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AMBIENT TEMPERATURE FATIGUE TESTS OF ELEMENTS OF AN ACTIVELY COOLED HONEYCOMB SANDWICH STRUCTURAL PANEL

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16. Abstract

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Sinusoidal loads were applied to all specimens. The honeycomb sandwich specimen was loaded in both tension and compression; the other specimens were loaded in tension only. The cooling tubes were pressurized with oil throughout the fatigue tests.

The most significant results of these tests follow: All specimens exceeded their design life of 20 000 cycles without damage. Crack growth rates obtained in the plain skin specimens were used to determine the crack growth characteristics of 2024-T81 aluminum alloy. Cracks in skins either bonded or soldered to cooling tubes propagated past the tubes without penetration. The coolant tubes served as crack arresters and temporarily stopped crack growth when a crack reached a tube-skin interface. The honeycomb core demonstrated that it could contain leakage from a tube.

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SUMMARY

Elements of an actively cooled structural panel for a hypersonic aircraft have been investigated for fatigue characteristics. The study involved a bonded honeycomb sandwich panel with d-shaped coolant tubes. The curved portion of these tubes was embedded in the honeycomb, and the flat portion was bonded or soldered to the inner surface of the outer skin. The elements examined were two plain skin specimens (sheets of 2024-T81 aluminum alloy); two specimens with skins attached to manifolds and tubes (one specimen was bonded, the other soldered); and a specimen representative of a corner section of the complete cooled sandwich.

Sinusoidal loads were applied to all specimens. Both the plain sheet specimens and the manifold-tube-skin specimens were loaded in tension only. (The former were stressed between 0 and 106.9 MPa (0 and 15 500 psi) whereas the latter were stressed between 0 and 82.8 MPa (0 and 12 000 psi).) The honeycomb sandwich specimen was loaded with a completely reversed cycle (between 82.8 MPa (12 000 psi) compression and 82.8 MPa (12 000 psi) tension). The cooling tubes were pressurized with oil to 517 kPa (75 psi) throughout the fatigue tests.

The most significant results of these tests follow. All specimens exceeded their design life of 20 000 cycles without damage. Crack growth rates obtained from cracks growing in the plain skin specimens were used to determine the crack growth characteristics of 2024-T81 aluminum alloy. Cracks in skins either bonded or soldered to cooling tubes propagated past the tubes without penetration. The coolant tubes served as crack arresters and temporarily stopped crack growth when a crack reached a tube-skin interface. The honeycomb core demonstrated that it could contain leakage from a tube.

INTRODUCTION

Analytical studies (refs. 1 and 2) have indicated that active cooling systems may protect aluminum structures from the severe aerodynamic heating encountered during hypersonic flight of liquid hydrogen fueled aircraft. The most promising systems considered consisted of cooled structural panels in a closed loop system with a liquid coolant (either water and glycol or water and methanol) and a heat exchanger to transfer heat from the coolant to the hydrogen fuel. Since a primary load carrying structure with integral cooling passages is not consistent with the current state of the art, the National Aeronautics and Space Administration Langley Research Center initiated a program for evaluation of the design, fabrication, and performance of several concepts of actively cooled structural panels (ref. 3). One of these concepts consists of a bonded honeycomb sandwich panel with d-shaped coolant tubes. The curved portion of the tubes was embedded in the honeycomb, and the flat portion was bonded or soldered to the inner surface of the outer skin. Although the design of these honeycomb sandwich panels was controlled by a buckling failure mode, the complexities of the design led to concern about their fatigue characteristics. Consequently, elements of the panel design were subjected to an experimental fatigue study, and the results are reported in this paper. Three types of specimens were tested: plain sheets of 2024-T81 aluminum alloy; skins with manifolds and tubes attached (one bonded, one soldered); and a corner section consisting of the honeycomb sandwich with tubes, manifolds, inner and outer skins, and panel edge closeouts.

Specific objectives of this study were: (1) to assess the capability of specimens of actively cooled honeycomb sandwich panels to survive 20 000 fatigue cycles at the design loads, (2) to determine how a crack propagating in the outer skin interacts with the coolant tubes, and (3) to determine the ability of the honeycomb to contain leakage from a tube.

Certain commercial bonding agents are identified in this paper in order to specify adequately which materials were used in the research effort. In no case does such identification imply recommendation or endorsement of the materials by NASA.

SYMBOLS

Values are given in both SI and U.S. Customary Units. Calculations were made in U.S. Customary Units.

a_f	final crack length, m (ft)
a_o	initial crack length, m (ft)
$\bar{c}$	crack growth resistance
N	number of loading cycles, cycles
n	crack growth exponent

R	ratio of minimum load to maximum load
S	applied stress, Pa (psi)

FATIGUE SPECIMENS

Fatigue specimens were designed to represent areas of an actively cooled panel which would be used on a hypersonic airplane. A sketch of the 0.61 by 6.1 m (2 by 20 ft) panel described in reference 3 is shown in figure 1 with its innermost side (the side not in contact with the aerodynamic stream) facing up in order to display the aircraft frames to which it is attached. Fatigue specimens, representing three areas on the panel, are also illustrated in figure 1. Plain skin specimens represented outer skins in the center of the panel; specimens with manifolds and tubes attached to an outer skin represented a panel end; and a honeycomb sandwich specimen with cooling tubes and manifolds represented a panel corner.

Plain Skin Specimens

Two specimens were made from sheets of 2024-T81 aluminum alloy 1.016 mm (0.040 in.) thick. Tapered loading doublers were bonded to each end to reduce stress concentrations at the loading adapters. (See fig. 2.) These plain skin specimens measured 12.7 by 27.9 cm (5.0 by 11.0 in.).

Manifold-Tube-Skin Specimens

Two specimens consisted of an assembly of manifolds and tubes attached to a 1.016-mm (0.040-in.) aluminum alloy (2024-T81) skin. These specimens, which measured 12.7 by 27.9 cm (5.0 by 11.0 in.), had a pair of 6061-T6 aluminum alloy manifolds connected by four d-shaped tubes (also made of 6061-T6 aluminum alloy). The tubes were brazed to the manifolds. A photograph of the manifold-tube assembly taken during fabrication is shown in figure 3.

One specimen had the manifold-tube assembly bonded to the skin with a bonding agent (Eccobond 58C) which was impregnated with silver to improve its thermal conductivity. A birefringent plastic sheet was bonded to the skin of this specimen on the side opposite the tubes to allow photoelastic analysis of the specimen during loading. Figure 4 shows photographs of (a) the specimen, tube side up; (b) the specimen, tube side down with the loading grips; and (c) a close-up of the manifold-tube joints bonded to the skin.

The other manifold-tube-skin specimen had the skin soldered to the manifold-tube assembly with a solder composed of 91-percent tin and 9-percent zinc. Prior to soldering, a bronze strike and a thin electrodeposited layer of tin were applied to the surface to be soldered. The tin improved solder wetting and the bronze kept the tin from reacting with the aluminum. During fabrication, the flux used with the solder outgassed and formed large voids in sections where sizable areas were to be soldered (between the manifold and the face sheet). To allow gases to escape and to minimize voids, holes 1.6 mm (0.063 in.) in diameter were drilled in the area of the skin which was to be over the manifolds. The photographs of figure 5 illustrate: (a) the soldered specimen with tube side down (note the hole pattern in the skin at the manifold), (b) the soldered specimen with tube side up adjacent to offset grips, and (c) a close-up of the manifold-tube joints soldered to the skin.

Both manifold-tube-skin specimens had doublers attached at the manifolds to join the manifolds to the grips. These doublers were representative of the doublers which would be used to join two panels in series on an aircraft. Two types of grips were used: symmetric grips on the bonded specimens and offset grips on the soldered specimens (shown in figs. 4(b) and 5(b), respectively).

Honeycomb Sandwich Specimens

The honeycomb sandwich specimen was similar to the bonded manifold-tube-skin specimen with the addition of a honeycomb core and 0.38-mm (0.015-in.) skin. A photograph of this specimen is shown in figure 6. Grooves were machined in the honeycomb core to allow the core to nest with the tubes. A foaming type adhesive (FM-404) was used to bond the curved portions of the manifold-tube-skin assembly to the grooved portion of the honeycomb. The flat portions of the manifold-tube-skin assembly and the plain skin on the reverse side of the sandwich were bonded with a film-type adhesive (FM-400). The honeycomb core had 3.8-mm (0.15-in.) hexagonal cells made of aluminum (5056) foil 0.0178 mm (0.0007 in.) thick. The specimen was 11.2 cm (4.4 in.) wide by 27.9 cm (11.0 in.) long. Doublers at both ends joined the specimens to the grips and simulated the joints between panels. Longitudinal doublers on both sides of one edge simulated a joint between parallel panels. All specimens which contained manifolds and cooling tubes were radiographically and ultrasonically inspected and were proof pressure tested to 775 kPa (112.5 psi) (one and one-half times their design pressure) prior to the fatigue tests.

APPARATUS

The fatigue testing machine used for this study was a standard servohydraulic 556-kN (125 000-lbf) capacity fatigue testing machine. All panels with tubes were pressurized using the apparatus shown in figure 7. A nitrogen gas bottle was used to pressurize the bladder of a hydraulic accumulator which, in turn, pressurized hydraulic fluid in the fatigue specimens. Hydraulic fluid was used in the model rather than nitrogen gas to avoid high-energy gas release at failure and to allow for liquid leakage as opposed to gas leakage.

TEST PROCEDURE

All specimens were fatigue tested at stress levels equal to the design limit load for the areas of the full-scale panel which they represented. With the exception of the bonded manifold-tube-skin specimen, all specimens with cooling passages had the design pressure of 517 kPa (75 psi) applied to the cooling passages during all tests. The bonded manifold-tube-skin specimen was not pressurized during the initial 20 000 loading cycles but was pressurized during the next 58 176 cycles. All loading cycles were sinusoidal and were run at the rate of 4 to 6 Hz.

Plain Skin Specimens

The plain skin specimens were cyclically loaded between 0- and 106.9-MPa (0- and 15 500-psi) tension ($R = 0$). After 20 000 cycles, a crack starter was cut in the center of the specimen by drilling a 2.77-mm (0.109-in.) hole and by saw cutting 0.79-mm (0.031-in.) slots on each side. (The total crack starter length was 4.34 mm (0.171 in.), tip to tip.) Fatigue tests were then resumed at the same loads as were applied earlier. The crack growth plotted against loading cycles was monitored by recording the number of cycles which had elasped as the cracks grew past marks which were scribed perpendicularly to the direction of crack growth. The loading cycle continued until the sheet fractured.

Manifold-Tube-Skin Specimens

The manifold-tube-skin specimens were cyclically loaded between 0 and 82.8 kPa (0 and 12 000 psi) in tension ($R = 0$). After 20 000 loading cycles, crack starters were cut in the skin between tubes in the center of these specimens. The crack starter in the bonded specimen was identical to the crack starter cut in the plain skin specimens; but after a number of cycles with no crack propagation, the crack starter length was increased from 4.34 to 9.53 mm (0.171 to 0.375 in.) measured tip to tip. The crack starter in the soldered specimen was a saw cut slot with V-grooves on each end. The V-grooves were cut with a razor blade. The total length of the crack starter (measured tip to tip) was 10.40 mm (0.410 in.).

After the crack starters were induced, the cyclic loading was resumed until the crack propagated past a tube. Although the bonded specimen was cyclically loaded, the crack did not begin growing even after the crack starter length was increased. To expedite the test, the stress was increased to 103.5 MPa (15 000 psi).

Honeycomb Sandwich Specimen

The honeycomb sandwich specimen, the only specimen stable in compression, was loaded by using a completely reversed cycle ($R = -1$) from 82.8-MPa (12 000-psi) tension to 82.8-MPa (12 000-psi) compression. After 24 780 cycles, the specimen was depressurized, and a hole was drilled through the outer skin, through one of the cooling tubes, and into the honeycomb. A short sheet metal screw with a rubber washer around its shank was inserted into the hole in the skin to prevent oil from leaking out the front of the specimen but permitting internal leakage into the honeycomb. This procedure was followed to determine the ability of the honeycomb core to contain coolant which could leak from a crack in a coolant tube (the fail-safe feature of the design).

The specimen was repressurized, and the cyclic loading was resumed with the same loads used earlier. After 10 000 additional cycles, the stresses were increased to ±100.2 MPa (±14 500 psi).

RESULTS AND DISCUSSION

The results and conditions of each test for each specimen are presented in table I. All five specimens survived a minimum of 20 000 fatigue cycles (design life (see ref. 3)) at design loads.

Plain Skin Specimens

Both plain skin specimens survived the initial 20 000 cycles undamaged and a minimum of 30 000 additional cycles after the crack starters were cut into the skins. (See table I.) The experimental crack growth rates of both plain skin specimens were used to calculate the material property constants, crack growth resistance $\bar{c}$ and crack growth exponent n for 2024-T81 aluminum alloy. These constants, unavailable in the literature, were used in the following equation which was derived in reference 4:

$$N = \frac{\bar{c}^n}{S^n \pi^{n/2}\left(\frac{n}{2} - 1\right)}\left(\frac{1}{a_o^{n/2-1}} - \frac{1}{a_f^{n/2-1}}\right) \tag{1}$$

Here, N is the number of loading cycles necessary for a crack to grow from a_o (initial crack length) to a_f (final crack length), and S is the applied stress. The experimental results were used in a best-fit solution to equation (1) to obtain 690 and 4, the values for $\bar{c}$ and n, respectively. (These values are similar to those of other aerospace metals.)

Crack length as a function of loading cycles is shown graphically in figure 8. Experimental results for both ends of the cracks growing in the plain sheet specimens are represented by the points on the graph, whereas the curve is a plot of equation (1) with the empirical values for $\bar{c}$ and n. The crack growth rates of all four crack tips are in good agreement with each other. This result indicates that the material was homogeneous and that crack growth rate may be predicted from equation (1) and the empirical constants.

Manifold-Tube-Skin Specimens

Bonded specimen.- A total of 56 176 loading cycles at design loads was completed on the bonded manifold-tube-skin specimen without crack propagation (20 000 cycles with no crack starter, 16 176 cycles with a 4.34-mm (0.171-in.) crack starter, and 20 000 cycles with a 9.53-mm (0.375-in.) crack starter). (See table I.) The maximum load was then increased to 103.5 MPa (15 000 psi) (125 percent of design load). After 22 000 cycles with the higher loads applied, a slow leak developed in a tube at a manifold-tube joint. Because the object of the test was to determine whether a crack growing in the skin would propagate into a tube as it grew past the tube, and because the leak was not in the area where the crack was growing, the test continued with no fluid pressure in the tubes. At the time of the leak, the crack in the skin had grown to the vicinity of a tube. After another 20 866 cycles, the crack had grown past the tube without propagating into it. Following the test, the specimen was immersed in water and pressurized to 517 kPa (75 psig) with air. No leakage was observed in the tube next to the cracked outer skin.

Another observation made during the tests was that as the crack grew in the skin and reached the tube-skin interface, the crack growth stopped for approximately 3000 cycles before proceeding past the tube. This crack-growth-retarding feature of the tube-skin interface extended the life of the specimen.

Soldered specimen.- After the soldered manifold-tube-skin specimen survived 20 000 cycles at design loads, a crack starter was cut in the center of the skin midway between tubes, and the cyclic loading at design loads was continued. The crack in the skin grew past the tube without damaging it (142 946 cycles later). When the crack in the skin propagated to the edge of the tube but prior to passing the edge, no crack growth was observed for approximately 5000 cycles. After this dwell period, the crack continued to grow in the sheet next to the tube. The intersection of the tube edge and sheet appears to act as a crack arrester in retarding crack growth for the soldered tube as was similarly apparent for the bonded tubes. The photographs (fig. 9) show the soldered specimen after the tests. Only the saw cut groove is clearly visible in the pictures. When the tests with the soldered manifold-tube-skin specimen were completed, a fine crack was observed in the soldered fillet at the edge of a tube. The crack in the fillet began at the crack in the skin and ran parallel to the tube for approximately 3.81 cm (1.5 in.). This crack did not appear to be deeper than the fillet thickness.

Joints.- In both manifold-tube-skin specimens (specimens 3 and 4 in table I), the specimens and the doublers to which the specimens were attached were observed to move in relation to each other. The doublers were attached to the specimen with flat-head through-bolts which passed through both doublers and a pair of flanges extending out from the upper and lower surfaces of the manifold. (See figs. 4(a), 4(b), 5(a), and 5(b).) During the tests, the unsupported portion of each bolt was observed to bend midway between flanges. The bending at the center caused the ends of the bolts to move. Additional support between the flanges is needed to restrict bending and to permit clamping action so that the bolts can be loaded in shear.

Bending motion was also observed in the center of the specimen, apparently due to misalignment of the load paths in the load adapters and the specimens. Symmetric adapters were used with the bonded specimen (fig. 4(b)), and offset adapters were used with the soldered specimen (fig. 5(b)). The offset loading adapters reduced the bending relative to that which occurred with the symmetric adapters but did not eliminate it.

Honeycomb Sandwich Specimen

After 24 789 cycles of fully reversed loading ($R = -1$) at design limit loads, no damage to the specimen was observed. An internal leak was then induced in the specimen (see section entitled "Test Procedure"). While the coolant system was being repressurized, the pressure built up more slowly than in the earlier pressurizations of this specimen. This lag in pressure buildup was apparently caused by oil seepage into the individual honeycomb cells which were now open to the oil as a result of the simulated internal leak. No external leakage was observed during this period. The cyclic loading was resumed using the fully reversed cycles at design loads. After 10 000 cycles with no change in the specimen, the loads were increased. The new stresses were 121 percent of the design stresses (±100.2 MPa (±14 500 psi)). A pressure drop was detected after 3000 cycles with the higher loads, but no external leakage was detected. The pressure was again slowly increased until design pressure (517 kPa (75 psig)) was attained with no detectable external leaks. This result indicated that the internal leak had spread to more honeycomb cells but was still contained within the specimen. The X-rays taken afterward showed oil in 8 to 10 honeycomb cells. With the cooling passages again pressurized, the tests continued for another 2571 cycles when a crack 3.8-cm (1.5-in.) long was observed on the inner skin of the specimen. The test was halted at this time although the cooling system still contained the pressure. The test demonstrated the ability of the 49.68-kg/m^3 (3.1-pcf) honeycomb to contain the coolant in the event of a crack in a tube.

The end motion on this specimen was even more pronounced than on the preceding two specimens. The crack in the inner skin occurred at a point where flexing resulted from the uneven distribution of loads entering the panel. In addition to fastener bending, the panel experienced a twisting motion because of the lateral stiffness variation induced by the asymmetric splice plates. (Similar motion was observed in another specimen which was inadvertently destroyed in a testing machine malfunction and was not reported herein.) A specimen with four splice plates (one on each edge) would have improved these conditions. However, even though the asymmetric loading condition existed, the specimen exceeded the design life.

SUMMARY OF RESULTS

In this study, specimens of sections of an actively cooled honeycomb sandwich panel were tested for fatigue at room temperature. Three types of specimens were tested: the first type represented the external skin; the second type, the skin with the manifold and cooling tube assembly attached (either bonded or soldered); and the third type, the honeycomb sandwich with internal cooling tubes and manifolds. The honeycomb sandwich specimen underwent fully reversed loading cycles at design loads while the other two types of specimens were cycled in tension only. Specimens with cooling tubes were pressurized during the tests. Crack growth rates were determined with the external skin specimens, and the possibility of a crack in the skin propagating into a tube was investigated with the manifold-tube-skin specimens. Pressure containment of the honeycomb, a potential fail-safe feature of this design, was investigated by simulating a leak from a tube into the honeycomb core.

The results of this investigation led to the following conclusions:

1. All specimens survived their design life (20 000 cycles) with design loads applied at room temperature even though the bolted end joints and specimen grips induced extraneous motions in the specimens.

2. The only failure not induced artificially occurred in a tube at the tube-manifold joint after more than 78 000 loading cycles at design loads or higher.

3. Cracks in skins either bonded or soldered to cooling tubes propagate past the tube without penetration.

4. The cooling tubes served as crack arresters and temporarily stopped crack growth when a crack reached the tube-skin intersection.

5. The honeycomb sandwich contained coolant leakage.

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August 16, 1977

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TABLE I.- FATIGUE TEST RESULTS FOR ELEMENTS OF AN ACTIVELY COOLED PANEL

Specimen number	Type	Initial condition	Coolant pressure		Stress range		Cycles	Comments
			kPa	psig	MPa	ksi		
1	Skin	As received	---	---	106.9	15.5	20 000	No change
		4.34 mm (0.171 in.) crack	---	---	106.9	15.5	34 450	Fracture
2	Skin	As received	---	---	106.9	15.5	20 000	No change
		4.34 mm (0.171 in.) crack	---	---	106.9	15.5	30 500	Fracture
3	Manifold-tube-skin (bonded)	As received	0	0	82.8	12.0	20 000	No change
		4.34 mm (0.171 in.) crack	517	75	82.8	12.0	16 176	No change
		9.53 mm (0.375 in.) crack	517	75	82.8	12.0	20 000	No change
		9.53 mm (0.375 in.) crack	517	75	103.5	15.0	22 000	Slow leak at manifold-tube joint
		9.53 mm (0.375 in.) crack	0	0	103.5	15.0	20 866	Crack grew past tube
4	Manifold-tube-skin (soldered)	As received	517	75	82.8	12.0	20 000	No change
		10.4 mm (0.41 in.) crack	517	75	82.8	12.0	142 946	Crack grew past tube
5	Honeycomb sandwich	As received	517	75	±82.8	±12.0	24 789	No change
		Simulated internal leak	517	75	±82.8	±12.0	10 000	No change
		Simulated internal leak	517	75	±100.2	±14.5	3 000	Specimen leaked internally
		Simulated internal leak	517	75	±100.2	±14.5	2 571	Inner skin crack

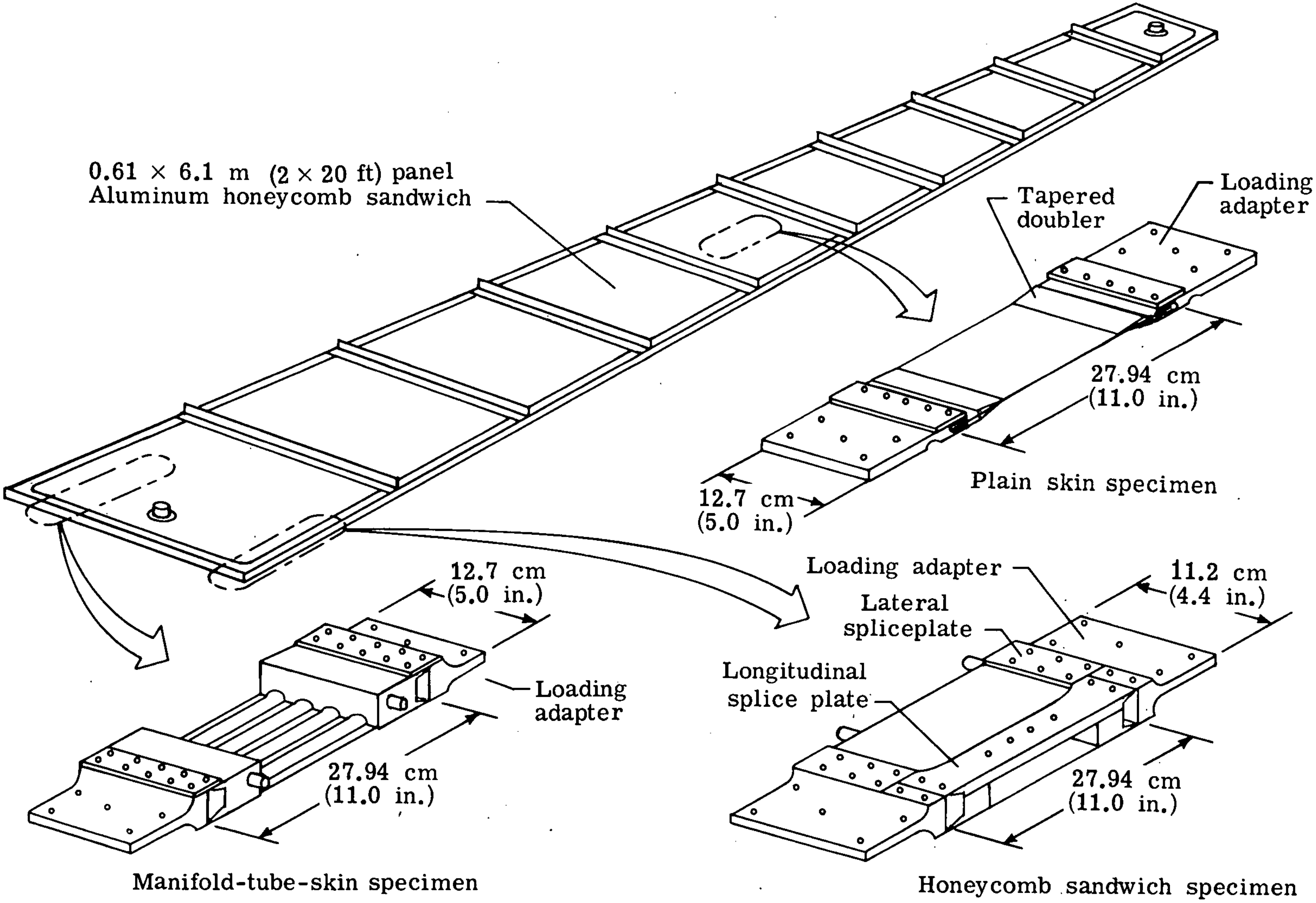

Figure 1.- Representative areas of fatigue specimens.

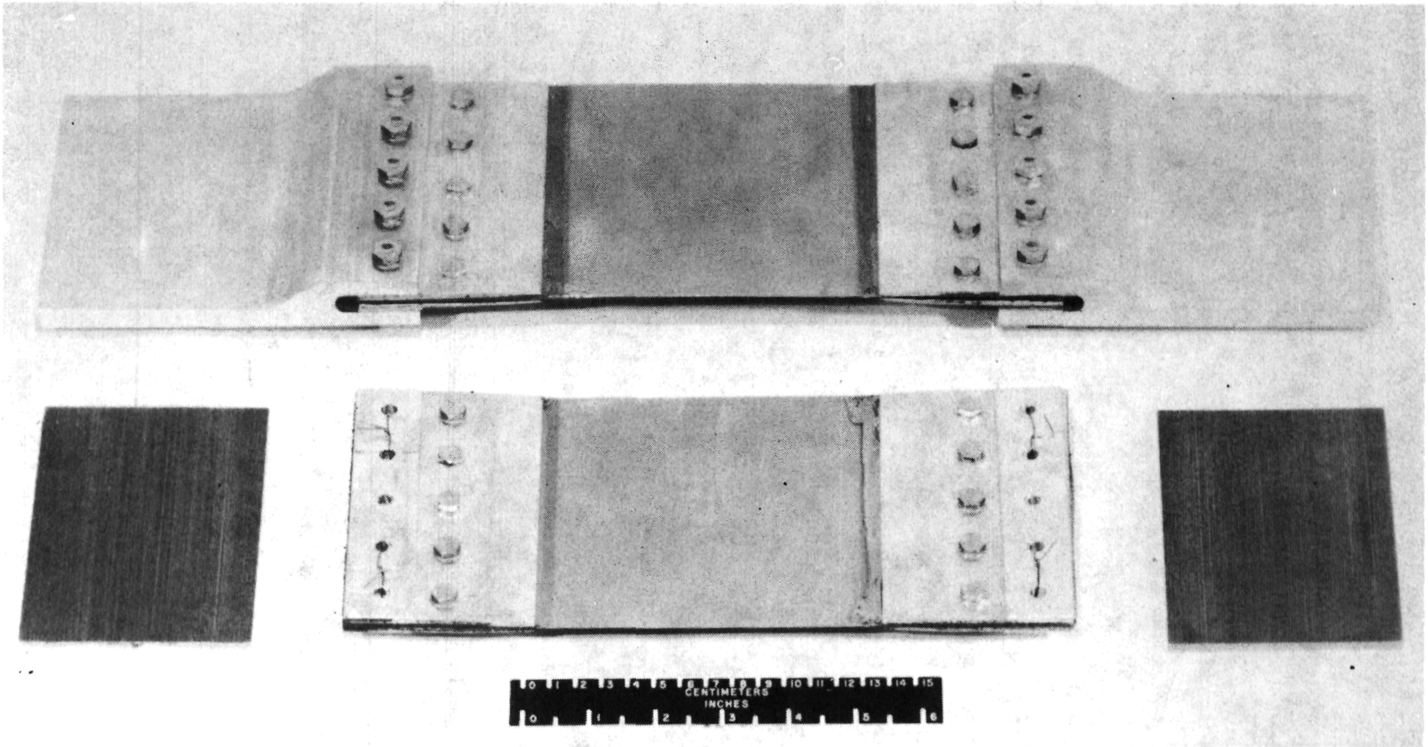

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Figure 2.- Plain skin specimens.

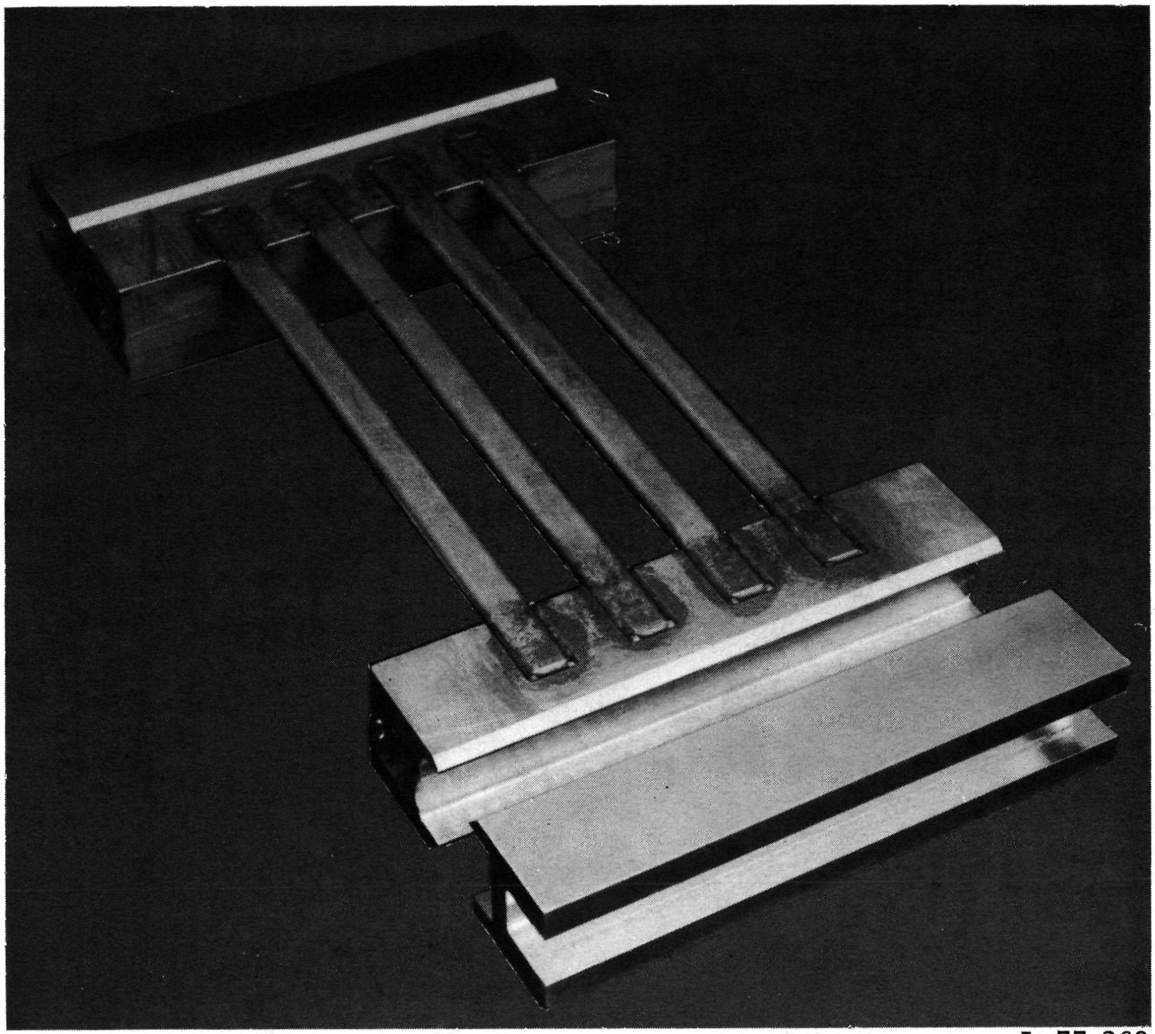

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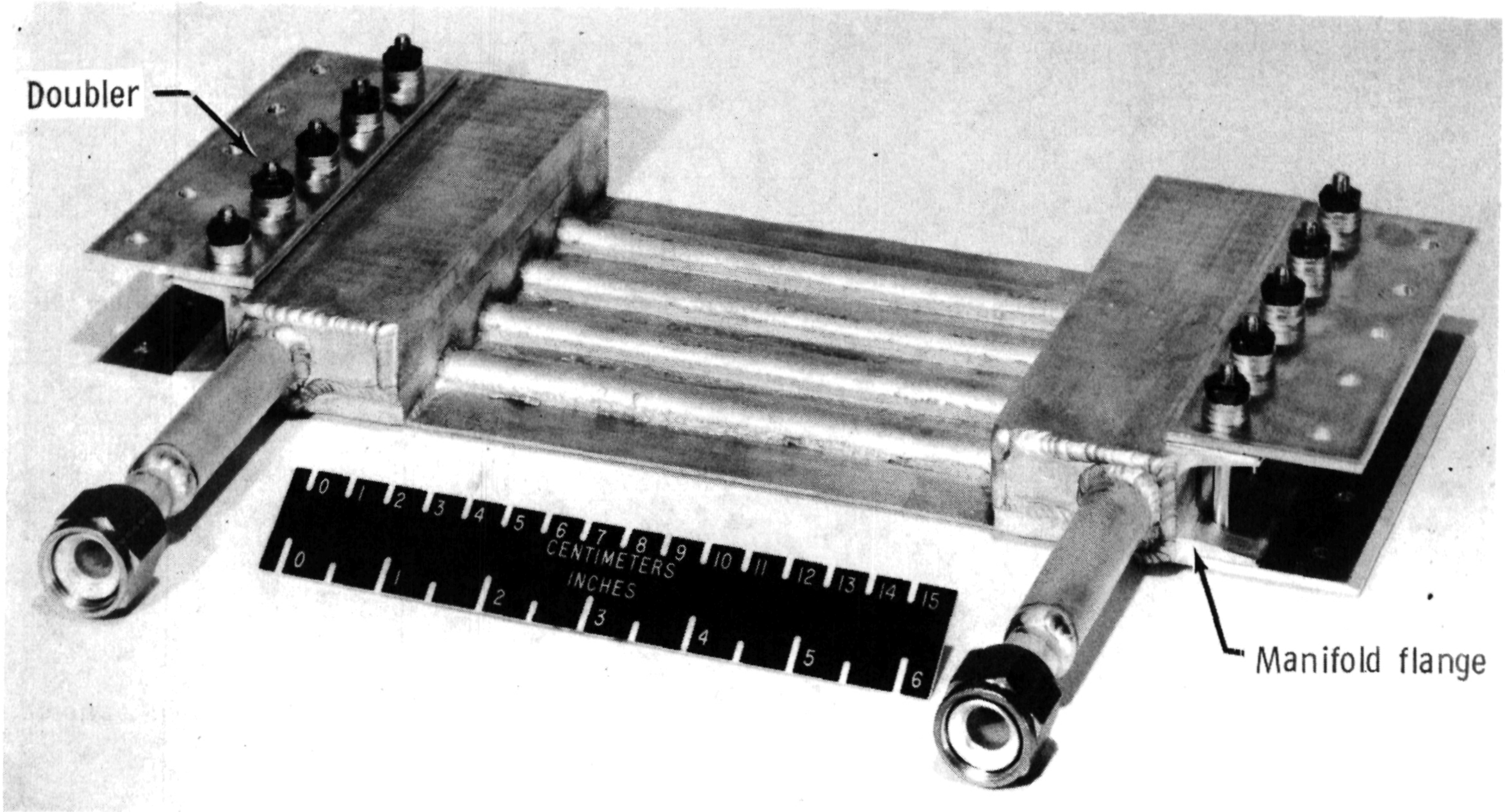
Figure 3.- Manifolds and tubes during fabrication.



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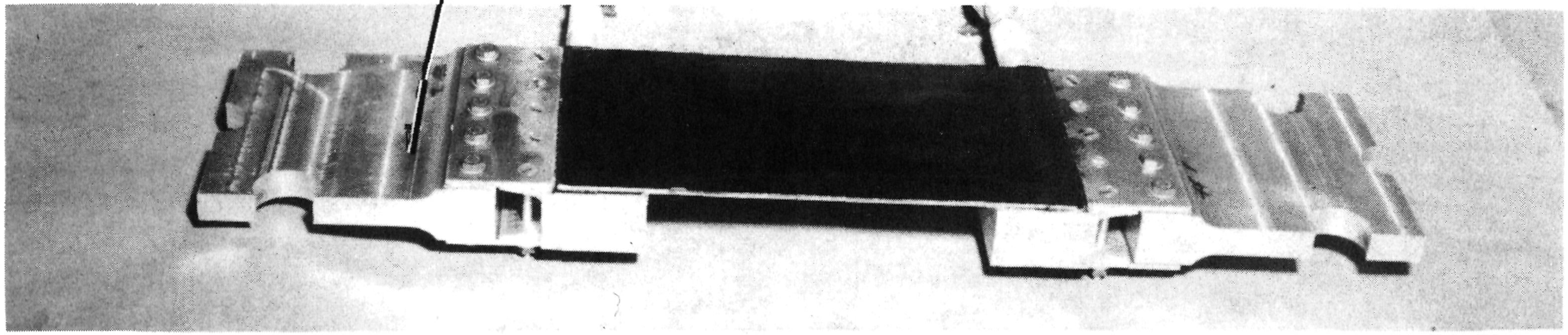
(a) Inner side view.

Figure 4.- Bonded manifold-tube-skin specimen.



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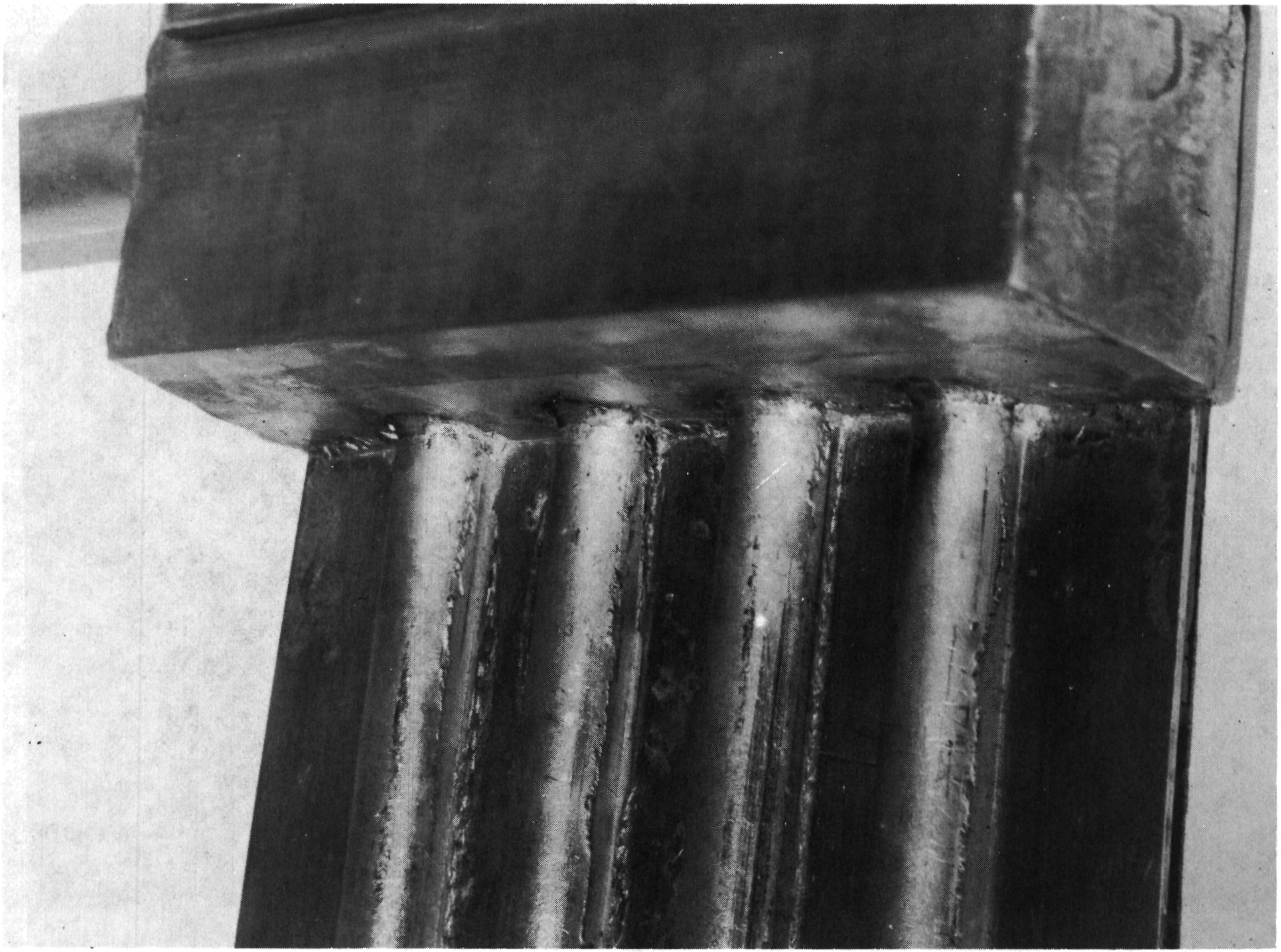
(b) Outer side view of specimen with symmetric end grips. (Heat sensitive crystals are on specimen.)

Figure 4.- Continued.



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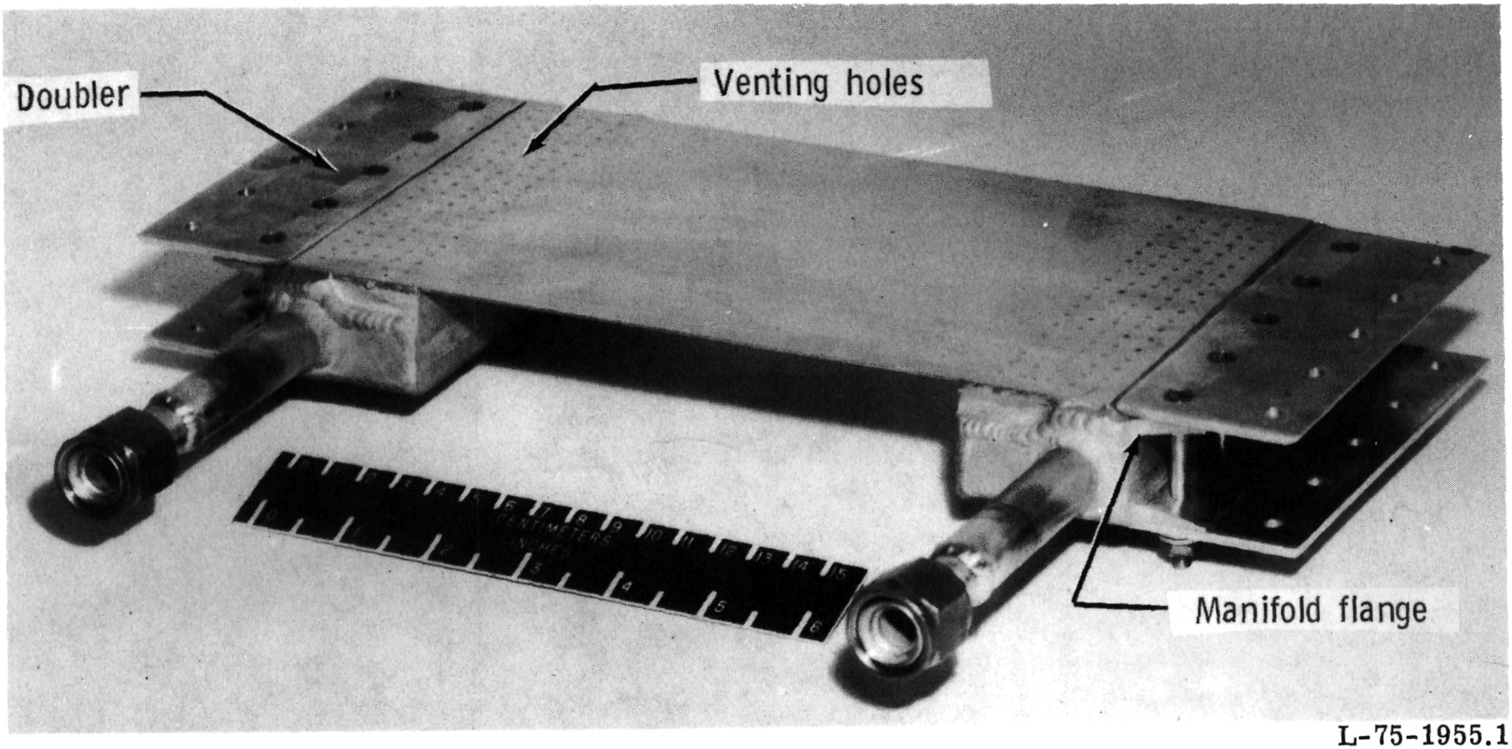
(c) Close-up of bonded tubes and brazed manifold-tube joints.

Figure 4.- Concluded.



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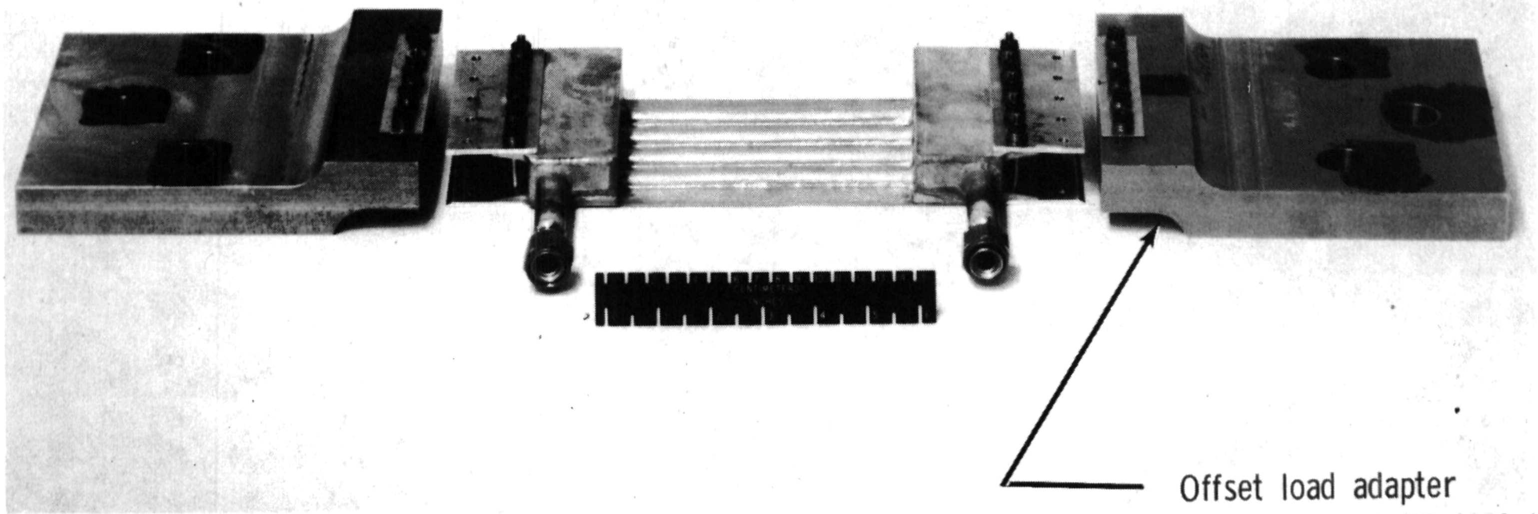
(a) Outer side view.

Figure 5.- Soldered manifold-tube-skin specimen.



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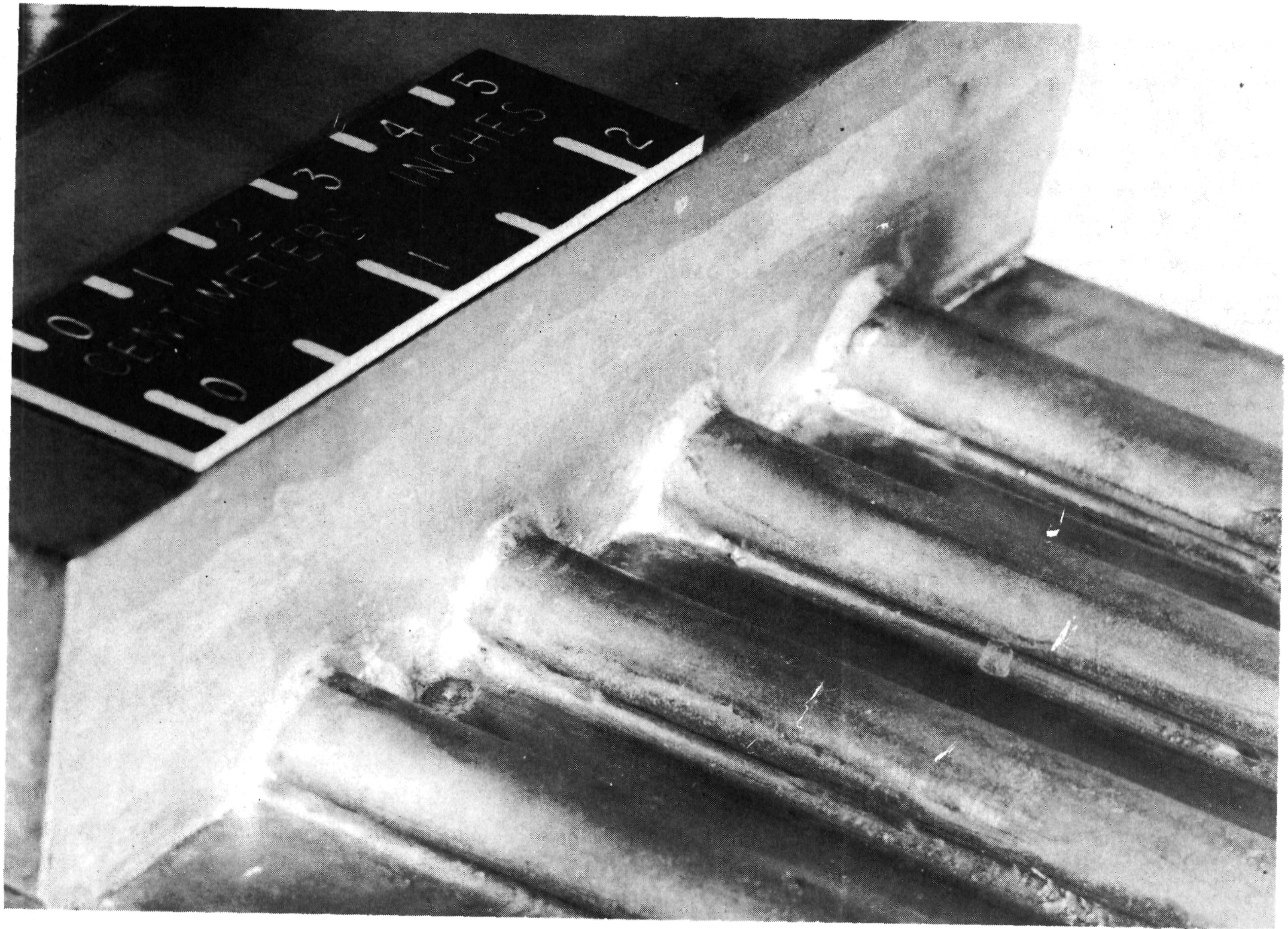
(b) Inner side view of specimen and offset grips.

Figure 5.- Continued.



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(c) Close-up of soldered tubes and brazed manifold-tube joints.

Figure 5.- Concluded.

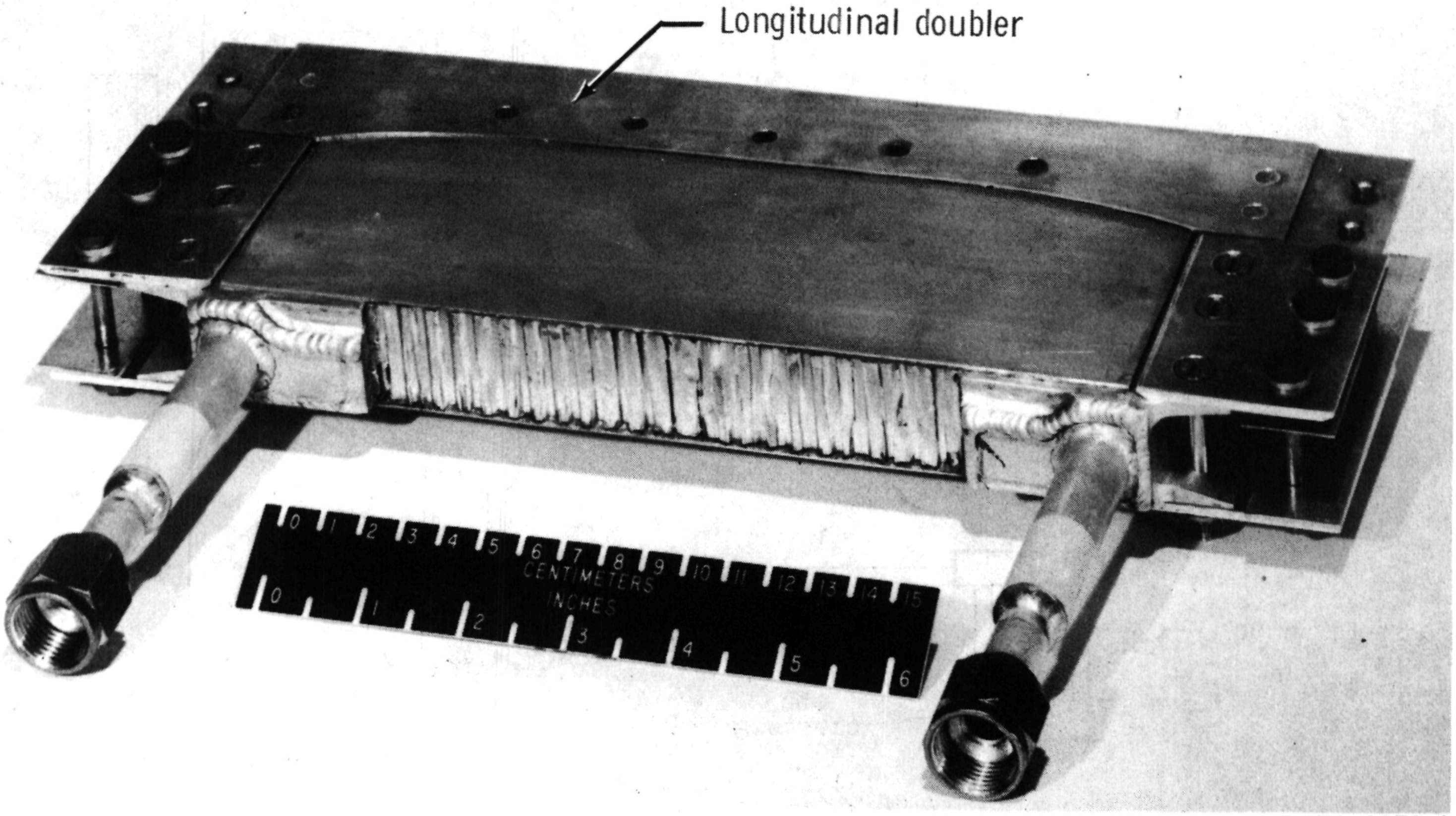

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Figure 6.- Honeycomb sandwich specimen.

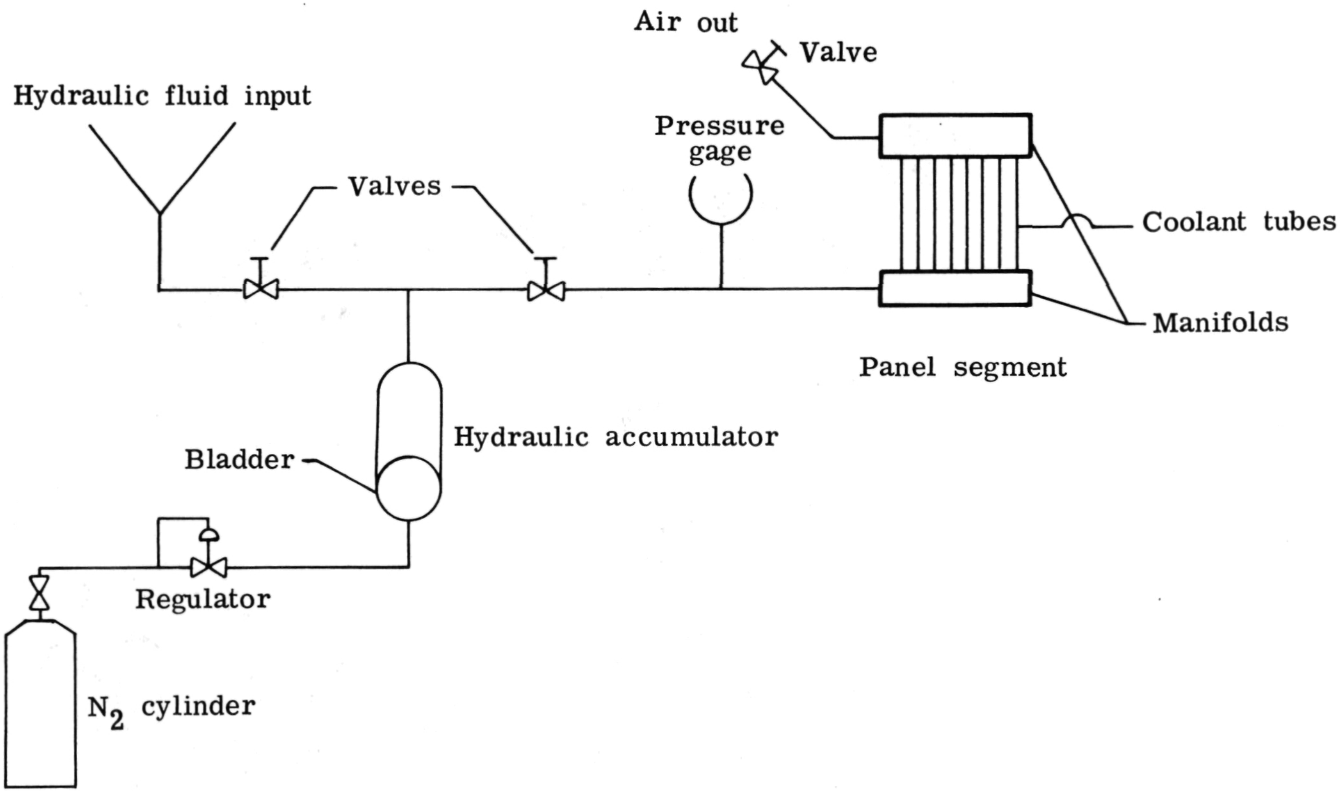


Figure 7.- Hydraulic pressure system.

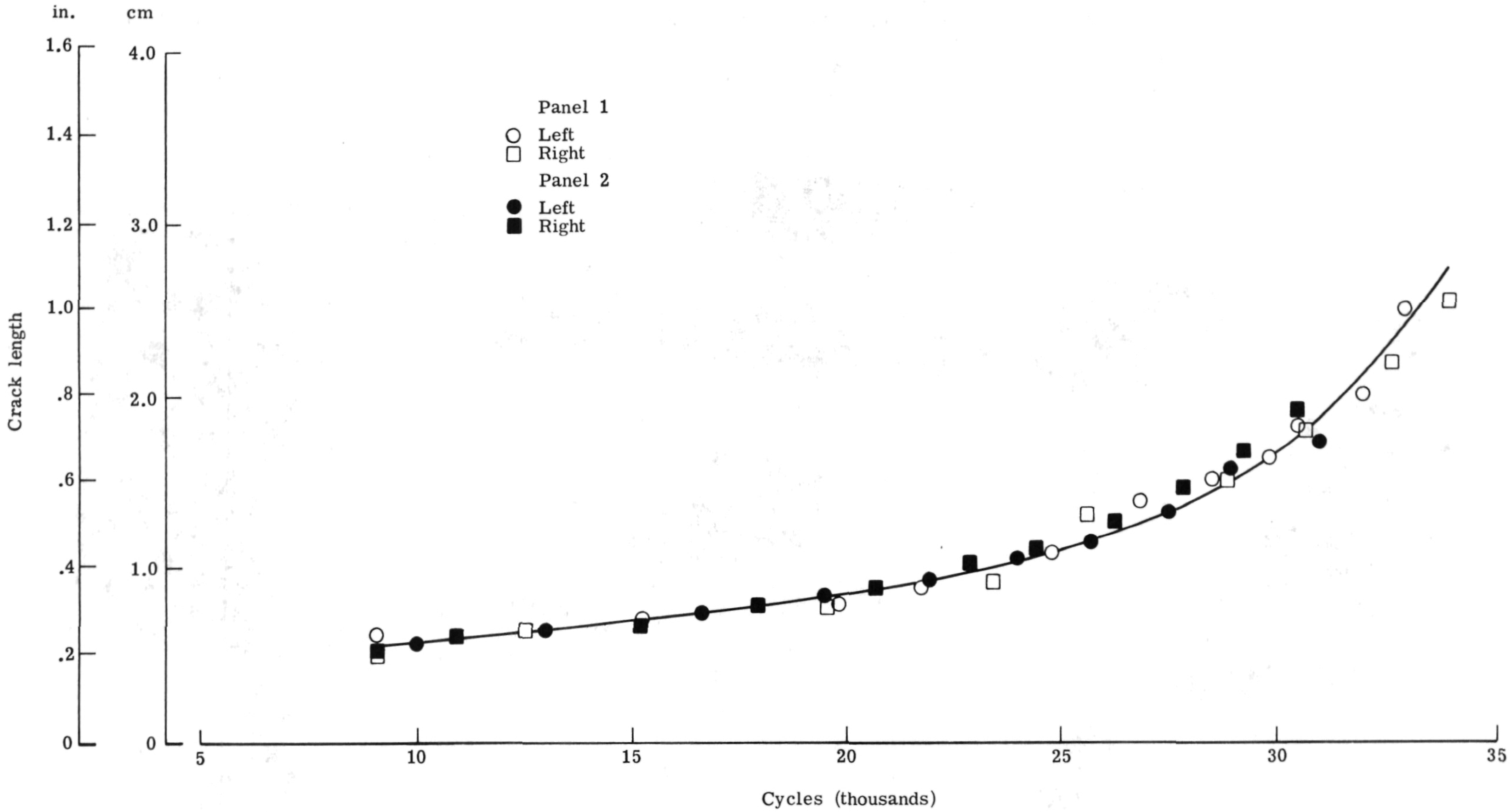
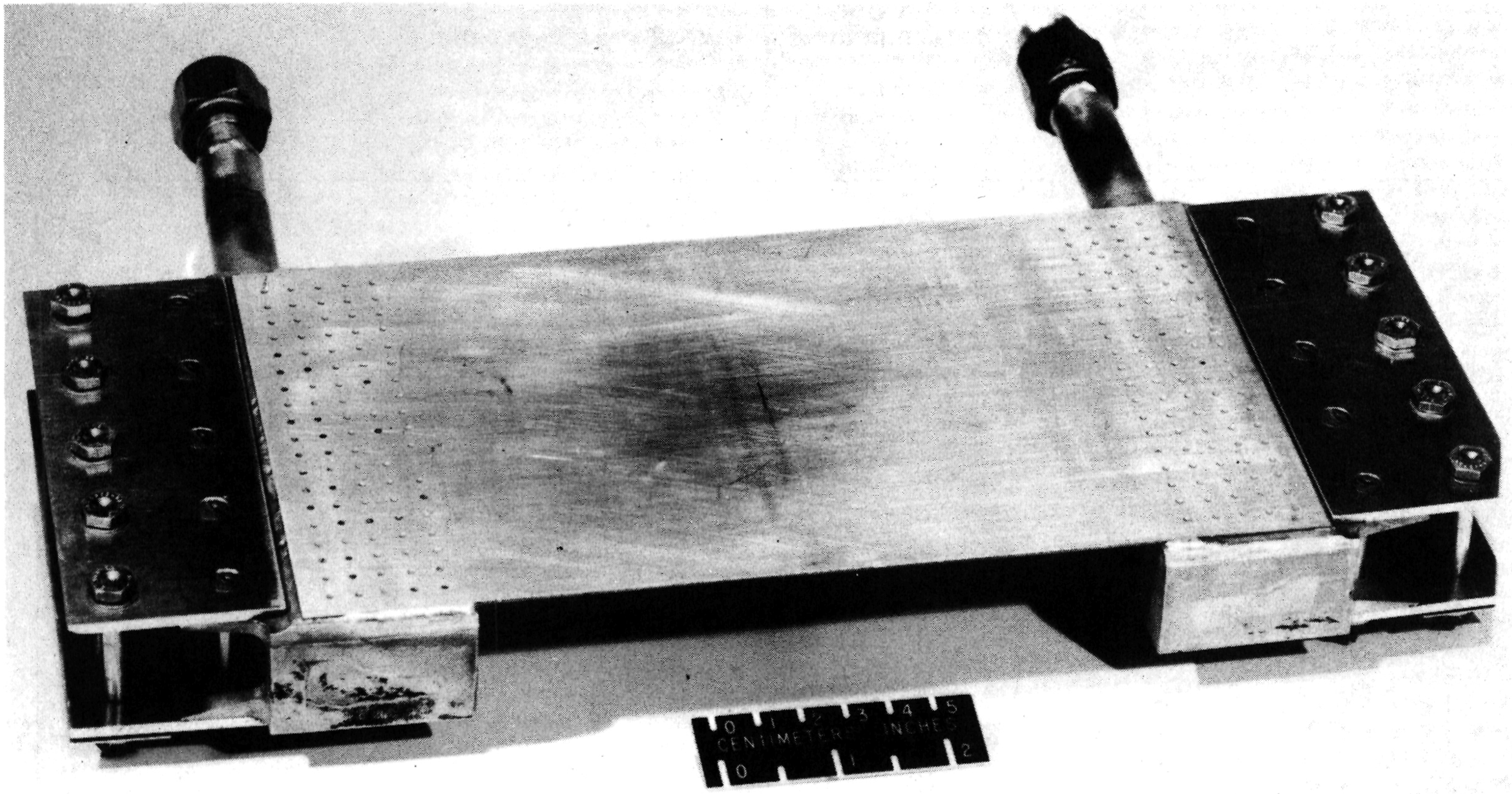


Figure 8.- Crack growth in plain skin specimens.

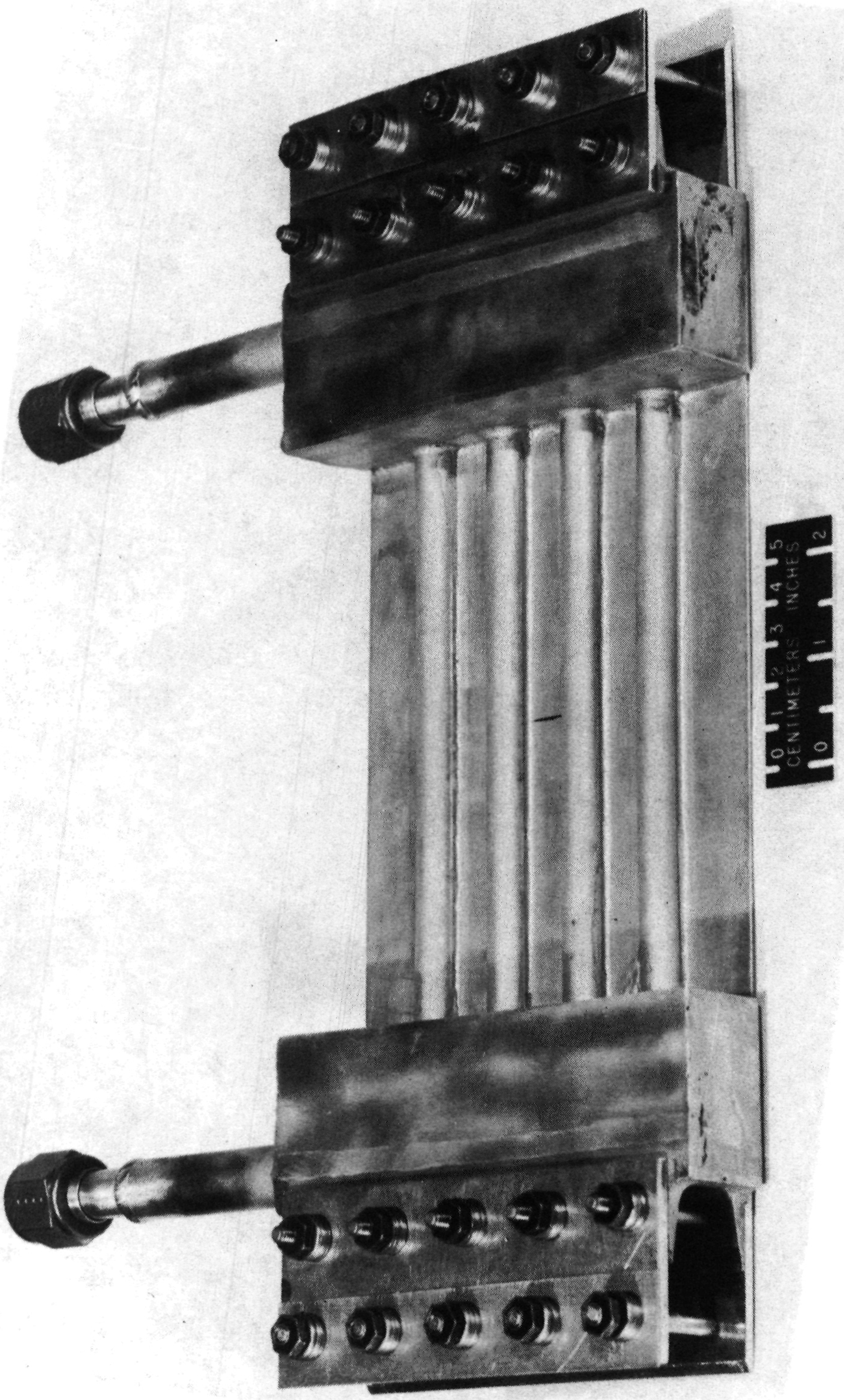


L-75-3825

(a) Outer side.

Figure 9.- Crack starter on outer skin of soldered specimen after completion of crack growth tests.

L-75-3823



(b) Inner side.

Figure 9.- Concluded.

-Langley, 1977 L-11552

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