lbf
Conventional hat		126 120 117	28 243 26 953 26 313	0.00370 .00350 .00343	164 156 159	36 953 35 077 35 847
Beaded web		113 111 120	25 337 24 870 26 996	0.00432 .00411 .00461	139 141 142	31 168 31 790 31 942
Modified beaded web		119 116 109	26 752 25 939 24 398	0.00438 .00415 .00401	154 154 154	34 543 34 576 34 510
Ribbed web		143 151 160	32 181 33 862 35 879	0.00478 .00497 .00517	161 164 168	36 281 36 857 37 734
Stepped web		154 154	34 545 34 676	0.00540 .00542	167 166	37 474 37 344

TABLE II.- SUPERPLASTICALLY FORMED/WELD-BRAZED COMPRESSION PANEL DATA

[Room temperature tests from reference 3]

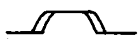
Stiffener configuration	Buckling load, kN	Buckling load, lbf	Average strain at buckling, in/in.	Maximum load, kN	Maximum load, lbf
Small conventional hat 	139	31 219	0.00384	189	42 551
	130	29 148	.00375	226	50 760
	137	30 818	.00387	223	50 239
Large conventional hat 	146	32 846	0.00394	226	50 922
	164	36 825	.00436	227	51 107
	143	32 054	.00399	219	49 209
Beaded web 	173	38 929	0.00578	210	47 105
	167	37 498	.00562	201	45 186
	147	33 019	.00479	190	42 681
Modified beaded web 	192	43 169	0.00628	221	49 675
	189	42 562	.00621	206	46 303
	187	42 150	.00631	221	49 632
Ribbed web 	218	49 025	0.00627	244	54 967
	178	40 024	.00502	247	55 422
	214	48 200	.00604	253	56 789
Stepped web 	221	49 653	0.00648	256	57 504
	205	45 988	.00605	247	55 607
	215	48 320	.00611	248	55 750

TABLE III.- TENSILE PROPERTIES OF Ti-6Al-4V SHEET MATERIAL[a]

Specimen	Cross-section area		Yield stress		Maximum stress		Modulus of elasticity	
	cm^2	in^2	MPa	ksi	MPa	ksi	GPa	ksi
Tests at room temperature								
1	0.165	0.0256	867	125.8	958	138.9	119	17 200
2	.163	.0253	883	128.1	972	140.9	119	17 300
3	.164	.0254	885	128.3	985	142.9	119	17 200
Tests at 316°C (600°F)								
4	0.162	0.0251	569	82.5	707	102.6	110	16 100
5	.165	.0256	563	81.6	703	102.0	108	15 700
6	.166	.0257	572	82.9	714	103.5	110	16 000

[a]Tensile specimens were thermally exposed to simulate the temperatures and times associated with an SPF/WB cycle.

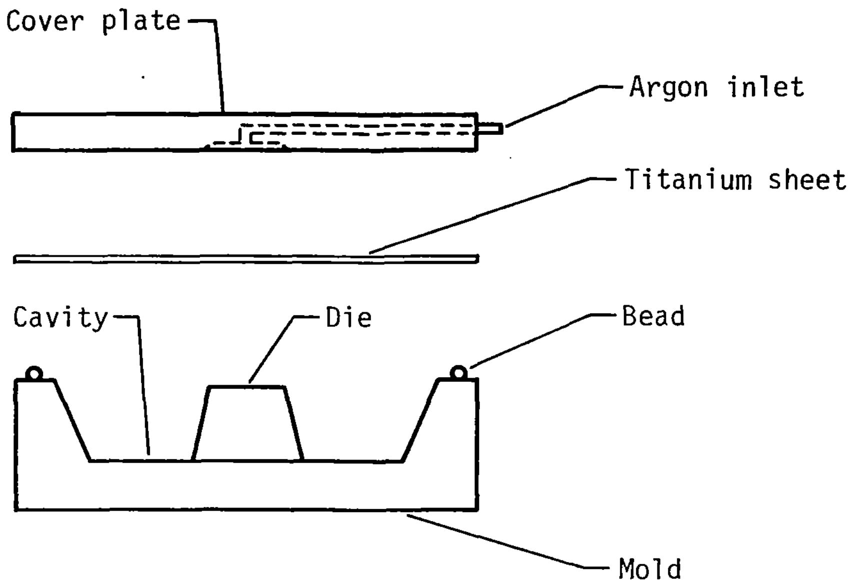
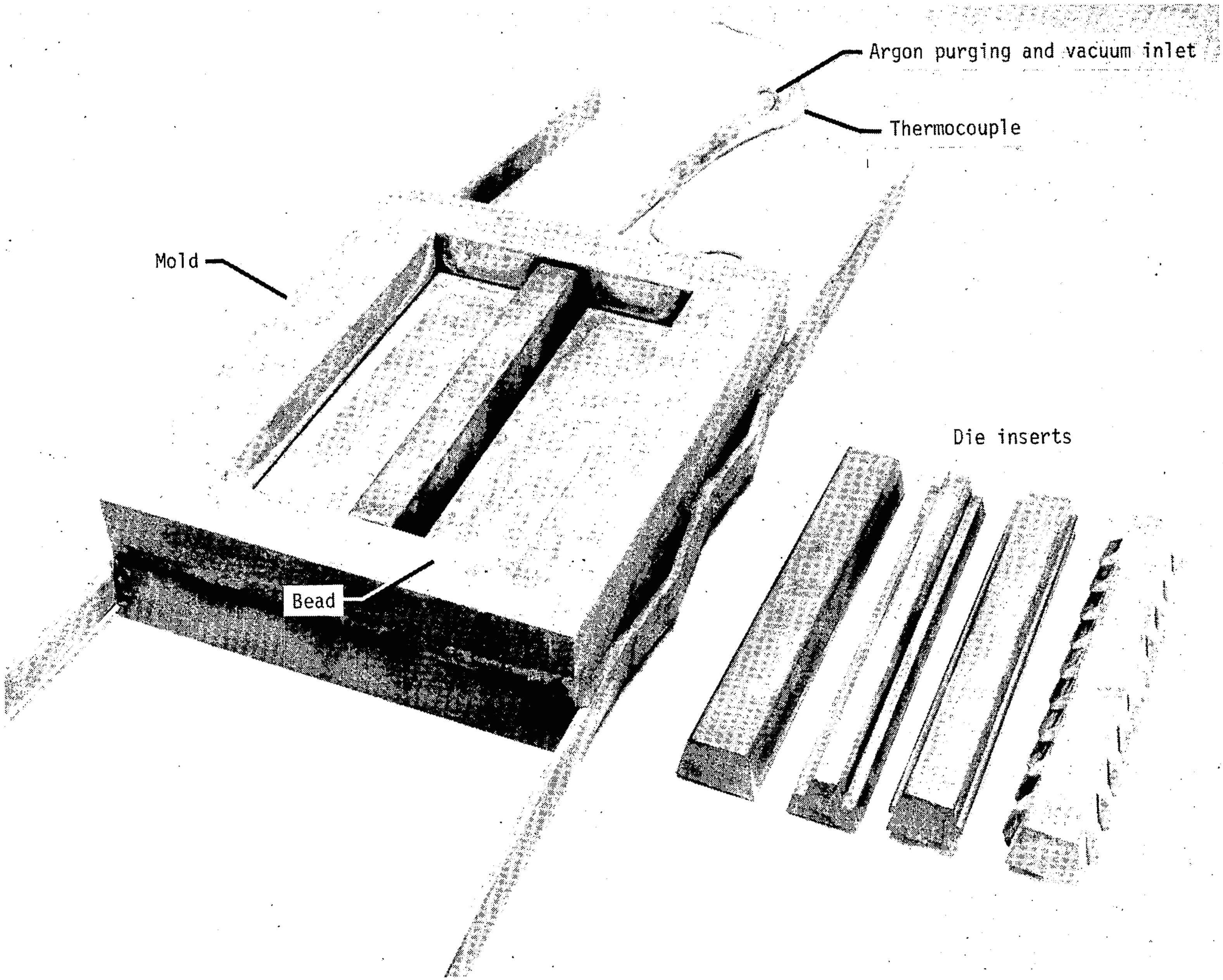


Figure 1.- Cross section of tooling for superplastic forming.



L-80-8431.1

Figure 2.- Tooling for superplastic forming of stiffeners.

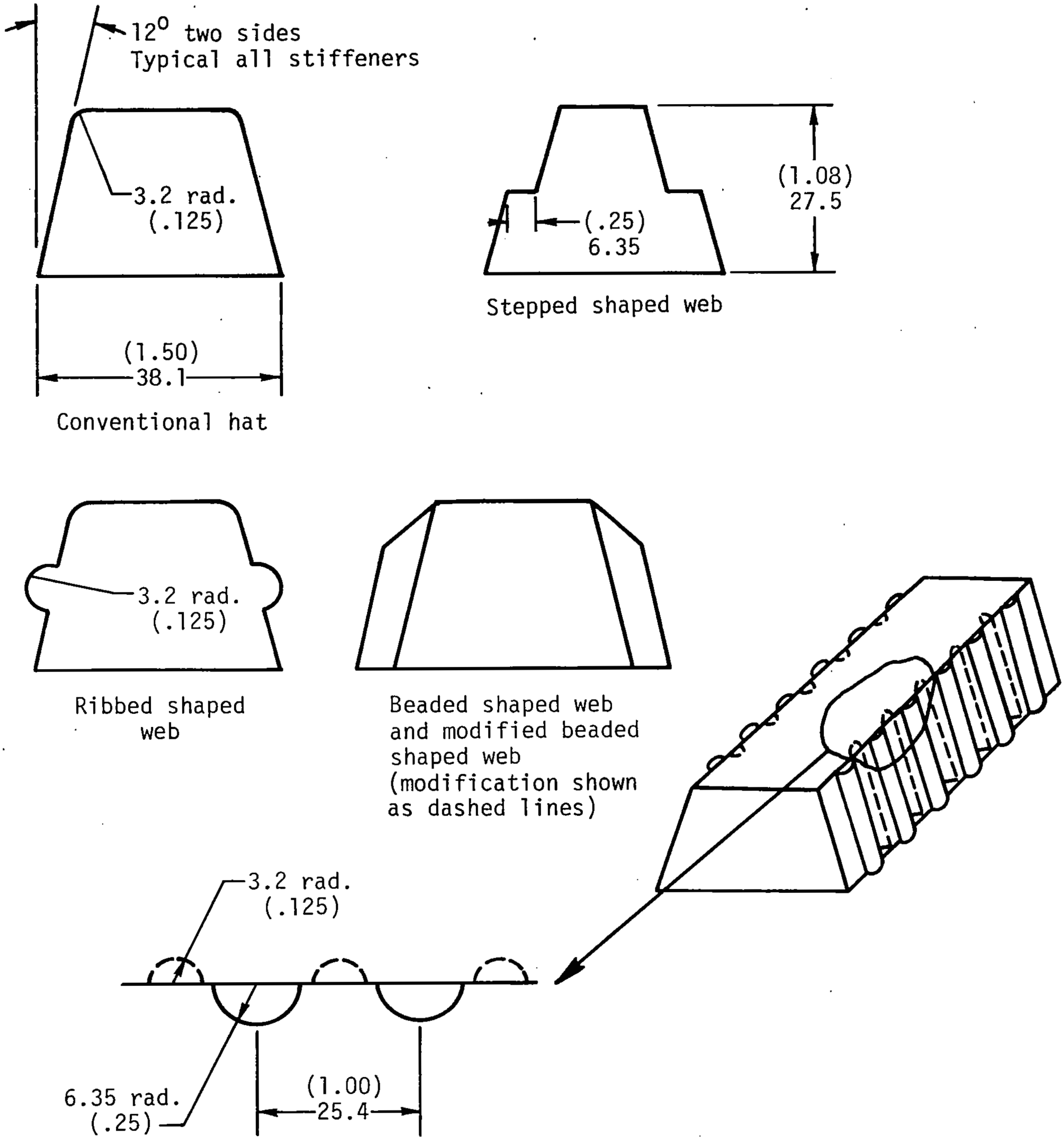
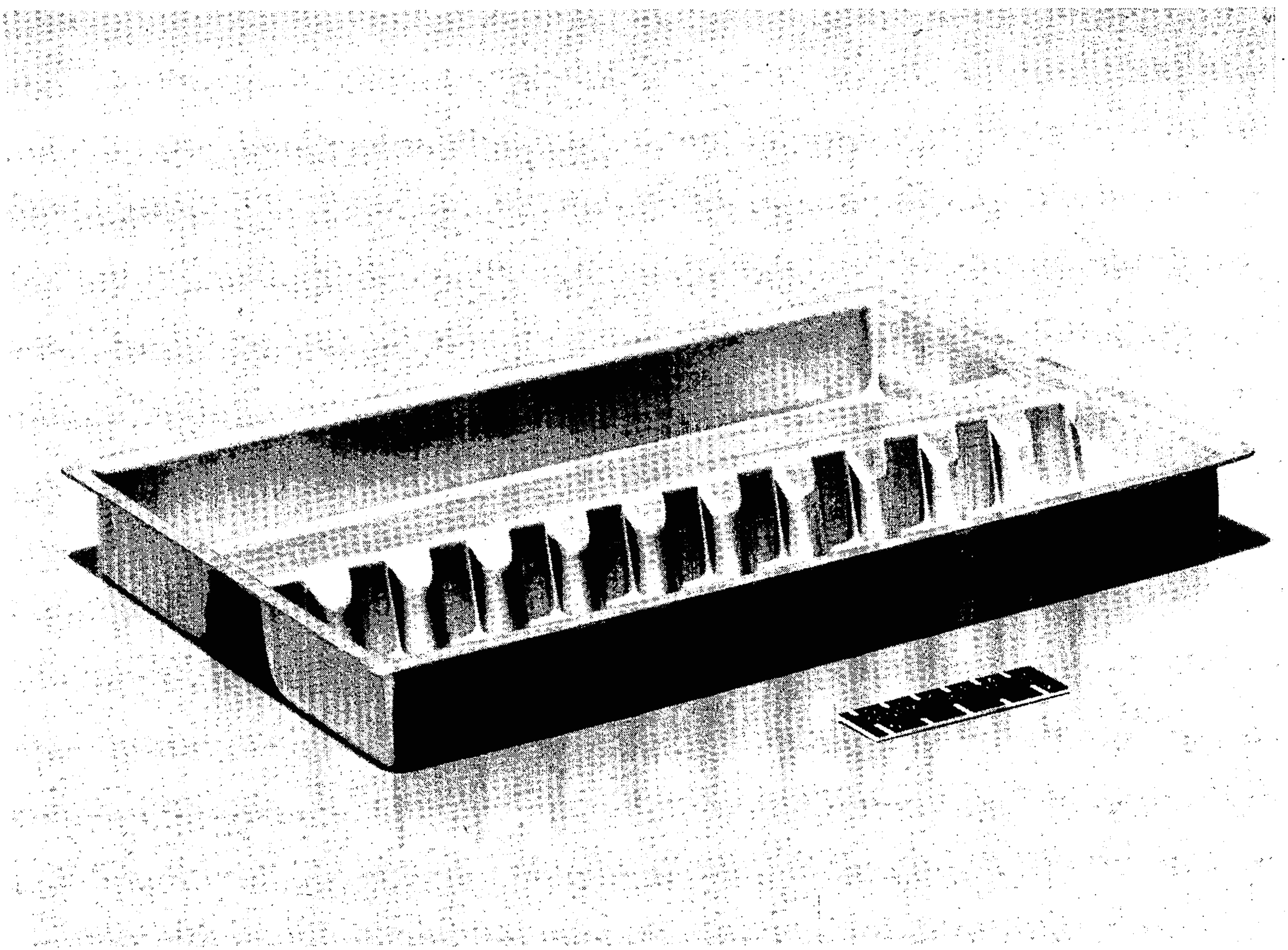
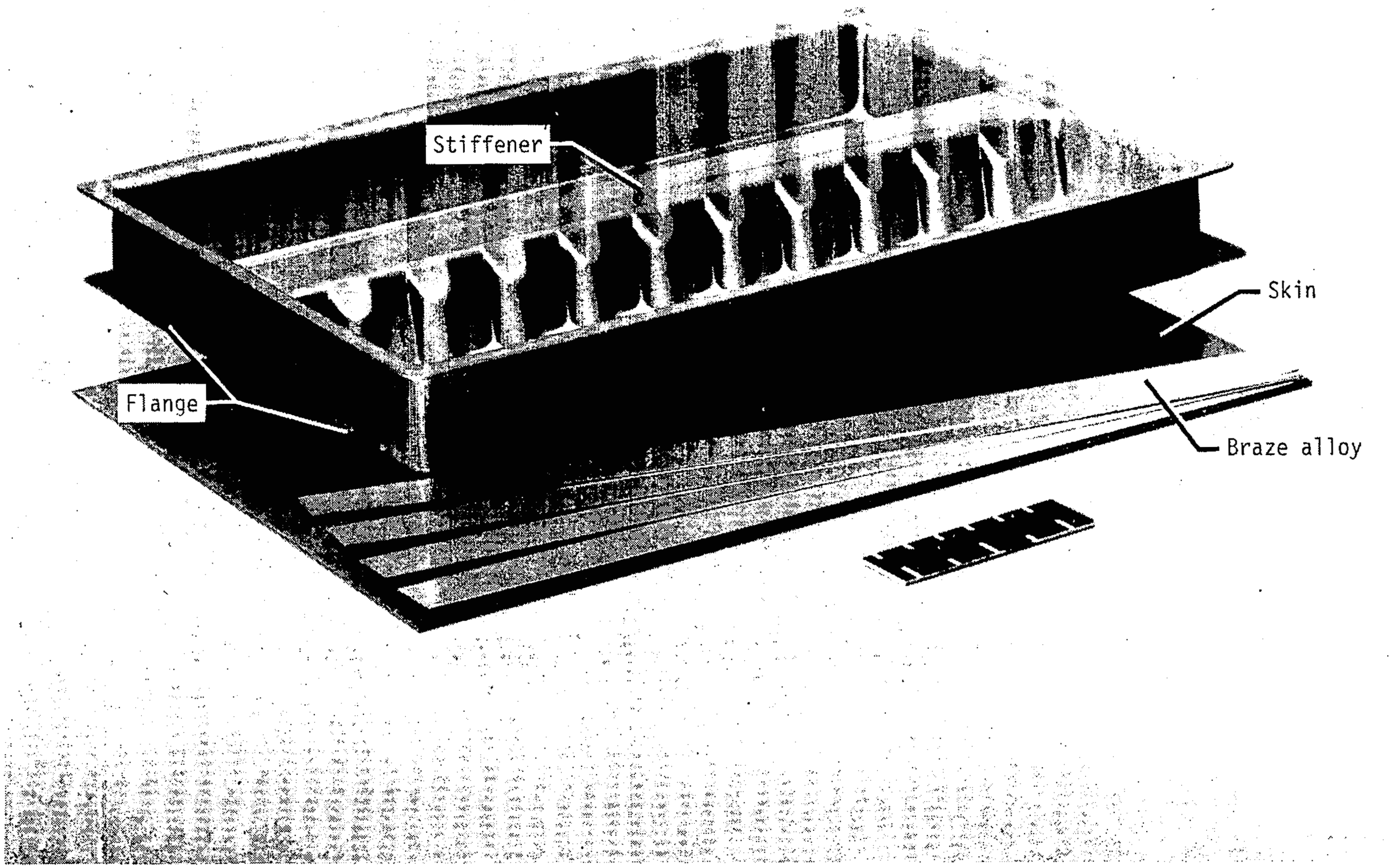


Figure 3.- Configuration of die inserts. Dimensions are in millimeters (inches).



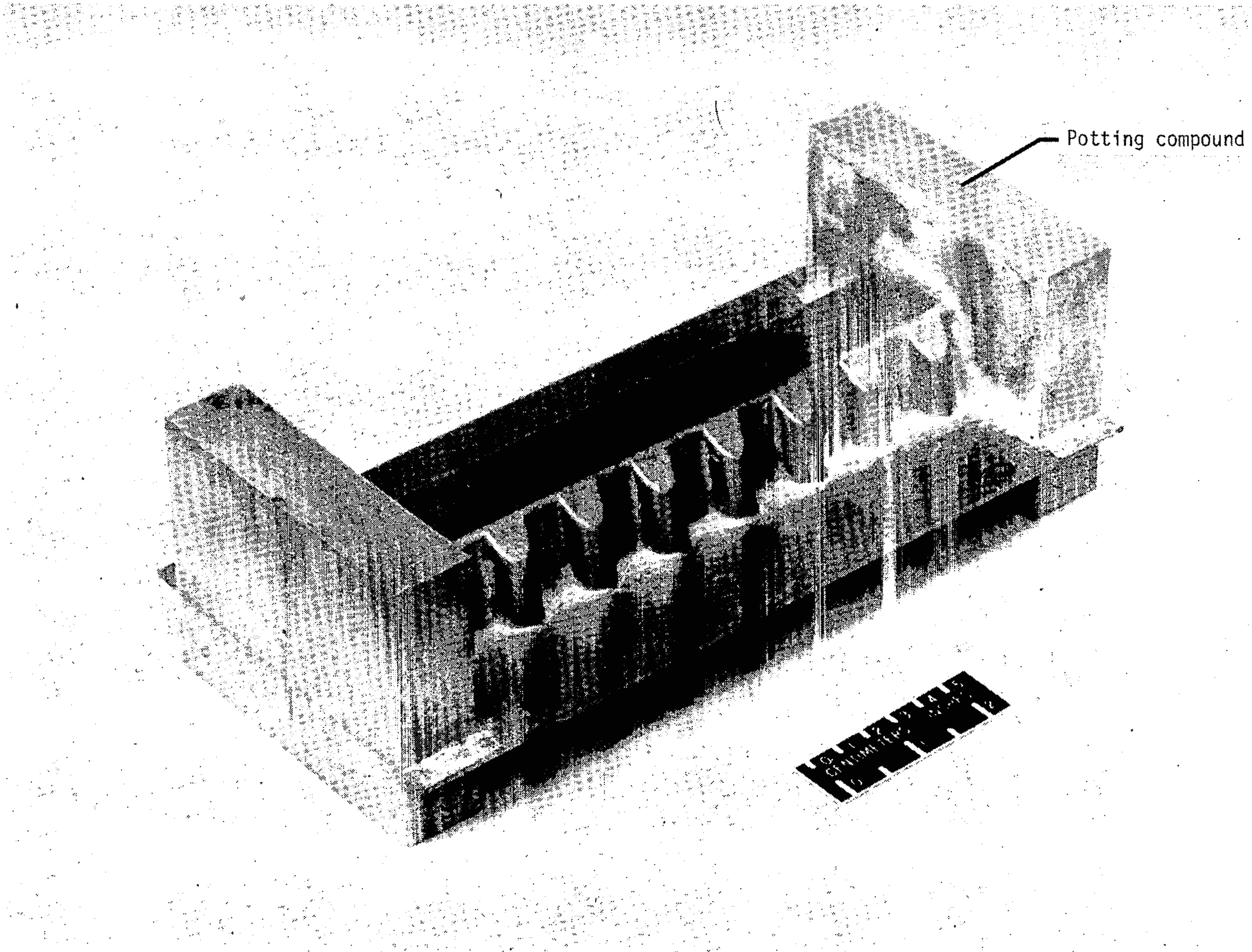
L-81-4743

Figure 4.- As-formed beaded shaped web stiffener.



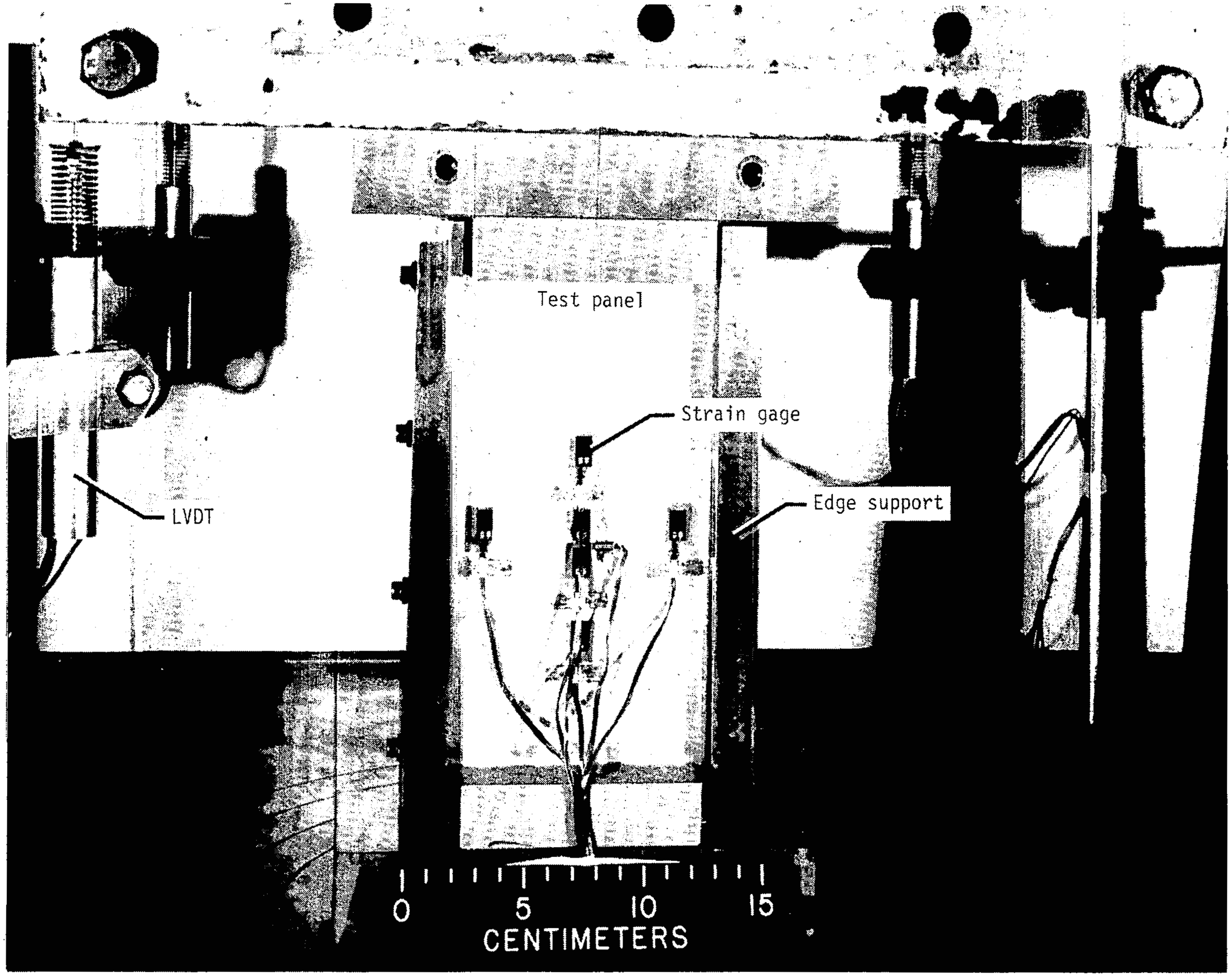
L-81-4742.1

Figure 5.- Compression panel components.



L-80-7622.1

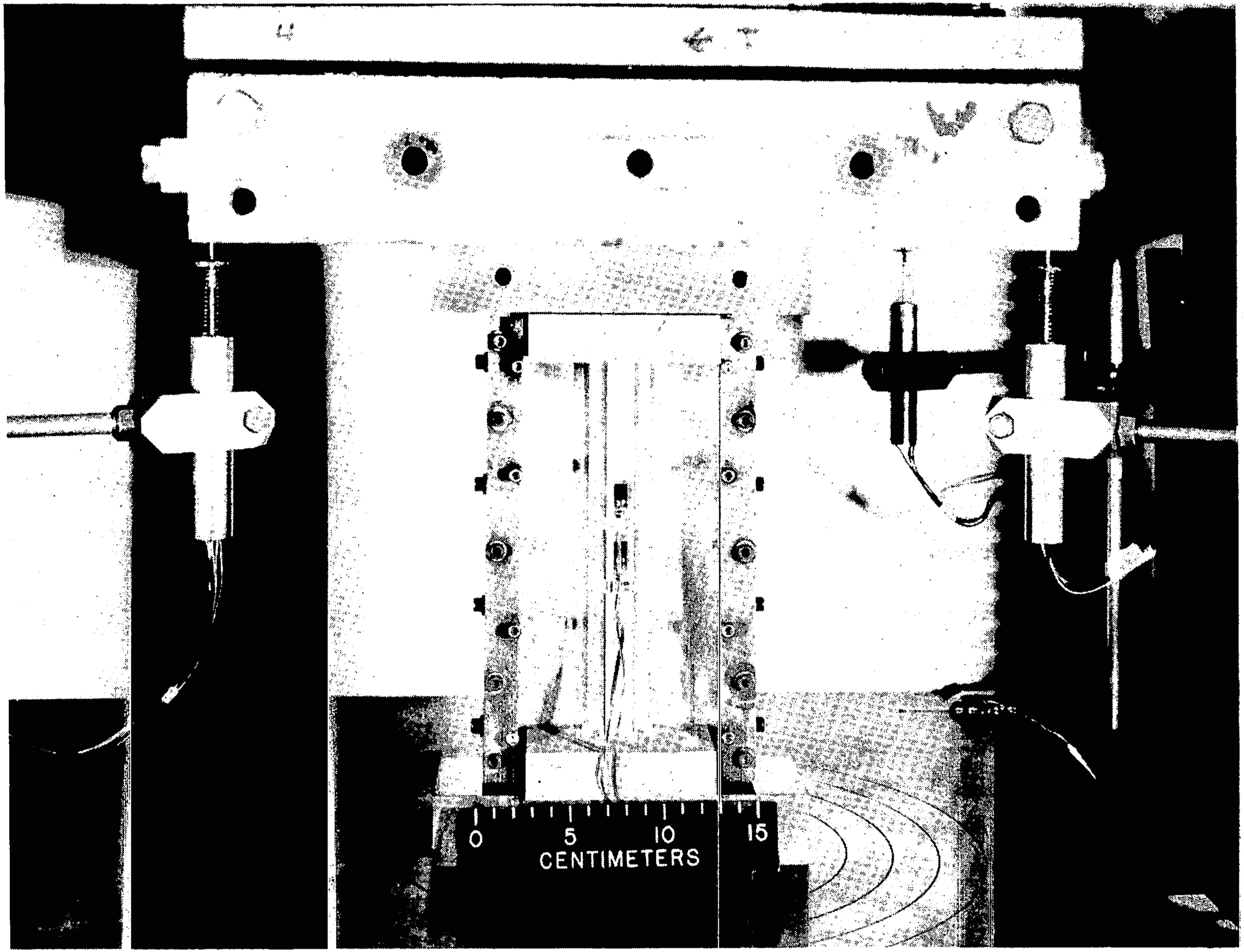
Figure 6.- Skin-stiffened test panel.



L-81-1555.1

(a) Skin side.

Figure 7. Room-temperature test setup for skin-stiffened panels.



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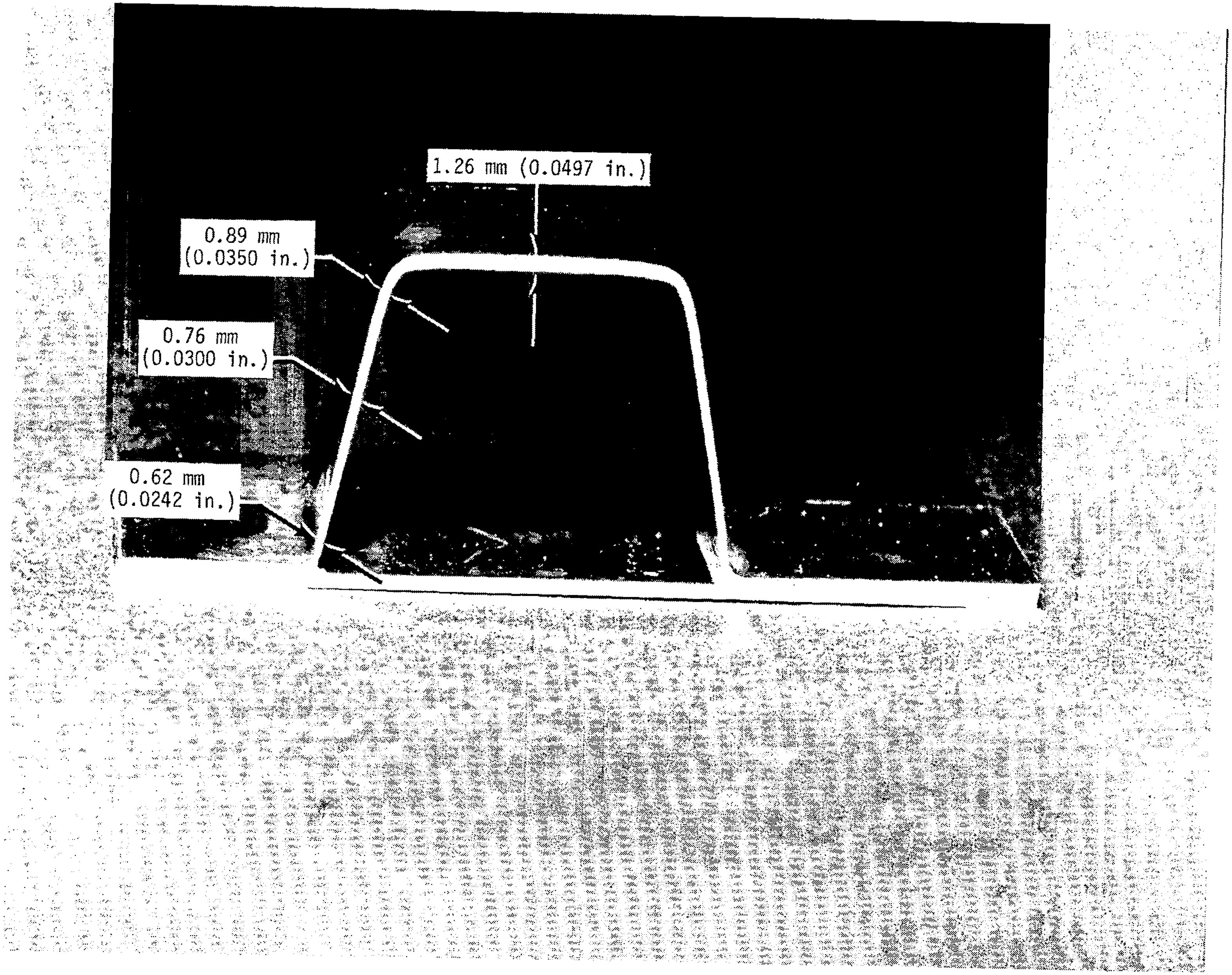
(b) Stiffener side.

Figure 7.- Concluded.



L-82-7043.1

Figure 8.- Typical thinning in a superplastically formed titanium stiffener.

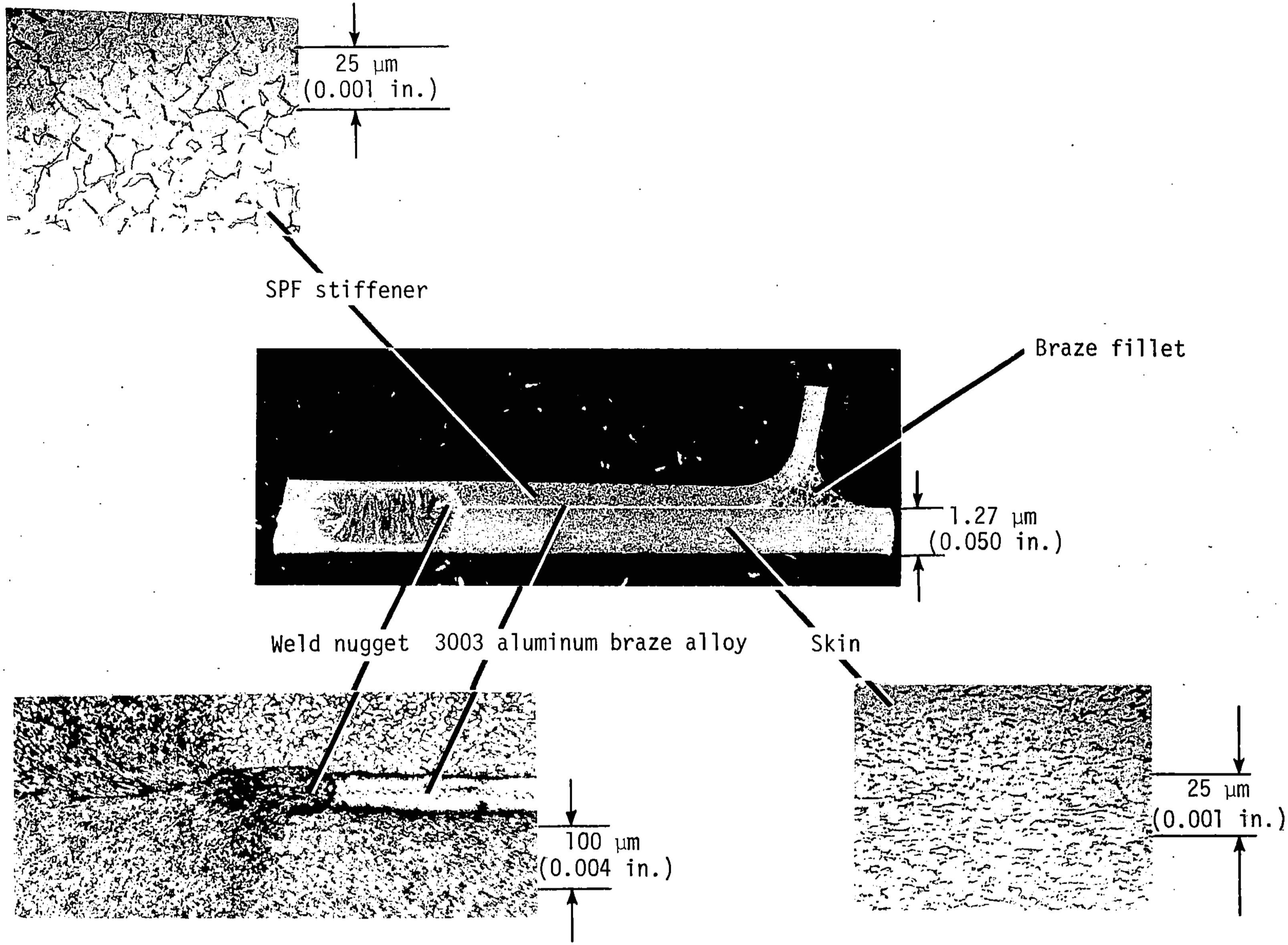


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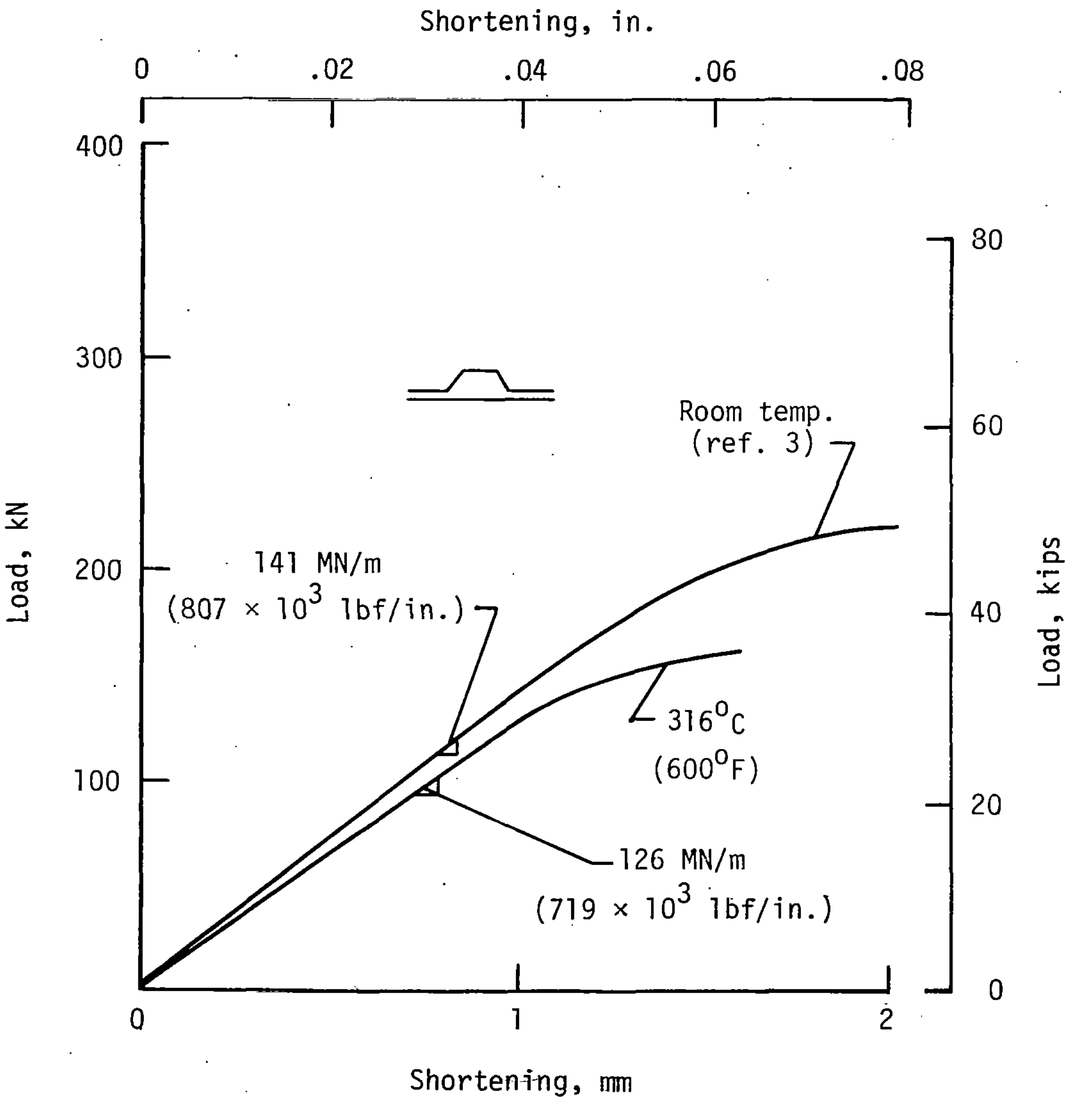
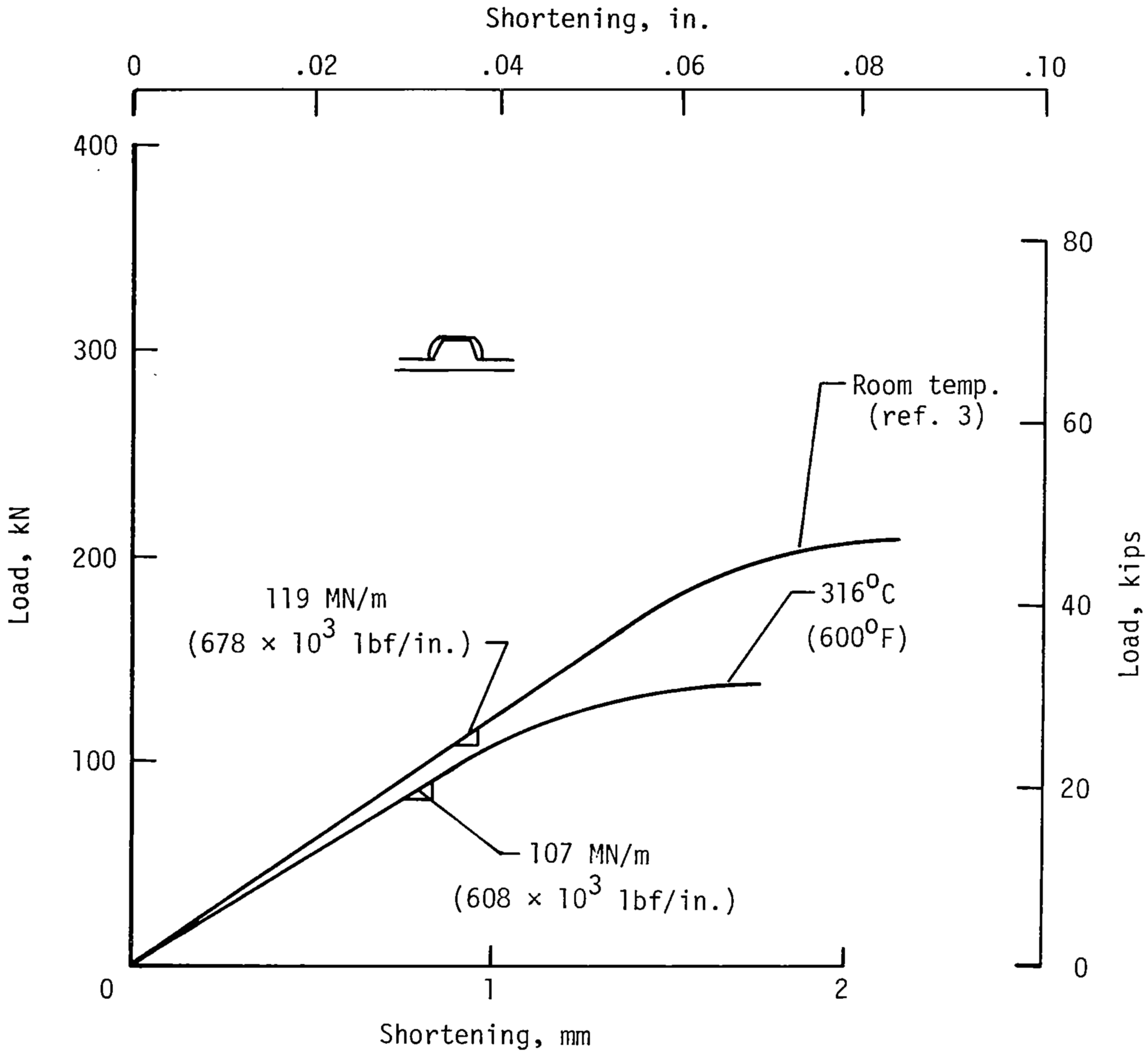
Figure 9.- Photomicrographs of superplastically formed/weld-brazed joint cross section.



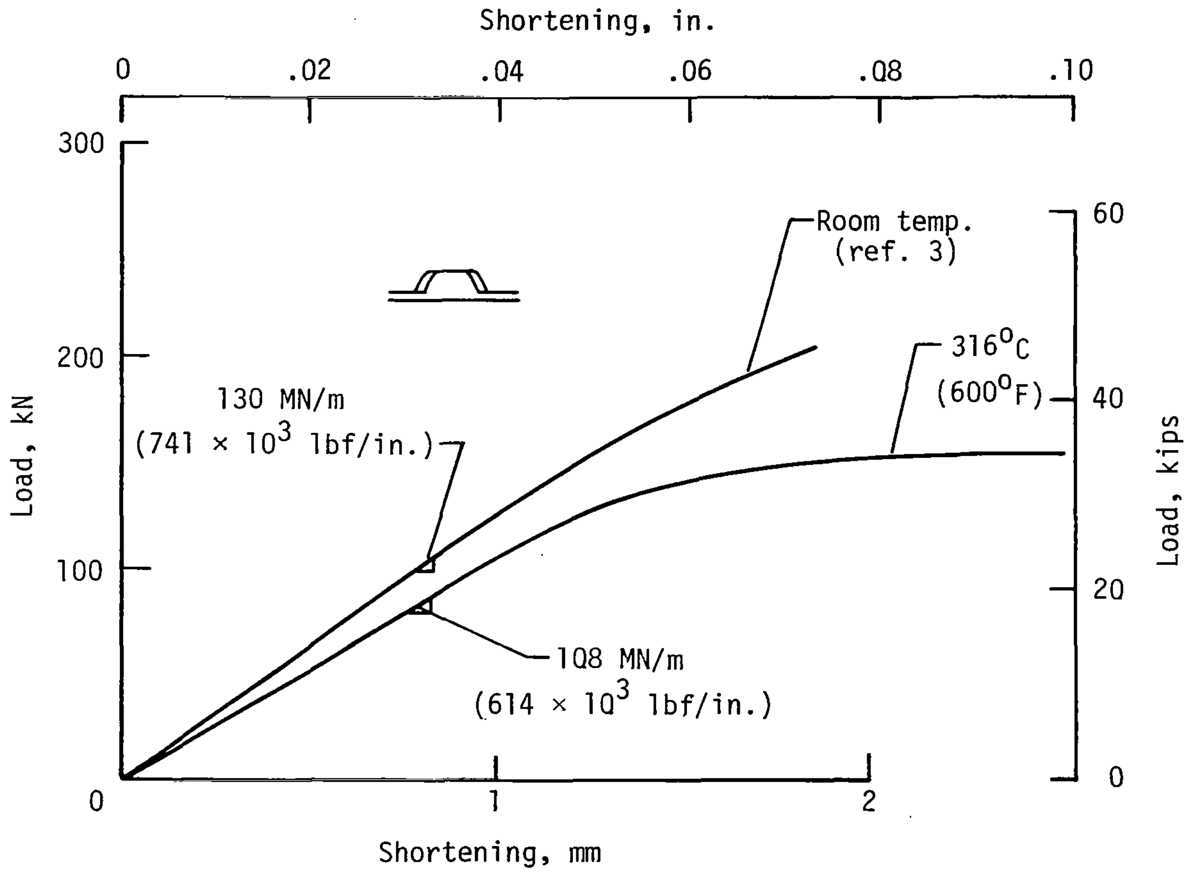
(a) Conventional hat.

Figure 10.- Load-shortening curves for skin-stiffened panels.



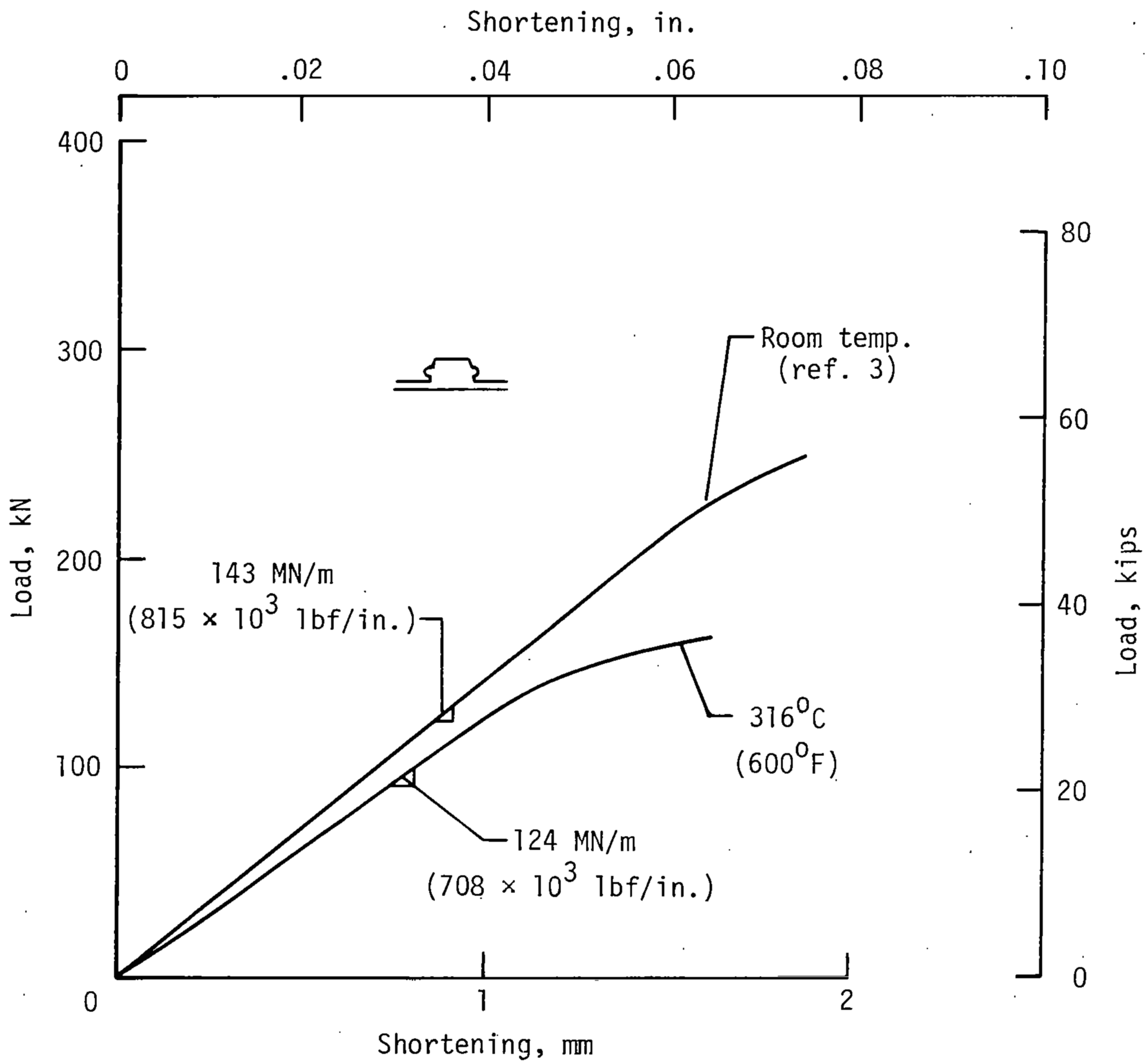
(b) Beaded shaped web.

Figure 10.- Continued.



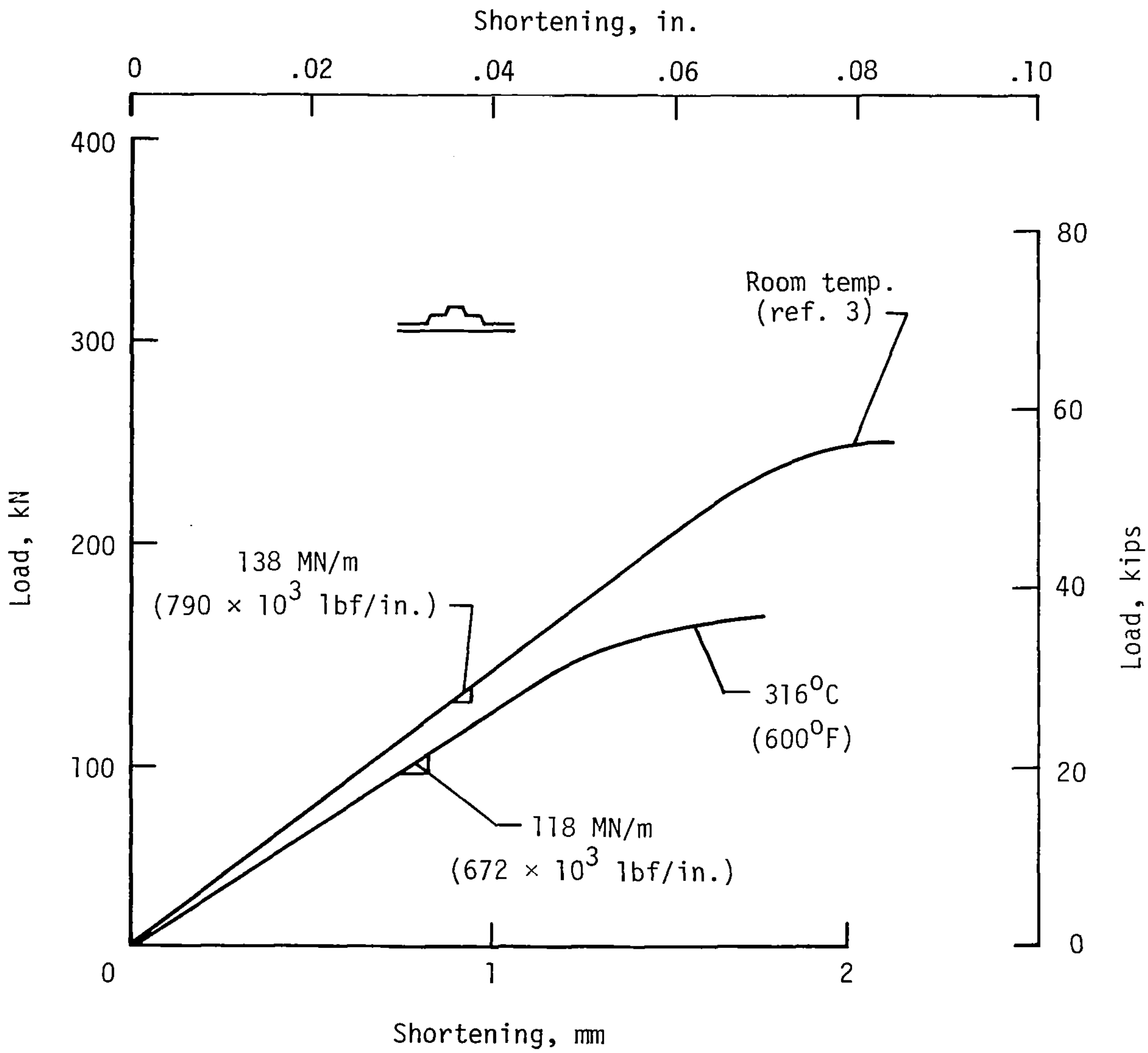
(c) Modified beaded shaped web.

Figure 10.- Continued.



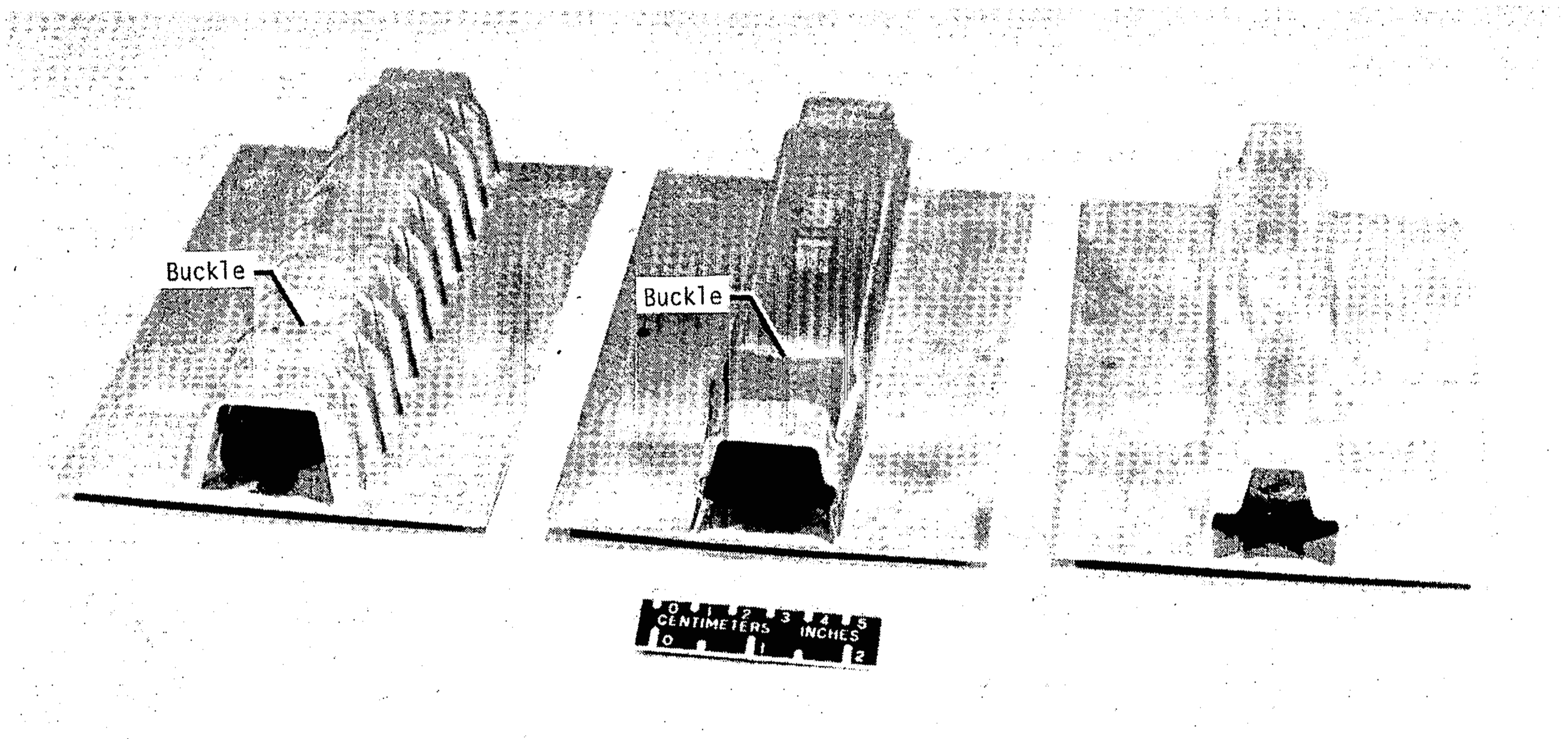
(d) Ribbed shaped web.

Figure 10.- Continued.



(e) Stepped shaped web.

Figure 10.- Concluded.



L-82-3501.1

Figure 11.- Tested skin-stiffened panels.

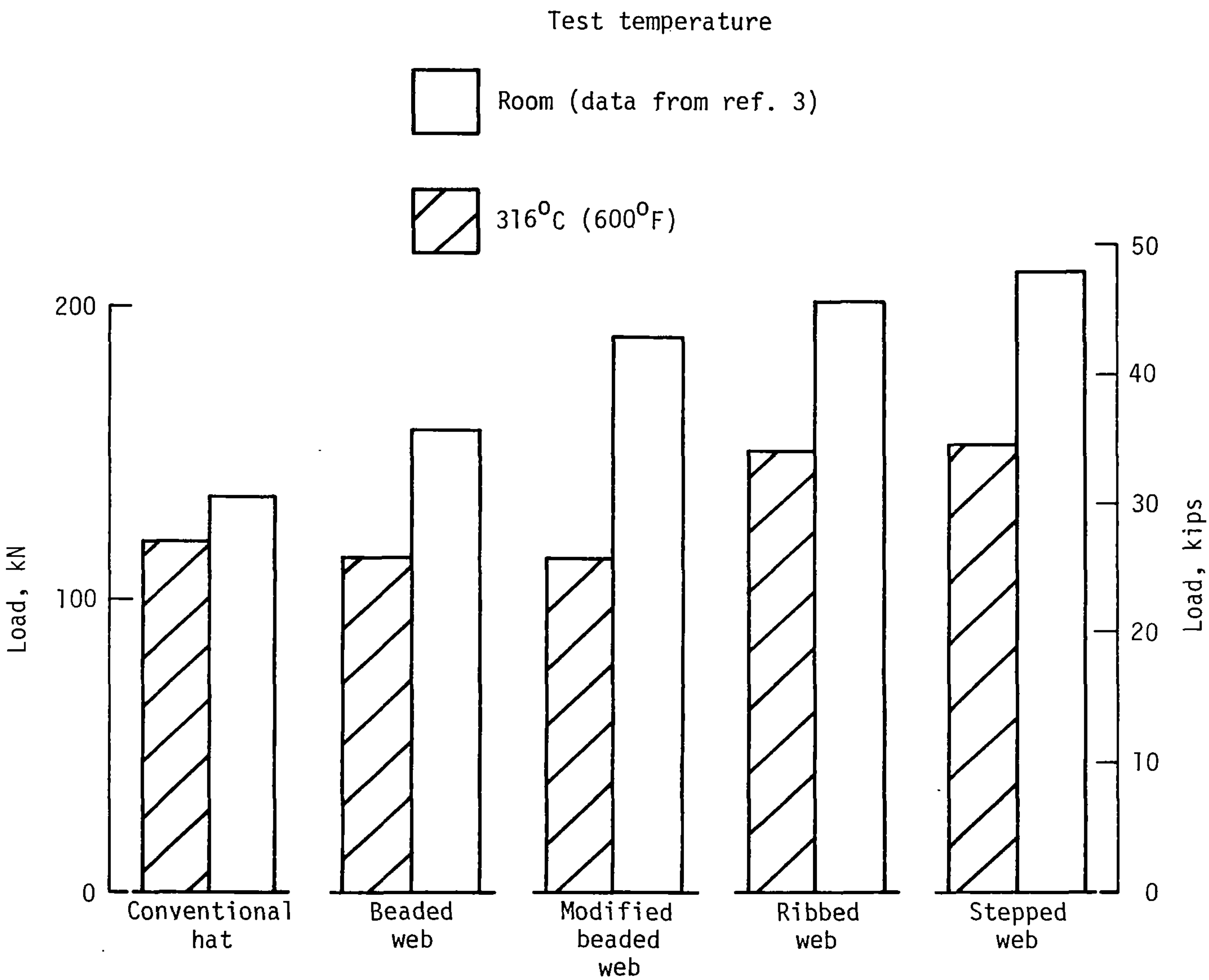


Figure 12.- Room temperature and 316°C (600°F) average buckling loads of skin-stiffened panels.

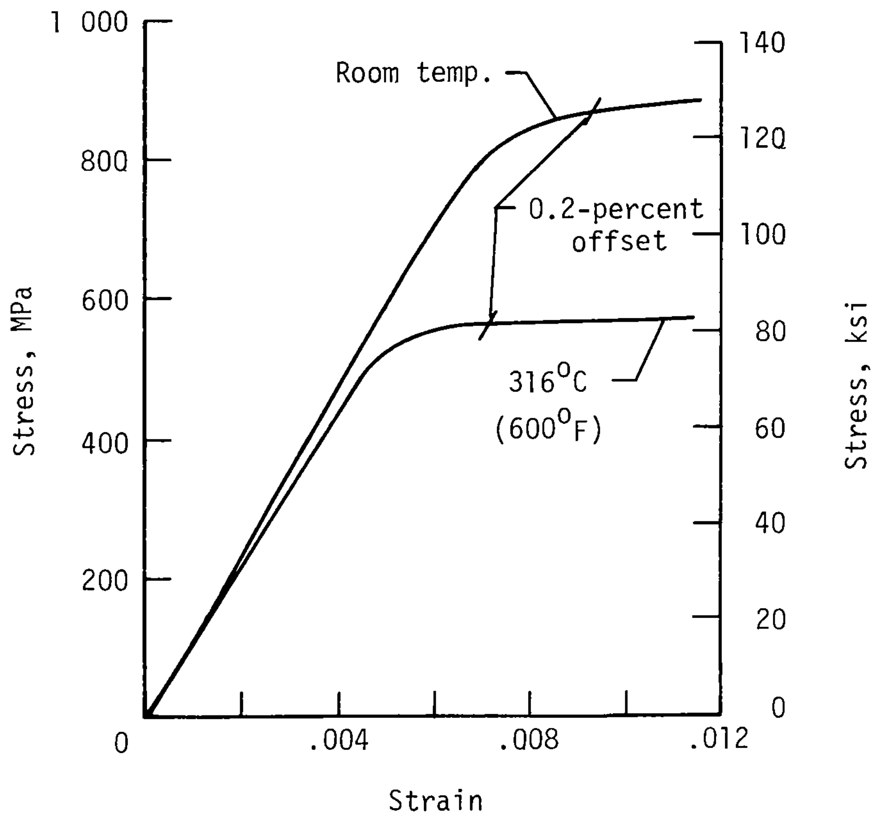


Figure 13.- Room temperature and 316°C (600°F) tensile stress-strain data for Ti-6Al-4V sheet material.

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15. Supplementary Notes

16. Abstract

The objective of this study was to investigate the 316°C (600°F) buckling behavior of superplastically formed/weld-brazed titanium compression panels having advanced shaped stiffeners. Fabrication of the advanced shaped stiffeners was made possible by the increased formability afforded by the superplasticity characteristics of the titanium alloy Ti-6Al-4V. Stiffeners having the configurations of a conventional hat, a beaded web, a modified beaded web, a ribbed web, and a stepped web were investigated. The data from the panel tests include load-shortening curves, local buckling strengths, and failure loads. The superplastic formed/weld-brazed panels with the ribbed web and stepped web stiffeners developed 25 and 27 percent higher buckling strengths at 316°C (600°F) than panels with conventionally shaped stiffeners. The buckling load reductions for panels tested at 316°C (600°F), compared with panels tested at room temperature, were in agreement with predictions based on titanium material property data. The advantage that higher buckling loads can be readily achieved by superplastically forming of advanced stiffener shapes was demonstrated. Application of these advanced stiffener shapes offers the potential to achieve substantial weight savings in aerospace vehicles.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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