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STRUCTURAL TESTS ON A TILE/STRAIN ISOLATION PAD THERMAL PROTECTION SYSTEM

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SUMMARY

The aluminum skin of the Space Shuttle is covered by a Thermal Protection System (TPS) consisting of a low density ceramic tile bonded to a matted-felt material called SIP (Strain Isolation Pad). The structural characteristics of the TPS were studied experimentally under selected extreme load conditions. Three basic types of loads were imposed: tension, eccentrically applied tension, and combined in-plane force and transverse pressure. For some tests transverse pressure was applied rapidly to simulate a transient shock wave passing over the tile. The failure mode for all specimens involved separation of the tile from the SIP at the silicone rubber bond interface. An eccentrically applied tension load caused the tile to separate from the SIP at loads lower than experienced at failure for pure tension loading. Moderate in-plane as well as shock loading did not cause a measurable reduction in the TPS ultimate failure strength. A strong coupling, however, was exhibited between in-plane and transverse loads and displacements.

INTRODUCTION

The Space Shuttle is protected against high temperature resulting from aerodynamic heating by a surface covering of several thousand low density Reusable Surface Insulation tiles (RSI). These tiles are relatively brittle with a low coefficient of thermal expansion and cannot be attached directly to the aluminum skin of the Space Shuttle. The tile instead are bonded using silicon rubber to a matted-felt material called SIP (Strain Isolation Pad). The SIP is bonded to the aluminum skin, also using silicon rubber adhesive.

The structural characteristics of this RSI tile/SIP thermal protective system were studied in a series of experiments which are reported upon herein.

The purposes of these experiments were (1) to determine the structural performance of the Thermal Protective System (TPS) under selected extreme load conditions and (2) to provide test data for later use in analysis validation. Three basic types of experiments were conducted: (1) tension tests, (2) tension loads eccentrically applied, and (3) combined in-plane load and transverse pressure. In some combined load tests, transverse pressure was rapidly applied to simulate a transient shock wave passing over the tile. Prior to conducting experiments, all specimens were required to pass a proof test tension/compression load cycle involving acoustic emission acceptance criteria identical to that used for accepting tile on the Space Shuttle. This paper describes the test techniques and the structural response of the TPS to the various test conditions.

SPECIMEN DESCRIPTION

Specimens used in this investigation were constructed using LI 900 tile surface treated with boro-silicate and 0.41 cm (0.16-in.) thick SIP in accordance with accepted fabrication methods approved for Space Shuttle. RTV 560 silicone rubber was used to bond the tile to the SIP and the SIP to a thick aluminum plate. All tiles were rectangular parallelepipeds, 15.2 cm (6 in.) square, 3.56 cm (1.4 in.) thick, and had a density of 144 kg/m^3 (9 lb/ft^3). The SIP bonded surface dimensions were 12.7 cm (5-in.) by 12.7 cm (5-in.). A 0.95 cm (0.38 in.) wide filler bar material of composition similar to the SIP was bonded to the aluminum plate around the perimeter of the SIP. Prior to bonding, the aluminum plate was primed with Koropon.

A specimen in sequential stages of fabrication is shown in figure 1. In separate operations, the filler bar was bonded to the aluminum plate and the SIP to the tile. Next, the tile/SIP assembly was bonded to the aluminum plate. Two types of 2024 aluminum plates were used in the investigation: tension specimen plates (illustrated in fig. 1) and combined load specimen plates. The bonding surface of aluminum plates were machined to a measured flatness of ±0.0254 mm (±0.001 inch) for tension specimen plates and ±0.0508 mm (±0.002 in.)

for combined load specimen plates. The tile was prepared for bonding by grinding the surface to a flatness of ±.0254 mm (±0.001 inch). Tension specimens successfully passing the proof test were prepared for testing by bonding a thick aluminum load introduction plate to the coated surface of the tile.

The modulus of the tile is approximately three orders of magnitude higher than the modulus of the SIP. The deformation response to loading, therefore, occurs primarily in the SIP. In addition, the SIP stress-strain response is highly nonlinear and exhibits hysteretic behavior.

TEST DESCRIPTION

Three types of loading were imposed on specimens in this investigation: tension, eccentrically applied tension, and combined in-plane force and transverse pressure. Schematic descriptions of these tests are shown in figure 2. Descriptions of the test techniques, as well as details of the proof test used to accept or reject specimens, are described below.

Proof Test

A proof test was conducted on each specimen prior to its acceptance for structural testing in accordance with techniques approved for testing TPS on the Space Shuttle. The test involved applying transverse tension loads to the TPS sufficient to impose an average stress on the SIP of 41.4 kPa (6 psi). The tension load was followed by unloading and the immediate application of compression loading. The compression load removes the displacement set caused by the tension load. Tension loading was at the rate of 13.8 kPa/minute (2 psi/min) stress on the SIP. The tension load was held for 30 seconds at the 20.7 (3 psi), 27.6 (4 psi), and 34.5 (5 psi) stress levels and for 60 seconds at the 41.4 kPa (6 psi) stress level. Acoustic emission data was monitored and recorded during tension loading.

TPS specimens were accepted for structural testing if the acoustic counts during the proof test did not exceed any of the following conditions.

1. 250 counts during the first 30 seconds of the 60-second proof hold load.
2. 100 counts during the second 30 seconds of the 60-second proof hold load and shall be less than counts during first 30 seconds

when counts exceed 50 for either the first or second 30-second hold.

3. 2000 counts from start of test at zero load to the midpoint of proof load hold interval. If 2000 counts are exceeded then retest is permitted. Total counts of first test less total counts of second test must then be equal to or less than 2000.

Following the proof test each tile was alcohol wiped and examined to identify any cracks in the tile coating. Specimens failing the proof test were subsequently loaded to failure in the proof test fixture.

A photograph of the equipment used in the proof test is shown in figure 3 and a closeup view of a tile specimen and the associated instrumentation is shown in figure 4. A pneumatic jack was used to apply load and an automatic pressure regulator system imposed the preprogrammed load/time profile. Acoustic emission transducers were located at the four corners and displacement gages were located at the midpoint of the four sides of the tile. A load cell measured the force applied to the tile. Acoustic emission data and load were monitored in real time during the test. Load, displacement and acoustic emission data were recorded on magnetic tape for later data reduction.

Tension Tests

Constant Displacement Rate.- Three specimens were loaded to failure in transverse tension in a constant displacement rate test machine. A displacement rate of 0.13 cm/min (0.05 inch/min) was used. The SIP displacement response to loading was measured at the midpoint of the four sides of the tile. A schematic of the test setup is presented in figure 5.

Pressure Applied Tension.- One specimen was loaded to failure in transverse tension by imposing reduced pressure on the top surface of the tile. The experimental setup is shown in figure 6. A narrow mylar bellows suspended from a plexiglass plate and sealed to the tile with masking tape permitted unstrained transverse displacement of the tile. The transverse displacements of the tile at the midpoint of the four sides of the tile and the pressure inside the bellows were recorded during the test.

Eccentrically Applied Tension

Three specimens were loaded to failure by an eccentrically applied tension load. The experimental setup is shown in figure 7. Loads were applied at a constant displacement rate of 0.13 cm/min (0.05 inch/min). The aluminum plate to which the top surface of the tile was bonded was rigidly constrained against rotation. Loads were introduced into the aluminum plate to which the SIP was bonded through a spherical bearing. This arrangement permitted the line of reaction to remain unchanged during the process of loading yet did not constrain the rotation of the tile and aluminum plate caused by the eccentric loading.

Combined In-Plane Force and Transverse Pressure

Three tests were conducted in which in-plane loads and combinations of in-plane and transverse loads were imposed on the tile. The apparatus for conducting these tests is shown in the photograph of figure 8 and schematically in figure 9. The foundation of the apparatus is the same as used in pressure applied transverse tension tests with the added capability of in-plane loading. As shown in figure 9, in-plane loads were applied along the tile diagonal. The aluminum plate to which the SIP was attached was mounted on roller bearings while the tile was rigidly constrained against in-plane displacement by a yoke arrangement which butted up against two sides of the tile (see fig. 10). The yoke reaction attachment was mounted on roller bearings in a slide constraint permitting the reaction free transverse translation of the yoke in response to any transverse displacement of the tile. The flexible bellows permitted negative pressure loads to be imposed on either all or part of the tile top surface. The flexible bellows thickness (i.e., dimension between the plexiglass plate and the top surface of the tile) was initially 0.96 cm (0.38 in.). This dimension permitted unrestrained transverse displacement capability of the tile while minimizing in-plane reaction forces on the tile during tests involving pressure applied to only a portion of the tile top surface.

In-plane loads were applied at the rate of 67 N/min (15 lbs/min) and pressure was applied at the rate of 28 kPa/min (4 psi/min). For tests in which the pressure was applied rapidly to simulate a shock, a pressurization rate of approximately 207 kPa/sec (30 psi/sec) was achieved. The technique for applying pressure shock involved pumping down a large pressure bottle to the desired pressure and releasing a solenoid value to rapidly reduce the pressure in the desired chamber. Measurements obtained during tests included the in-plane and transverse displacement of the tile, in-plane force and the pressure in chambers P_2 and P_3. A high speed oscilloscope was used to obtain the shock pressure versus time history. Data were monitored in real time and recorded on magnetic tape for later data reduction.

RESULTS AND DISCUSSION

Proof Tests

Results of the proof test are summarized in Table I. A total of 26 specimens were subjected to proof testing of which 19 passed the acoustic emission criteria and 7 failed. Specimens failing the test were loaded to failure in tension using the proof test fixture. Ultimate SIP stress at failure ranged from 66 kPa (9.6 psi) to 83 kPa (12.1 psi). All failures were at the bond surface between the SIP and the tile.

A typical plot for the SIP stress as a function of the tile displacement for a specimen passing the proof test is presented in figure 11. The creep behavior of the SIP is evident at the 28, 34, and 41 kPa (4, 5, and 6 psi) stress 30- and 60-second hold levels. The magnitude of the compression stress is calculated based on a 161 cm^2 (25 in^2) area disregarding the stiffness contribution of the filler bar. The SIP stress versus displacement response for other specimens deviated very little from the graph of figure 11.

The SIP stress versus displacement graph for a specimen which failed the proof test (acoustic emission criteria 3) is presented in figure 12. The initial loading curve is almost identical to that presented in figure 11 for specimens passing the proof test. Also presented is the graph of the second load cycle (permitted under criteria 3) and finally the response for the specimen on the final load cycle to failure. The displacement origin for these plots ignores any permanent set caused by previous loadings. A photograph of the failure surface for this specimen is shown in figure 13.

The failure was in the SIP/tile bond and looks similar to the failure surface of specimens which passed the proof tests and failed during other testing.

Tension Tests

The SIP failure stresses for the three specimens loaded in transverse tension at a constant displacement rate were 63, 73, and 79 kPa (9.2, 10.6 and 11.4 psi), see Table II. The SIP stress versus tile displacement response for these three specimens was similar as seen in figure 14. The failure for these specimens was in the bond between the tile and the SIP as shown for one of the specimens in figure 15. Small particles of the tile became detached and were distributed across the silicone rubber surface.

The tile loaded in tension by pressure failed at a SIP stress of 81 kPa (11.8 psi). This specimen had been previously loaded to a SIP tension stress of 30 kPa (4 psi). The SIP stress versus tile displacement curves for these two load cycles are presented in figure 16. A permanent set of approximately 0.05 cm (0.02 in.) resulted from the 30 kPa (4 psi) tension load cycle.

Eccentrically Applied Tension

The displacement response for three specimens loaded in tension with a 3.18 cm (1.25 in.) eccentricity as a function of the applied force is presented in figure 17. The failure load for the three specimens was 519, 586, and 694 N (117, 132, and 156 lb). The highest ultimate load value from the eccentrically applied tension tests is 32 percent lower than the lowest ultimate strength measured in pure tension tests. The displacement response for the three specimens is highly repeatable. The maximum displacement was recorded by displacement gage 4 and reached a magnitude of around 0.38 cm (0.15 in.). The opposite side of the tile (displacement gage 3) recorded negative displacements during the entire load history.

The large rotation of the plate to which the SIP is attached causes the failure to initiate in the region of maximum tensile stress (i.e., in the vicinity of gage 4). A photograph showing the rotation of the plate and disbond failure of the SIP to tile in this region is presented in figure 18 and a photograph of the SIP failure surface is presented in figure 19. No distinguishing features were detected in the failure surface and the appearance was similar to that for pure tension tests.

Combined In-Plane Force and Transverse Tension

In-Plane Load Plus Negative Pressure Applied to Tile Top Surface.- One specimen was subjected to combinations of in-plane load and negative pressure slowly applied to the entire top surface of the tile. The history of loading and the corresponding displacement response of the specimen is summarized in Table III. The sequence of loading for each load cycle involved applying an in-plane load at one corner of the specimen of approximately 133 N (30 lbs) followed by slowly reducing the pressure in the chamber enclosing the top of the tile. Each load cycle was begun at zero load with a new reference data zero. The displacement data, therefore, describes the response of the specimen for a particular load cycle, ignoring any permanent displacement set caused by previous loadings. The permanent set at the end of each load cycle, however, is recorded in Table III.

On the first load cycle, an in-plane displacement of 0.274 cm (0.108 in.) resulted corresponding to an in-plane load of 137 N (30.8 lb). The in-plane load imposes a moment on the tile and causes it to rotate as evidenced by the upward movement of 0.010 cm (0.004 in.) of the left side of the tile and downward movement of 0.081 cm (0.032 in.) for the right side. As discussed earlier, vertical displacements were recorded by displacement gages at the midpoint of the tile sides. The superposition of the negative pressure loading (transverse tension) to the in-plane load causes the tile to displace upward and also causes a significant reduction in the in-plane displacement. A strong coupling between in-plane and transverse loads and displacements was observed for all tests involving combined loads. It is speculated that the transverse fibers of the SIP align to react the shear and transverse tension loads at an angle other than normal and perform like a string truss.

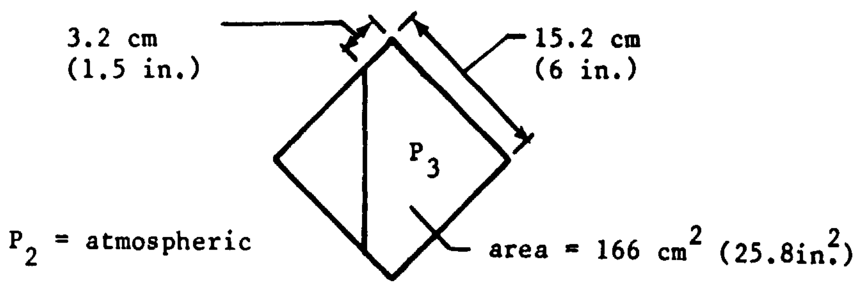
The displacement response of the tile to the pure in-plane loads (load cycles 1 through 5, Table III) is presented in figure 20. The specimen failed during load cycle 5 at an average tensile stress in the SIP of 112.4 kPa (16.3 psi) while simultaneously loaded in-plane with 162 N (36.5 lb). The displacement response for this load cycle is presented in figure 21. The displacement offset at zero load is caused by the in-plane load. Photographs of the SIP and tile failure surfaces are presented in figure 22. No distinguishing appearances were observed compared with failure surfaces observed for other specimens.

In-Plane Load Plus Negative Pressure Shock Applied to the Tile Top Surface.- One specimen was subjected to combinations of in-plane load and transverse tension applied as a negative pressure shock to the top surface of the tile. The sequence of loads imposed on the specimen and the corresponding displacement response is summarized in Table IV. For each load cycle, an in-plane load was first imposed followed by a transverse tension pressure shock load and subsequent unloading. The specimen carried the loads without failure for all test conditions. As for the combined load specimen described above, a data zero reference was used to start each load cycle.

A typical plot of pressure versus time for the 14 kPa (2 psi) shock is presented in figure 23. The pressurization rate for the first 7 kPa (1 psi) reduction in pressure was approximately 180 kPa/sec (26 psi/sec). The displacement response of the tile to pure in-plane loads (load cycles 1, 2, and 3; Table IV) is presented in figure 24. In-plane displacements cause a clockwise rotation and negative displacement of the tile. An in-plane displacement of approximately 0.20 cm (0.08 in.) resulted from a 133 N (30 lb) in-plane load.

In-Plane Load Plus Negative Pressure Shock Applied to a Portion of the Tile Top Surface.- One specimen was subjected to combinations of in-plane load and transverse tension applied as a negative pressure shock to a portion of the tile top surface. The history of loading and the corresponding displacement response of the tile are summarized in Table V. As above, each load cycle was begun at zero load with a new reference data zero. The permanent set at the end of each load cycle is recorded in Table III.

The negative pressure P_3 was applied to an area defined in the following sketch.



The negative pressure was rapidly imposed to simulate a transient aerodynamic pressure shock. Plots of pressure versus time for 10 kPa (1.5 psi) and 17 kPa (2.5 psi) shock conditions are shown in figure 23. The pressure versus time trace was repeatable with minor variations. The pressurization rate for the first 7 kPa (1 psi) reduction in pressure was approximately 145 kPa/sec (21 psi/sec) for the 10 kPa (1.5 psi) shock and 255 kPa/sec (37 psi/sec) for the 16 kPa (2.5 psi) shock.

The displacement response of the specimen to a pure in-plane load (load cycle 9) is plotted in figure 25. The response is similar to that recorded in figure 24 for a specimen subjected to a different previous load history.

Following the load history defined in Table V, the specimen was loaded to failure using the proof test fixture. The tile displacement response plotted as a function of the average SIP stress is presented in figure 26. The creep response shown in the graph was caused by holding the load for 30 sec at 7 kPa (1 psi) stress increments beginning at 28 kPa (4 psi). The stress in the SIP at failure was 82 kPa (11.9 psi).

CONCLUDING REMARKS

A limited number of precisely executed tests on an LI 900 tile/0.16 SIP thermal protection system establish the following structural characteristic trends.

1. Nineteen of 26 specimens tested (73 percent) passed the proof test acoustic emission criteria.
2. Specimens failing acoustic emission proof test criteria exhibited ultimate tensile strength values on the same order as specimens which passed the proof test criteria.

3. The failure surface for all specimens tested in this investigation was in the bond between the SIP and the tile. Examination showed small particles of the tile became dislodged from the tile and remained attached to the silicone rubber bonding material.
4. The ultimate tensile strength for four test specimens ranged from 63 kPa (9.2 psi) to 8. kPa (11.8 psi). For specimens with tile 3.6 cm (1.4-in.) thick, no significant difference in test results was observed whether loads were applied through a thick aluminum plate bond to the tile coated surface or applied as a negative pressure to this surface.
5. An eccentrically applied tension load caused the tile to separate from the SIP in the region of combined stress (tension plus bending) at loads lower than recorded at failure for pure tension loading. The displacement response of the tile corresponding to a 3.18 cm (1.25-in.) eccentricity was found to be very similar for three test specimens.
6. Several test condition combinations of in-plane load and transverse tension indicate moderate in-plane loads do not reduce the TPS transverse tensile strength.
7. Transverse tension applied as a representative pr ssure shock to "a portion of" or to "all of" the tile top surface did not result in failure.
8. The low in-plane stiffness of the SIP permits significant in-plane displacements to occur. For example, a first cycle in-plane load of 137 N (30.8 lb) resulted in an in-plane displacement of 0.274 cm (0.108 in.).
9. A strong coupling was exhibited between in-plane and transverse forces and displacements. A transverse tension load, for example, reduces the magnitude of the in-plane displacement caused by an in-plane force acting alone.
10. The previous history of loading is important if one is to predict the displacement response to the current set of loads.

TABLE I.- TPS PROOF TEST SUMMARY.

SPECIMENS TESTED	SPECIMENS PASSED	SPECIMENS FAILED ACOUSTIC EMISSION CRITERIA
28	[illegible]	7 (27%)

SPECIMENS FAILING ACOUSTIC EMISSION CRITERIA WERE LOADED IN TENSION TO FAILURE USING THE PROOF TEST FIXTURE. LOADS WERE APPLIED IN 6.9 kPa (1 PSI) INCREMENTS (CALCULATED BASED ON SIP BOND AREA) AND HELD FOR 30 SECONDS BEFORE INCREASING LOAD TO NEXT STRESS LEVEL.

SPECIMEN	SIP STRESS AT FAILURE, kPa (PSI)	TIME HELD AT MAXIMUM LOAD BEFORE FAILURE, SEC.	FAILURE MODE
1	66 (9.6)	13	SIP TO RSI BOND
2	81 (11.8)	14	SIP TO RSI BOND
3	83 (12.1)	3	SIP TO RSI BOND
4	82 (11.9)	2	SIP TO RSI BOND
5	72 (10.5)	5	SIP TO RSI BOND
6	81 (11.7)	9	SIP TO RSI BOND
7	75 (10.9)	1	SIP TO RSI BOND

TABLE II.- SIP FAILURE STRESS FOR SPECIMENS LOADED IN TRANSVERSE TENSION.

(a) CONSTANT DISPLACEMENT RATE TEST.

SPECIMEN	SIP FAILURE STRESS, kPa (PSI)
1	73 (10.6)
2	63 (9.2)
3	79 (11.4)

(b) NEGATIVE PRESSURE APPLIED TO TILE TOP SURFACE.

LOAD CYCLE	$P_2 = P_3$, kPa (PSI)	SIP STRESS, kPa (PSI)	COMMENT
1	21 (3.06)	30 (4.4)	HELD LOAD WITHOUT FAILURE
2	56 (8.17)	81 (11.8)	FAILURE, SIP TO RSI BOND

TABLE III.- IN-PLANE LOAD PLUS NEGATIVE PRESSURE SLOWLY APPLIED TO TILE TOTAL TOP SURFACE. P_1 = 1 ATMOSPHERE.

LOAD CYCLE	IN-PLANE LOAD		PRESSURE LOAD		DISPLACEMENT, CM (INCH)			COMMENTS
	N (LB)	EQUIVALENT SIDE PRESSURE, kPa (PSI)	P_2=P_2, kPa (PSI)	SIP STRESS, kPa (PSI)	IN-PLANE	VERTICAL LEFT	VERTICAL RIGHT	
1	137 (30.8)	17.9 (2.59)	0 (0)	0 (0)	.274 (.108)	.010 (.004)	-.081 (-.032)	HELD LOAD WITHOUT FAILURE
	168 (37.6)	21.9 (3.17)	33.4 (4.85)	48.1 (6.98)	.145 (.057)	.145 (.057)	.127 (.050)	HELD LOAD WITHOUT FAILURE
	5 (1.1)	.6 (.09)	0 (0)	0 (0)	.188 (.074)	.048 (.019)	.033 (.013)	PERMANENT SET FOR 1st LOAD CYCLE
2	133 (30.0)	17.4 (2.53)	0 (0)	0 (0)	.168 (.066)	-.036 (-.014)	-.109 (-.043)	HELD LOAD WITHOUT FAILURE
	165 (37.2)	21.6 (3.13)	46.8 (6.78)	67.3 (9.76)	-.048 (-.018)	.130 (.051)	.140 (.055)	HELD LOAD WITHOUT FAILURE
	2 (0.4)	.2 (.03)	0 (0)	0 (0)	.058 (.023)	.013 (.005)	.010 (.004)	PERMANENT SET FOR 2nd LOAD CYCLE
3	135 (30.3)	17.6 (2.55)	0 (0)	0 (0)	.175 (.069)	-.046 (-.018)	-.122 (-.048)	HELD LOAD WITHOUT FAILURE
	165 (37.0)	21.4 (3.11)	59.0 (8.56)	84.8 (12.3)	-.086 (-.034)	.140 (.055)	.155 (.061)	HELD LOAD WITHOUT FAILURE
	.9 (0.2)	.1 (.02)	0 (0)	0 (0)	.058 (.023)	.020 (.008)	.008 (.003)	PERMANENT SET FOR 3rd LOAD CYCLE
4	134 (30.2)	17.5 (2.54)	0 (0)	0 (0)	.170 (.067)	-.061 (-.024)	-.130 (-.051)	HELD LOAD WITHOUT FAILURE
	165 (37.0)	21.4 (3.11)	74.5 (10.8)	106.9 (15.5)	-.137 (-.054)	.163 (.064)	.196 (.077)	HELD LOAD WITHOUT FAILURE
	2 (.4)	.2 (.03)	0 (0)	0 (0)	.048 (.019)	.008 (.003)	.023 (.009)	PERMANENT SET FOR 4th LOAD CYCLE
5	133 (29.9)	17.4 (2.52)	0 (0)	0 (0)	.193 (.076)	-.066 (-.026)	-.155 (-.061)	HELD LOAD WITHOUT FAILURE
	162 (36.5)	21.2 (3.07)	77.9 (11.3)	112.4 (16.3)	-.137 (-.054)	.191 (.075)	.196 (.077)	FAILURE SIP TO RSI BOND

@ ZERO LOAD AND DATA ZERO REFERENCE BEGINNING EACH LOAD CYCLE.

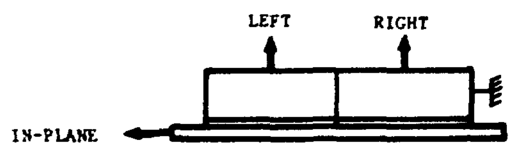


TABLE IV.- IN-PLANE LOAD PLUS NEGATIVE PRESSURE SHOCK APPLIED TO TILE TOTAL TOP SURFACE. P_1 = 1 ATMOSPHERE. SPECIMEN CARRIED LOAD WITHOUT FAILURE FOR ALL TESTS.

LOAD CYCLE	IN-PLANE LOAD		PRESSURE LOAD		DISPLACEMENT, CM (INCH)		
	N (LB)	EQUIVALENT SIDE PRESSURE, kPa PSI	$P_2=P_2$, kPa PSI	SIP STRESS, kPa (PSI)	INPLANE	VERTICAL LEFT	VERTICAL RIGHT
1 [a]	74 (16.6) 90 (20.2) 1 (.2)	9.65 (1.40) 11.72 (1.70) .14 (.02)	0 (0) 12.9 (1.87) 0 (0)	0 (0) 18.8 (2.72) 0 (0)	.135 (.053) .066 (.026) .056 (.022)	.003 (.001) .124 (.049) .030 (.012)	-.058 (-.023) .064 (.025) .018 (.007)
2 [a]	128 (28.8) 153 (34.3) 4 (1.0)	16.69 (2.42) 19.93 (2.89) .55 (.08)	0 (0) 13.6 (1.97) 0 (0)	0 (0) 19.6 (2.84) 0 (0)	.201 (.079) .114 (.045) .061 (.024)	-.010 (-.004) .086 (.034) .005 (.002)	-.104 (-.041) .005 (.002) -.008 (-.003)
3 [a]	129 (28.9) 149 (33.4) 126 (28.4)	16.75 (2.43) 19.37 (2.81) 16.48 (2.39)	0 (0) 13.2 (1.91) 0 (0)	0 (0) 19.0 (2.75) 0 (0)	.191 (.075) .099 (.039) .213 (.084)	-.013 (-.005) .084 (.033) .003 (.001)	-.107 (-.042) .010 (.004) -.094 (-.037)
4-12 [b]	145 (32.6) 6 (1.3)	18.89 (2.74) .76 (.11)	12.9 (1.87) 0 (0)	18.8 (2.72) 0 (0)	.119 (.047) .089 (.035)	.094 (.037) .010 (.004)	.013 (.005) -.008 (-.003)

a ZERO LOAD AND DATA ZERO REFERENCE BEGINNING EACH LOAD CYCLE.

b LOAD CYCLES 4-12 CONTINUOUS WITHOUT DATA ZERO REFERENCE. IN-PLANE LOAD OF APPROXIMATELY 129N (29 POUNDS) HELD WHILE 8 CYCLES OF APPROXIMATELY 13.1 kPa (1.9 PSI) SHOCK APPLIED. DATA PRESENTED FOR CYCLE 12.

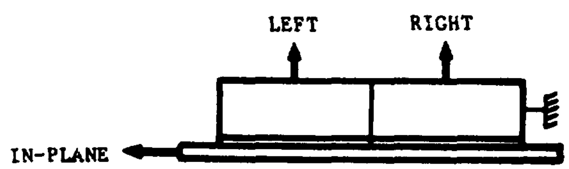


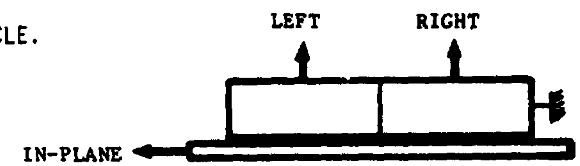
TABLE V.- IN-PLANE LOAD PLUS NEGATIVE PRESSURE SHOCK APPLIED TO PORTION OF TILE TOP SURFACE. $P_1 = P_2$ = 1 ATMOSPHERE. SPECIMEN CARRIED LOAD WITHOUT FAILURE FOR ALL LOAD CYCLES.

LOAD CYCLE [a]	IN-PLANE LOAD		PRESSURE LOAD		DISPLACEMENT, CM (INCH)		
	N (LB)	EQUIVALENT SIDE PRESSURE, kPa (PSI)	P_3, kPa (PSI)	RESULTANT TENSION LOAD, N (LB)	IN-PLANE	VERTICAL LEFT	VERTICAL RIGHT
1	0 0	0 0	15.0 (2.18) 0 (0)	250 (56.2) 0 (0)	-.030 (-.012) -.010 (-.004)	-.003 (-.001) .003 (.001)	.104 (.041) .038 (.015)
2	24.8 (5.6) 37.4 (8.4) (0)	3.24 (.47) 4.90 (.71) 0 (0)	0 (0) 10.4 (1.51) 0 (0)	0 (0) 173 (39.0) 0 (0)	.094 (.037) .089 (.035) .079 (.031)	.013 (.005) .008 (.003) .008 (.003)	-.048 (-.019) .033 (+.013) -.023 (-.009)
3	48.4 (10.9) 65.4 (14.7) 2.5 (.6)	6.34 (.92) 8.55 (1.24) .34 (.05)	0 (0) 10.6 (1.53) 0 (0)	0 (0) 176 (39.5) 0 (0)	.089 (.035) .084 (.033) .041 (.016)	.013 (.005) .010 (.004) .008 (.003)	-.058 (-.023) .023 (.009) -.018 (-.007)
4	73.5 (16.5) 91.9 (20.7) 2.5 (.6)	9.58 (1.39) 12.00 (1.74) .34 (.05)	0 (0) 10.6 (1.53) 0 (0)	0 (0) 176 (39.5) 0 (0)	.137 (.054) .119 (.047) .033 (.013)	.008 (.003) .008 (.003) .005 (.002)	-.066 (-.026) .008 (.002) -.010 (-.004)
5	98.0 (22.0) 117.5 (26.4) 1.8 (.4)	12.76 (1.85) 15.31 (2.22) .21 (.03)	(0) 10.4 (1.51) (0)	(0) 173 (39.0) (0)	.127 (.050) .122 (.048) .025 (.010)	.005 (.002) .003 (.001) .003 (.001)	-.076 (-.030) -.003 (-.001) -.010 (-.004)
6	146.8 (33.0) 164.7 (37.0) 0 (0)	19.17 (2.78) 21.44 (3.11) 0 (0)	(0) 10.3 (1.5) (0)	0 (0) 172 (38.7) 0 (0)	-- -- --	-- -- --	-- -- --

LOAD CYCLE [a]	IN-PLANE		PRESSURE LOAD		DISPLACEMENT, CM (INCH)		
	N (LB)	EQUIVALENT SIDE PRESSURE, kPa (PSI)	P_3, kPa (PSI)	RESULTANT TENSION LOAD[b], N (LB)	IN-PLANE	VERTICAL LEFT	VERTICAL RIGHT
7	203 (45.5)	26.4 (3.83)	(0)	(0)	.180 (.071)	-.023 (-.009)	-.107 (-.042)
	219 (49.3)	28.6 (4.15)	10.0 (1.45)	116 (26.1)	.175 (.069)	-.020 (-.008)	-.071 (-.028)
	2 (.4)	.2 (.03)	(0)	(0)	.028 (.011)	-.003 (-.001)	-.010 (-.004)
8	257 (57.8)	33.6 (4.87)	(0)	(0)	.254 (.100)	-.023 (-.009)	-.150 (-.059)
	276 (62.0)	36.0 (5.22)	10.3 (1.49)	119 (26.8)	.251 (.099)	-.023 (-.009)	-.114 (-.045)
	2 (.6)	.3 (.05)	(0)	(0)	.076 (.030)	-.008 (-.003)	-.023 (-.009)
9	310 (69.6)	40.4 (5.86)	(0)	(0)	.221 (.087)	-.028 (-.011)	-.145 (-.057)
	328 (73.8)	42.8 (6.21)	10.3 (1.49)	119 (26.8)	.218 (.086)	-.028 (-.011)	-.117 (-.046)
	364 (81.8)	47.5 (6.89)	(0)	(0)	.247 (.097)	-.038 (-.015)	-.155 (-.061)
	384 (86.2)	55.9 (8.10)	10.3 (1.49)	119 (26.8)	.241 (.095)	-.036 (-.014)	-.135 (-.053)
	392 (88.0)	51.0 (7.40)	(0)	(0)	.259 (.102)	-.041 (-.016)	-.163 (-.064)
	422 (94.8)	55.0 (7.98)	18.4 (2.67)	214 (48.1)	.247 (.097)	-.036 (-.014)	-.104 (-.041)
	390 (87.7)	50.9 (7.38)	(0)	(0)	.269 (.106)	-.048 (-.019)	-.157 (-.062)
	437 (98.2)	57.0 (8.27)	17.1 (2.48)	198 (44.6)	.259 (.102)	-.043 (-.017)	-.119 (-.047)
	390 (87.6)	50.8 (7.37)	(0)	(0)	.277 (.109)	-.051 (-.020)	-.157 (-.062)
	427 (95.9)	55.7 (8.08)	17.7 (2.56)	205 (46.1)	.262 (.103)	-.043 (-.017)	-.112 (-.044)
	3 (.7)	.4 (.06)	(0)	(0)	.069 (.027)	+.008 (+.003)	-.008 (-.003)

a ZERO LOAD AND DATA ZERO REFERENCE BEGINNING EACH LOAD CYCLE.

b APPLIED TO 166 cm^2 (25.8 in^2) OF TILE TOP SURFACE.



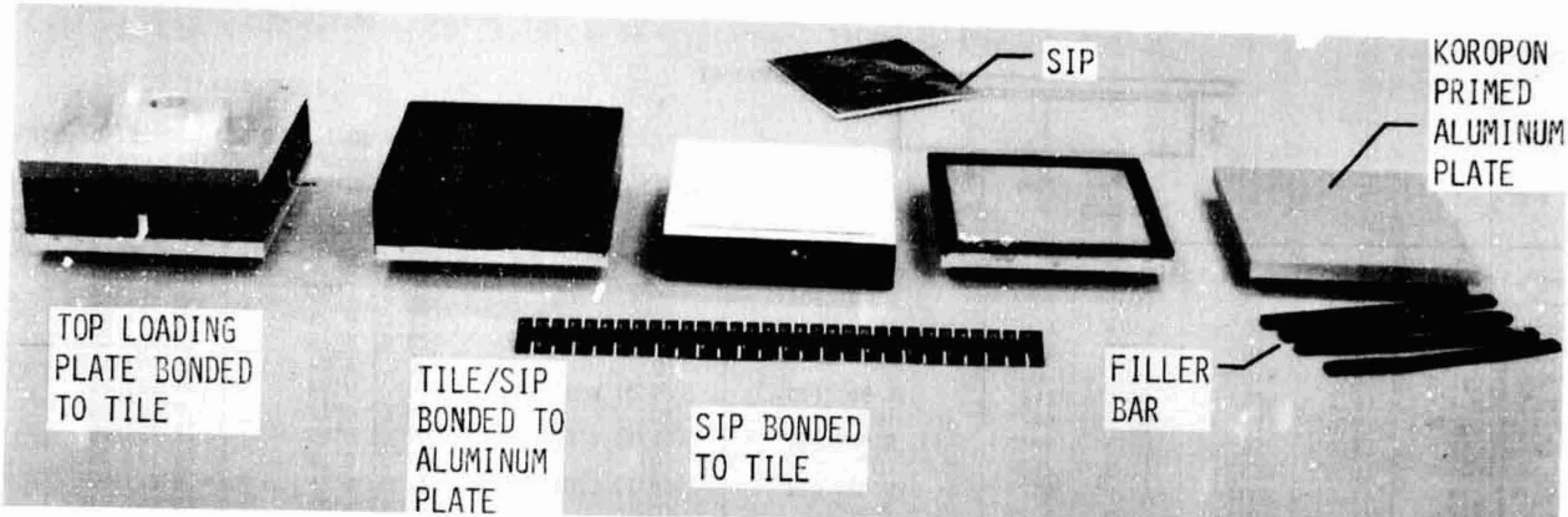


Figure 1. - Photographs illustrating sequential stages of specimen fabrication.

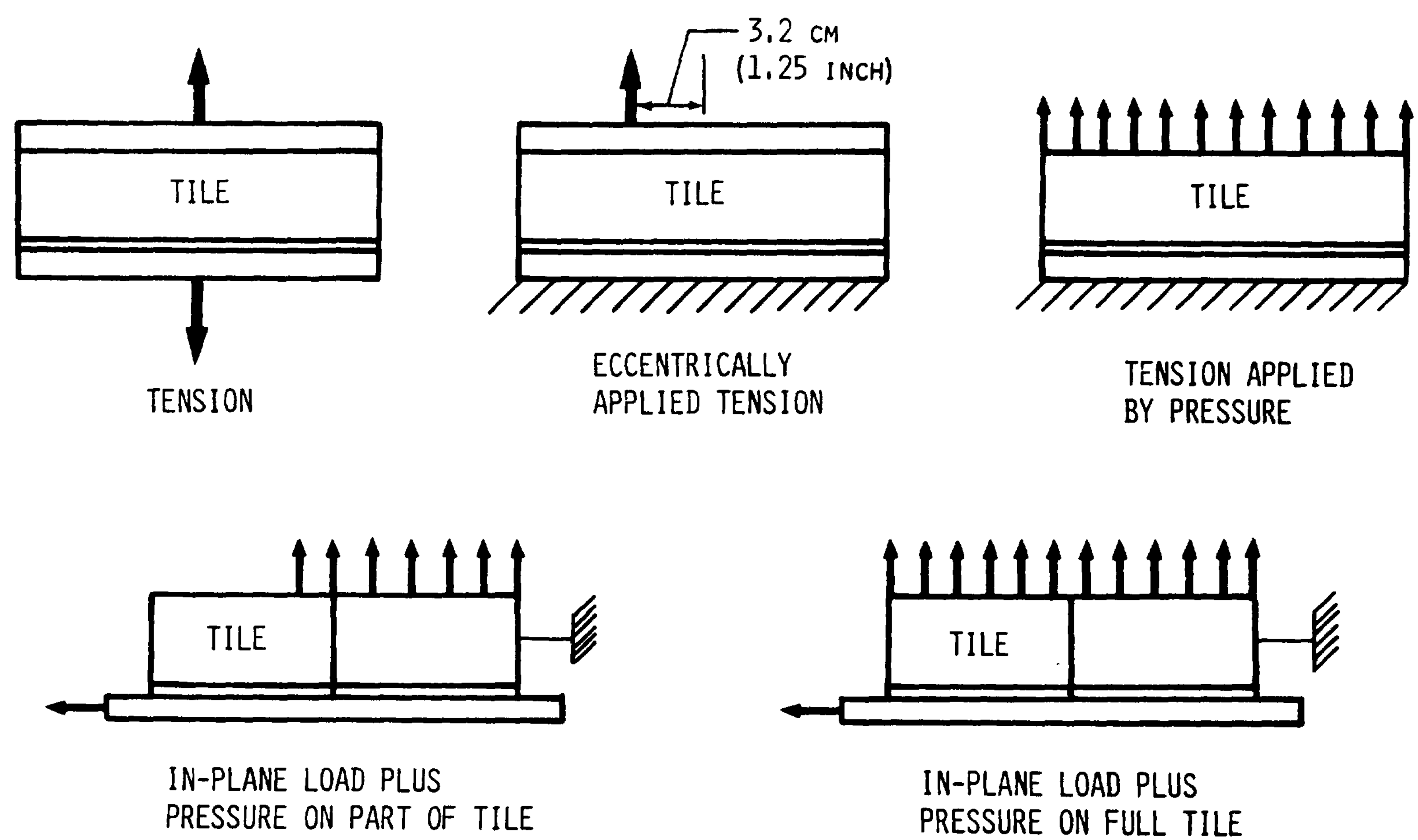


Figure 2. - Test configurations.

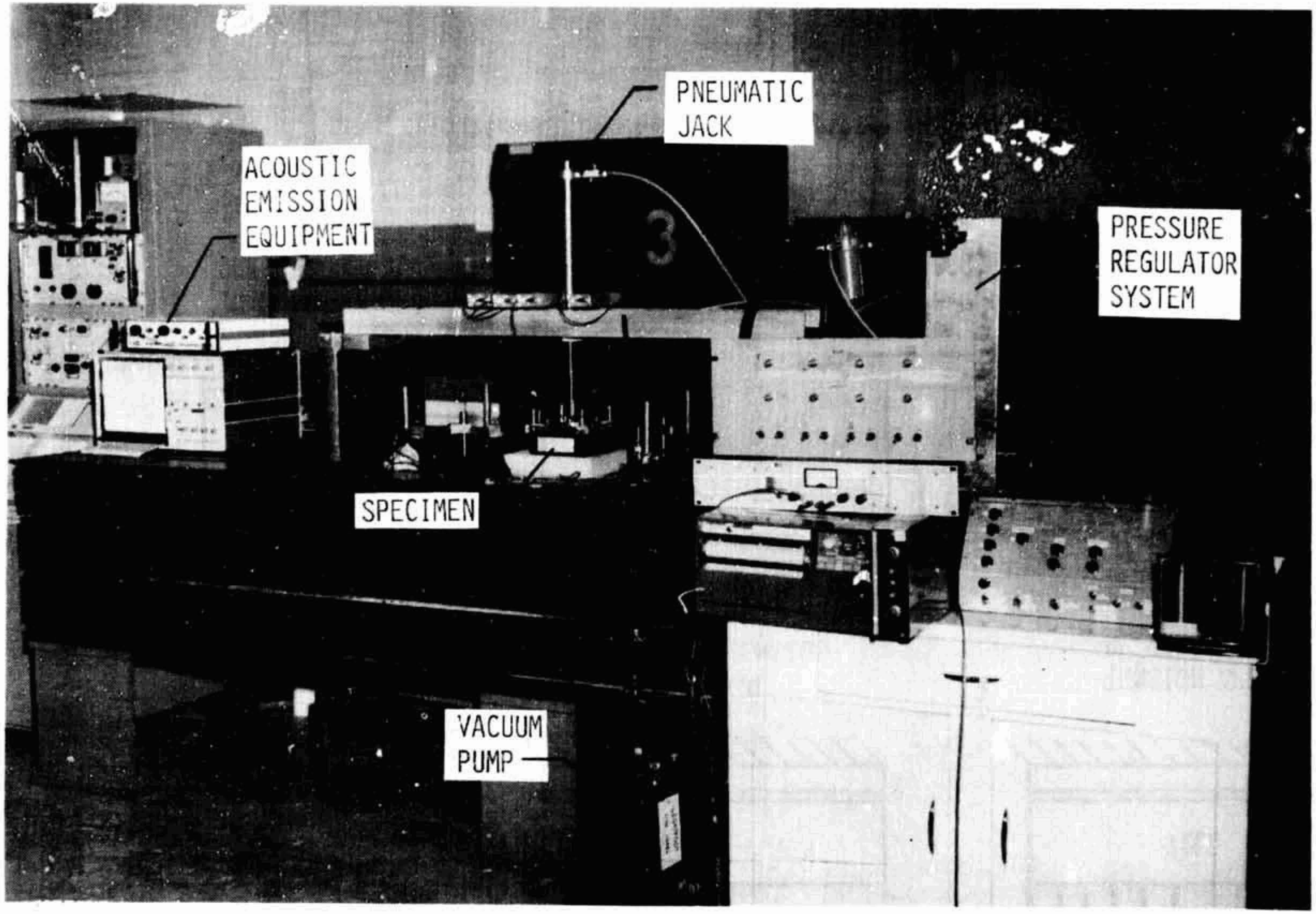


Figure 3. - Proof test setup.

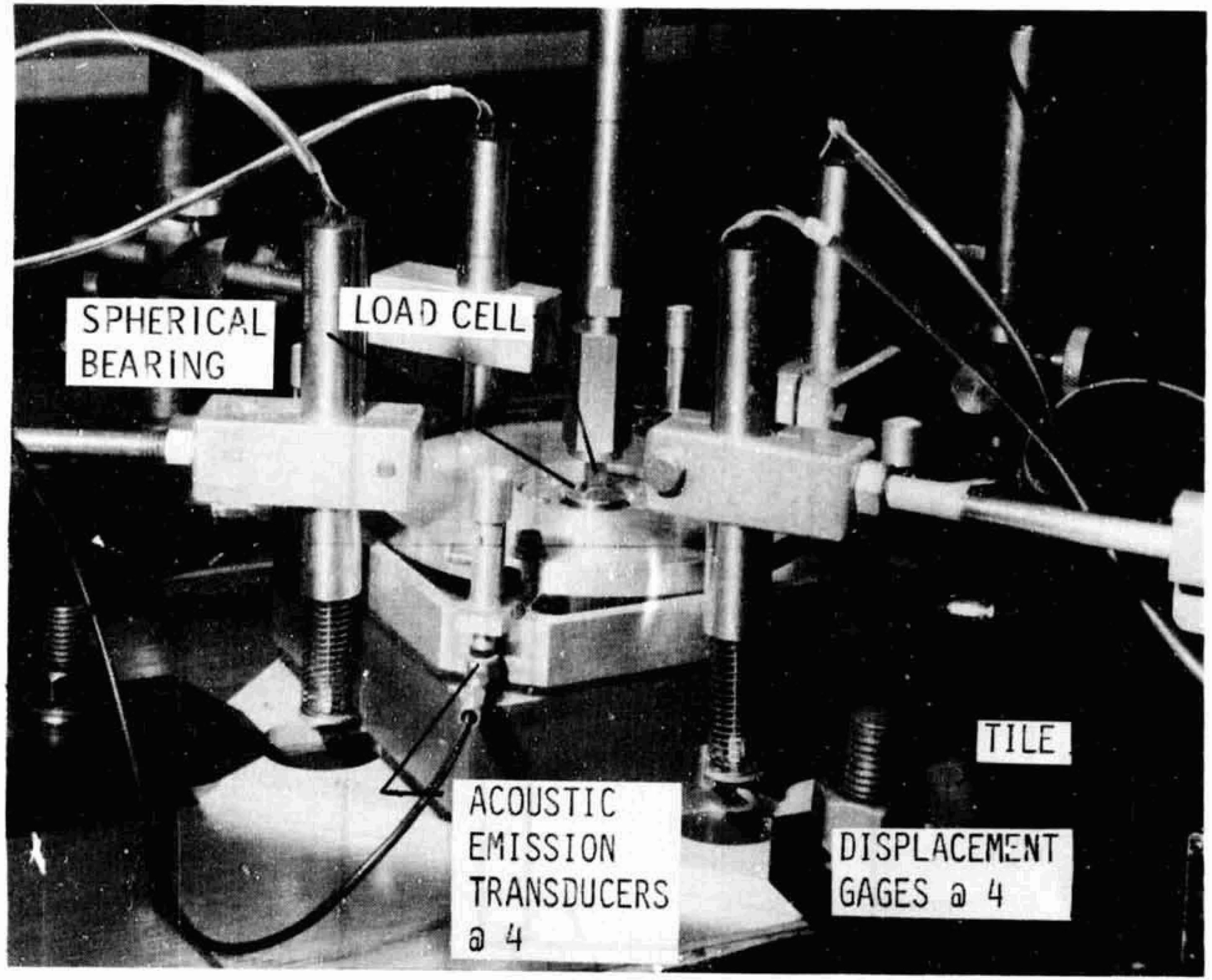


Figure 4. - Proof test instrumentation.

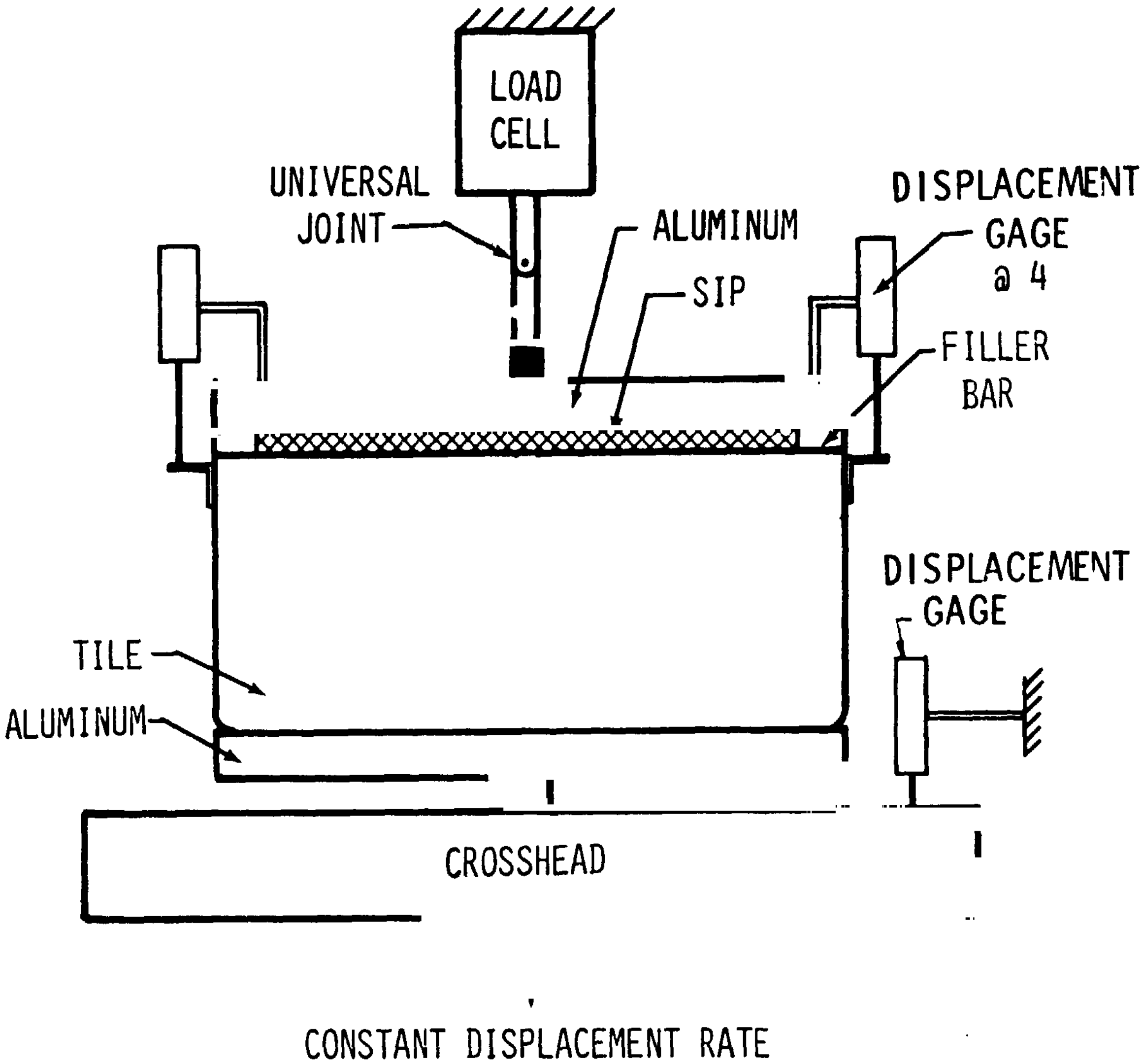


Figure 5. - Tension test setup and instrumentation.

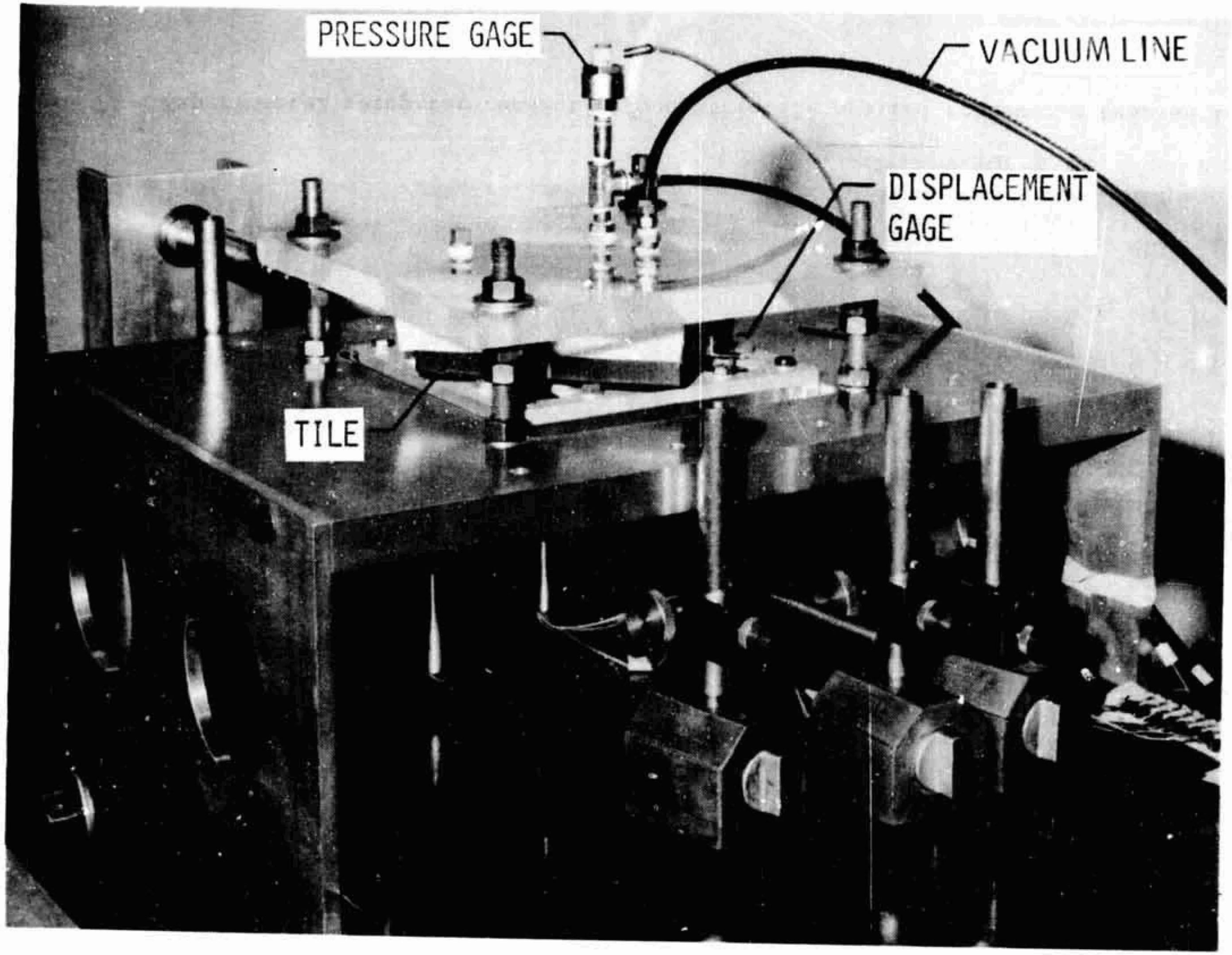


Figure 6. - Apparatus for loading tile in transverse tension using reduced pressure on the top surface of the tile.

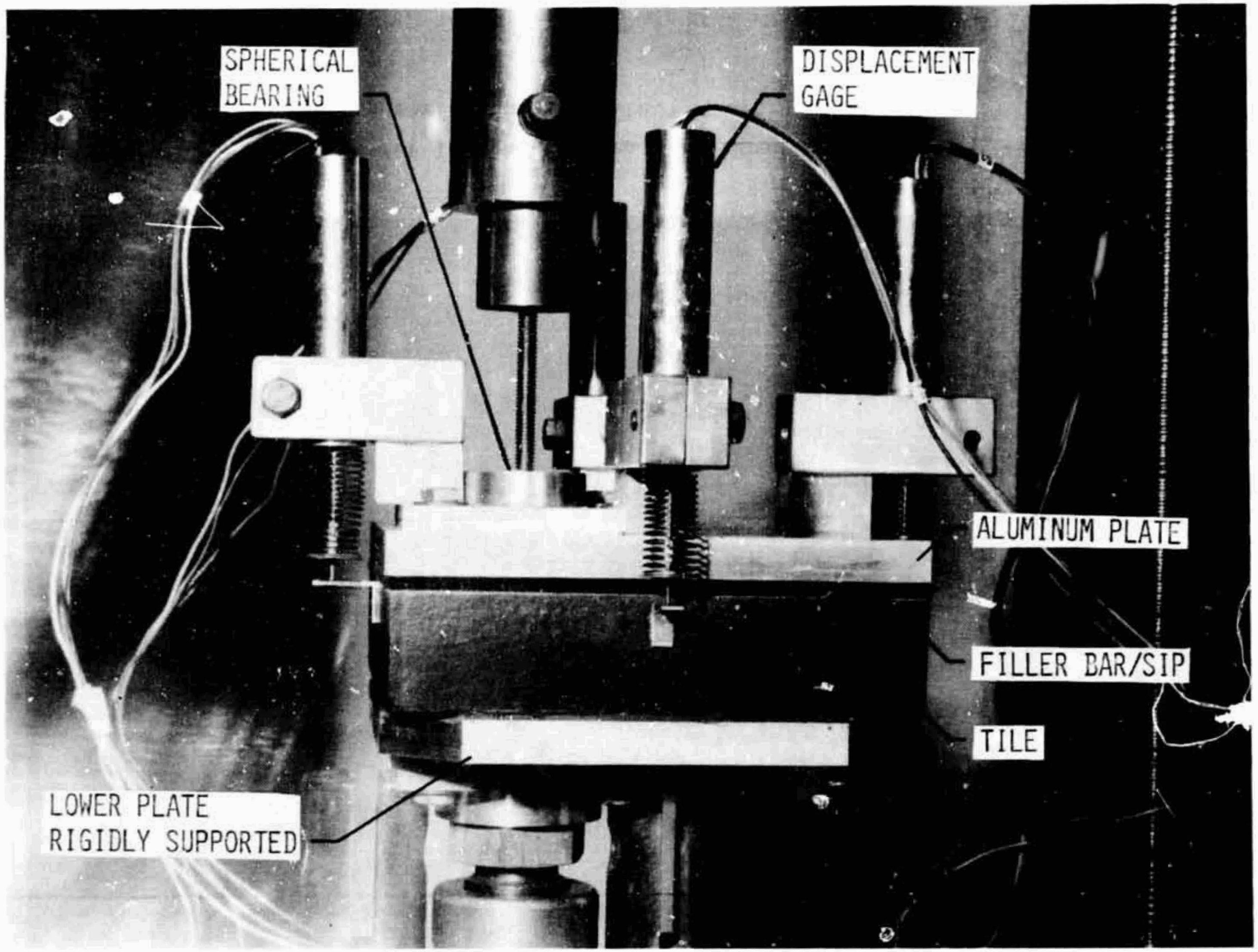


Figure 7. - Experimental setup for conducting eccentrically applied transverse tension loads.

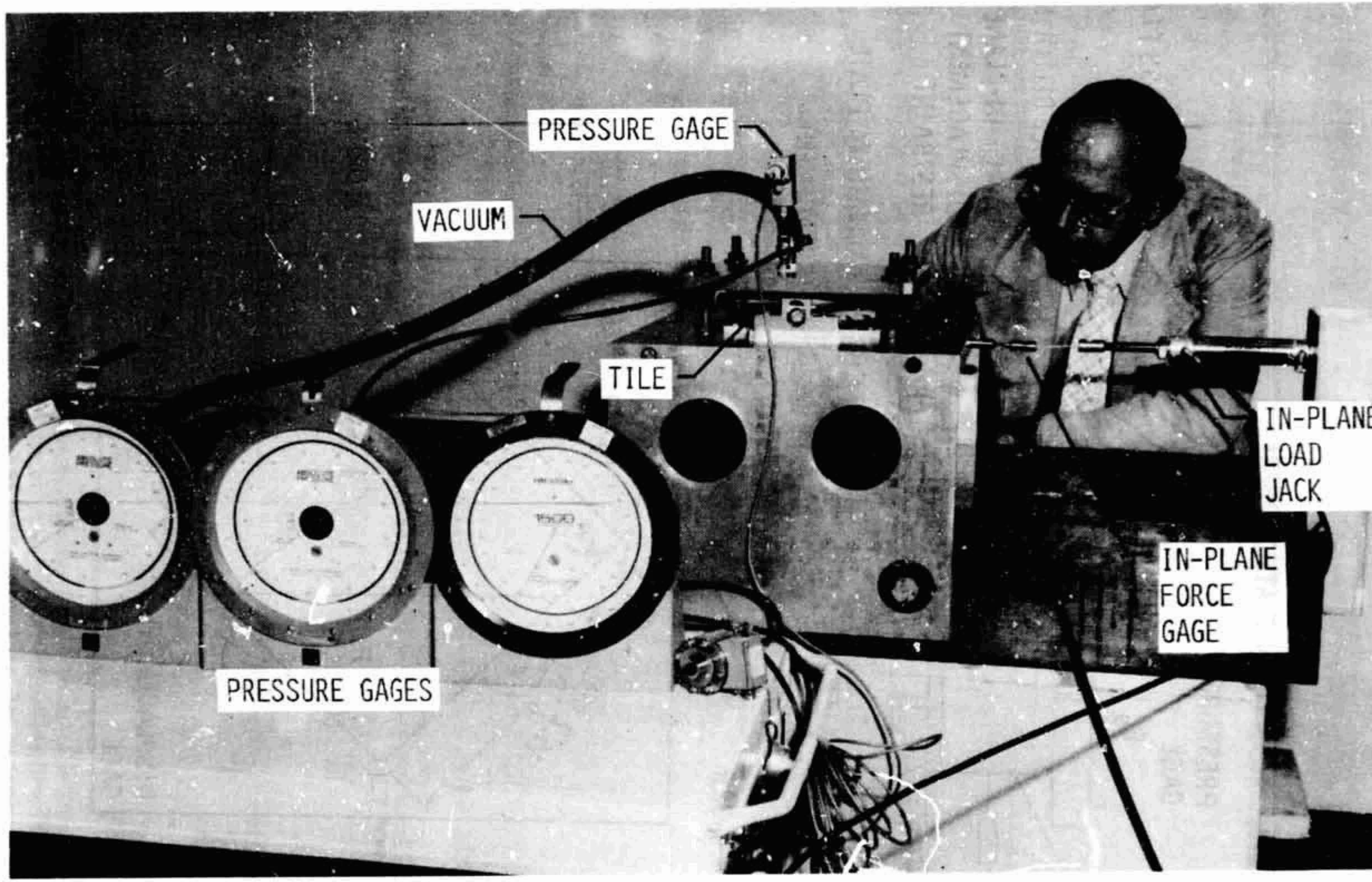


Figure 8. - Test setup for imposing combined in-plane load and transverse pressure.

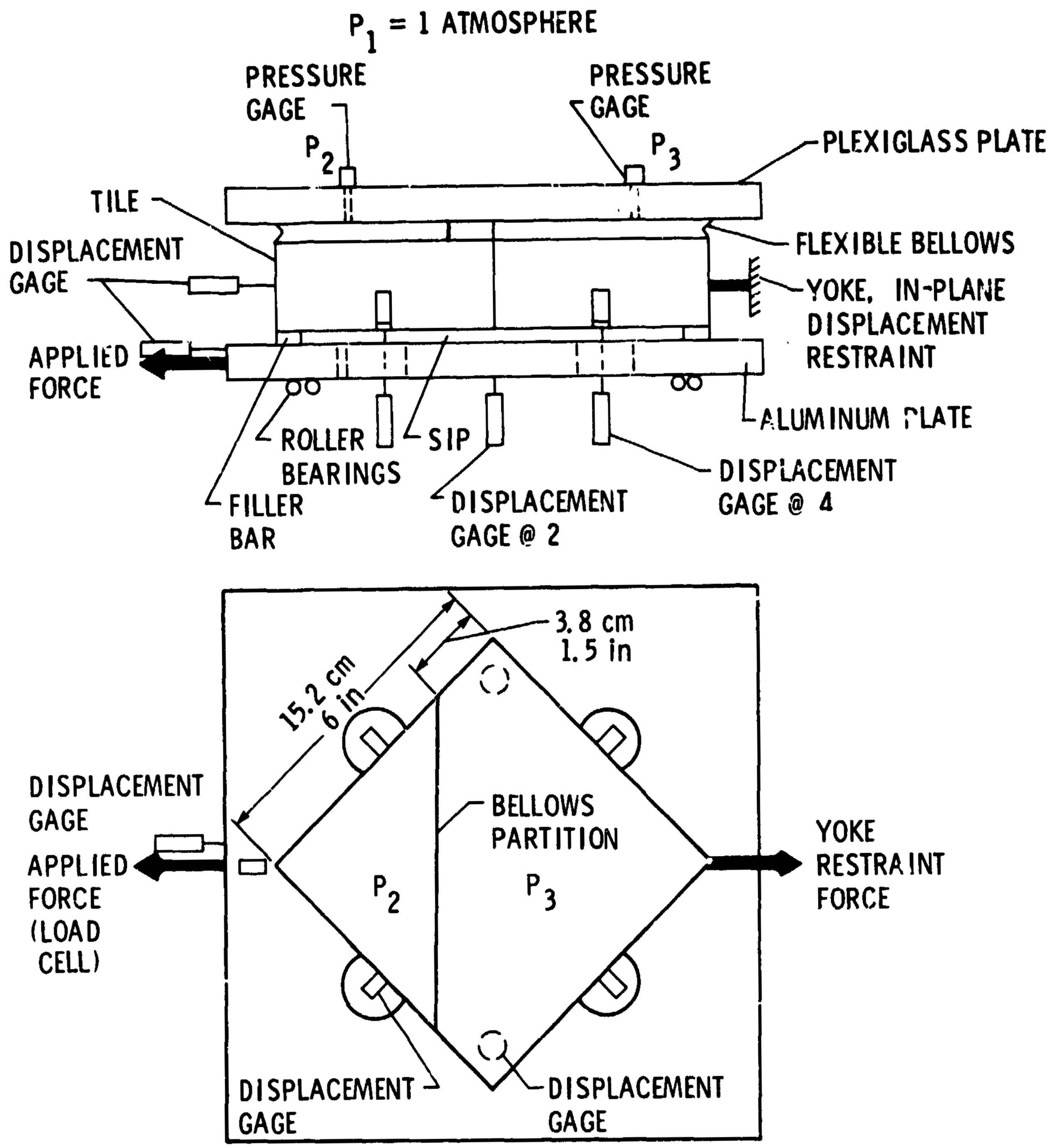


Figure 9. - Schematic of equipment and instrumentation for imposing combined in-plane and transverse pressure loads.

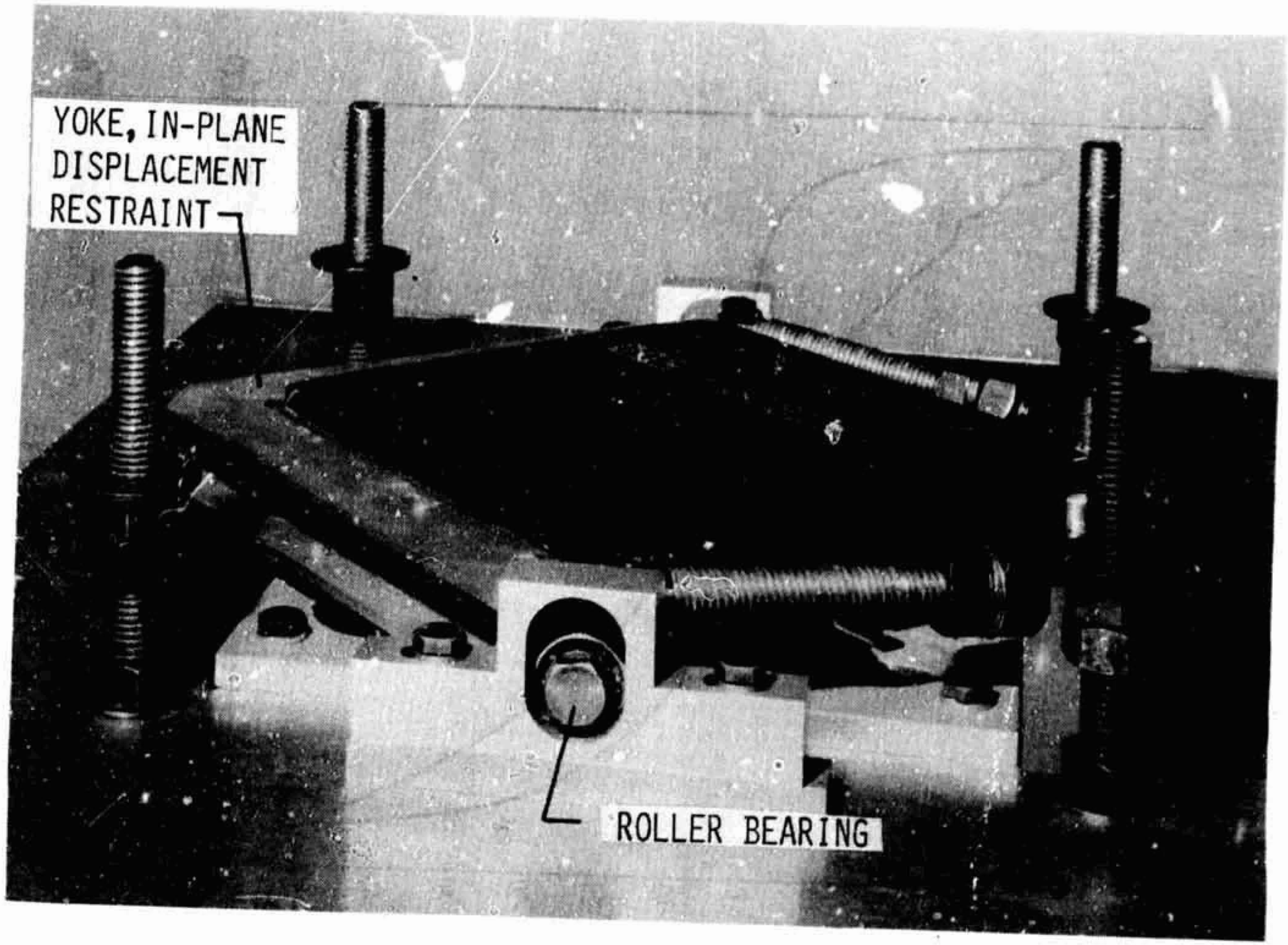


Figure 10. - Tile in-plane restraint apparatus.

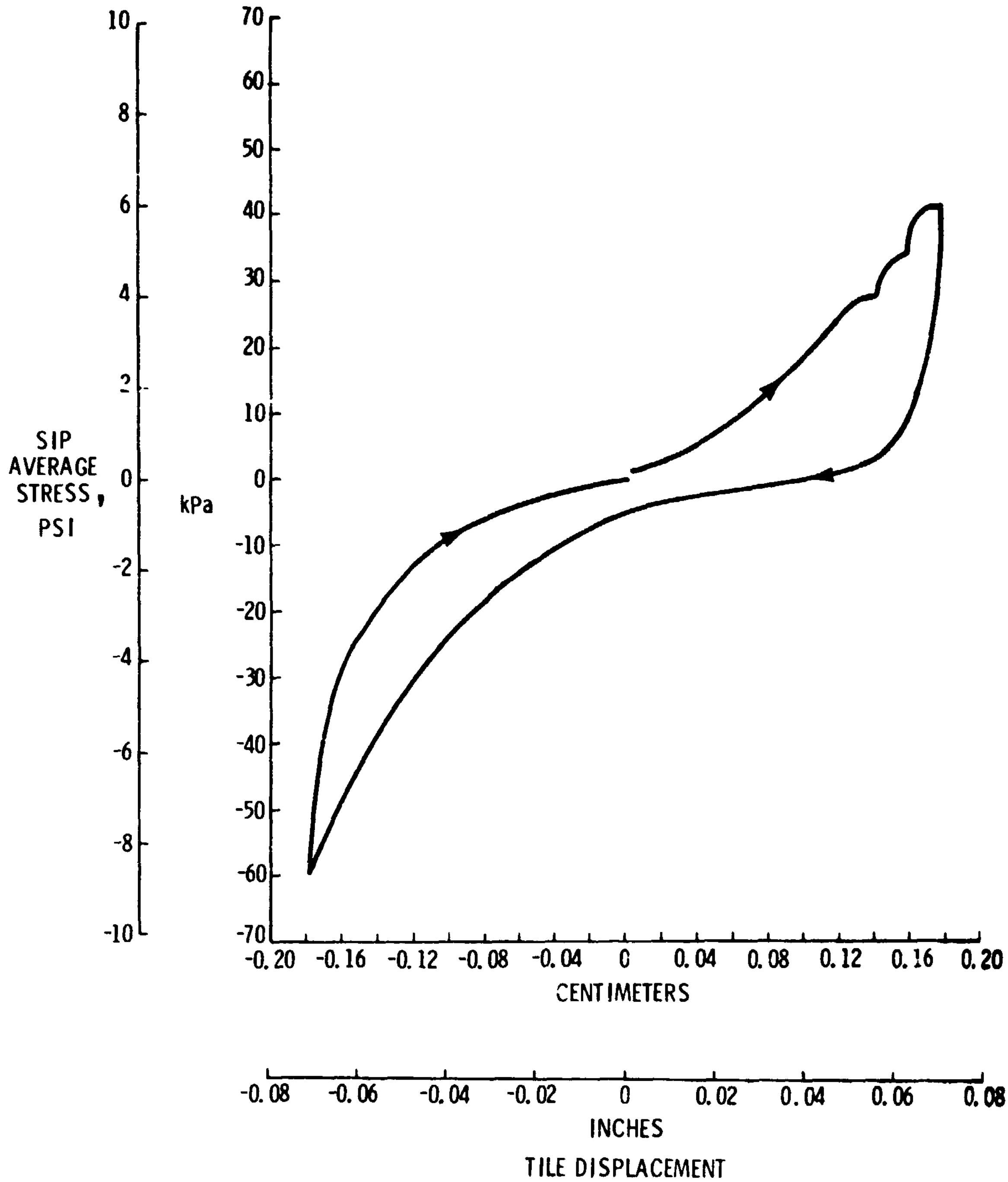


Figure 11. - SIP average stress versus tile transverse displacement for specimen passing proof test.

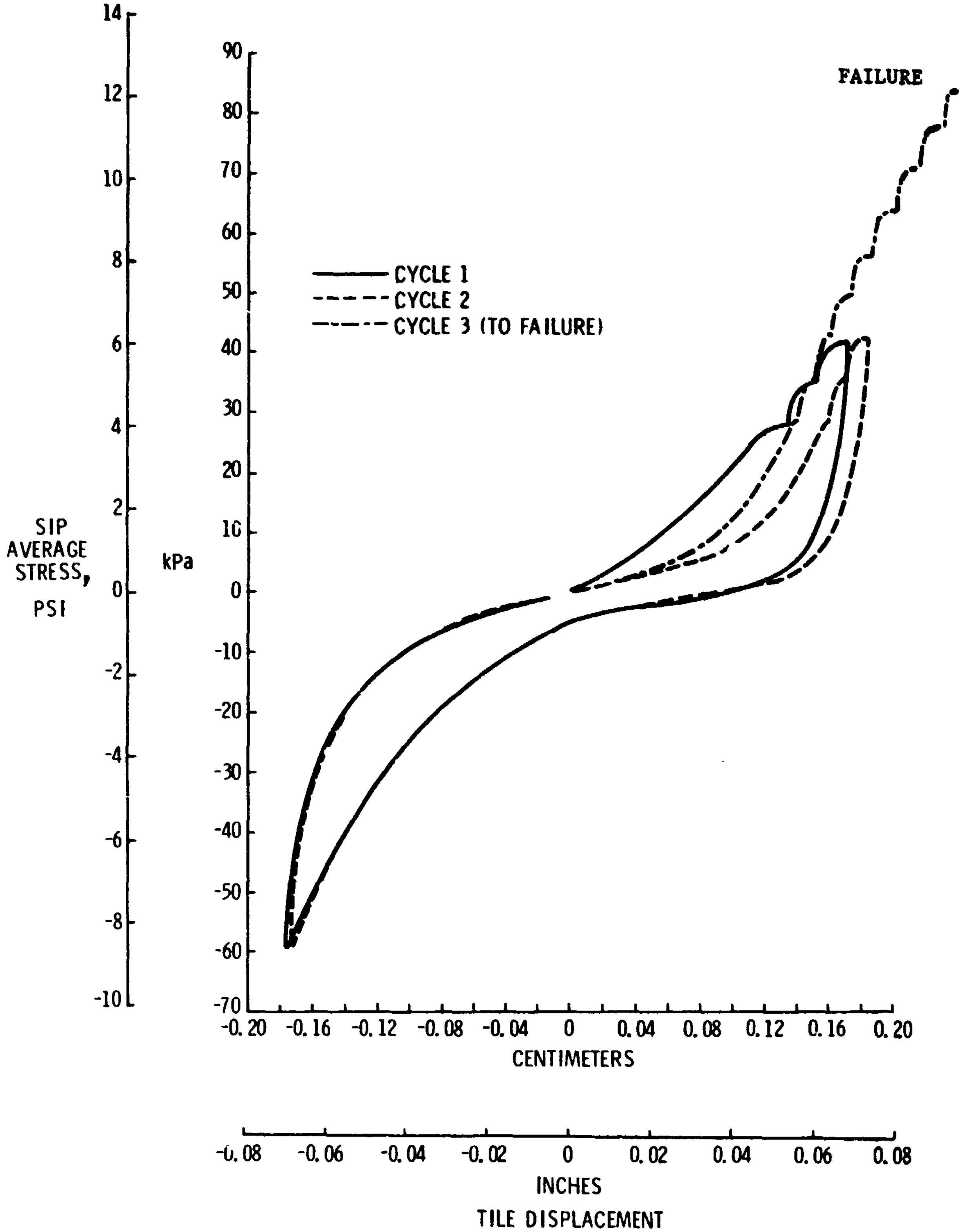


Figure 12. - SIP average stress versus tile transverse displacement for specimen failing proof test (acoustic criteria 3).

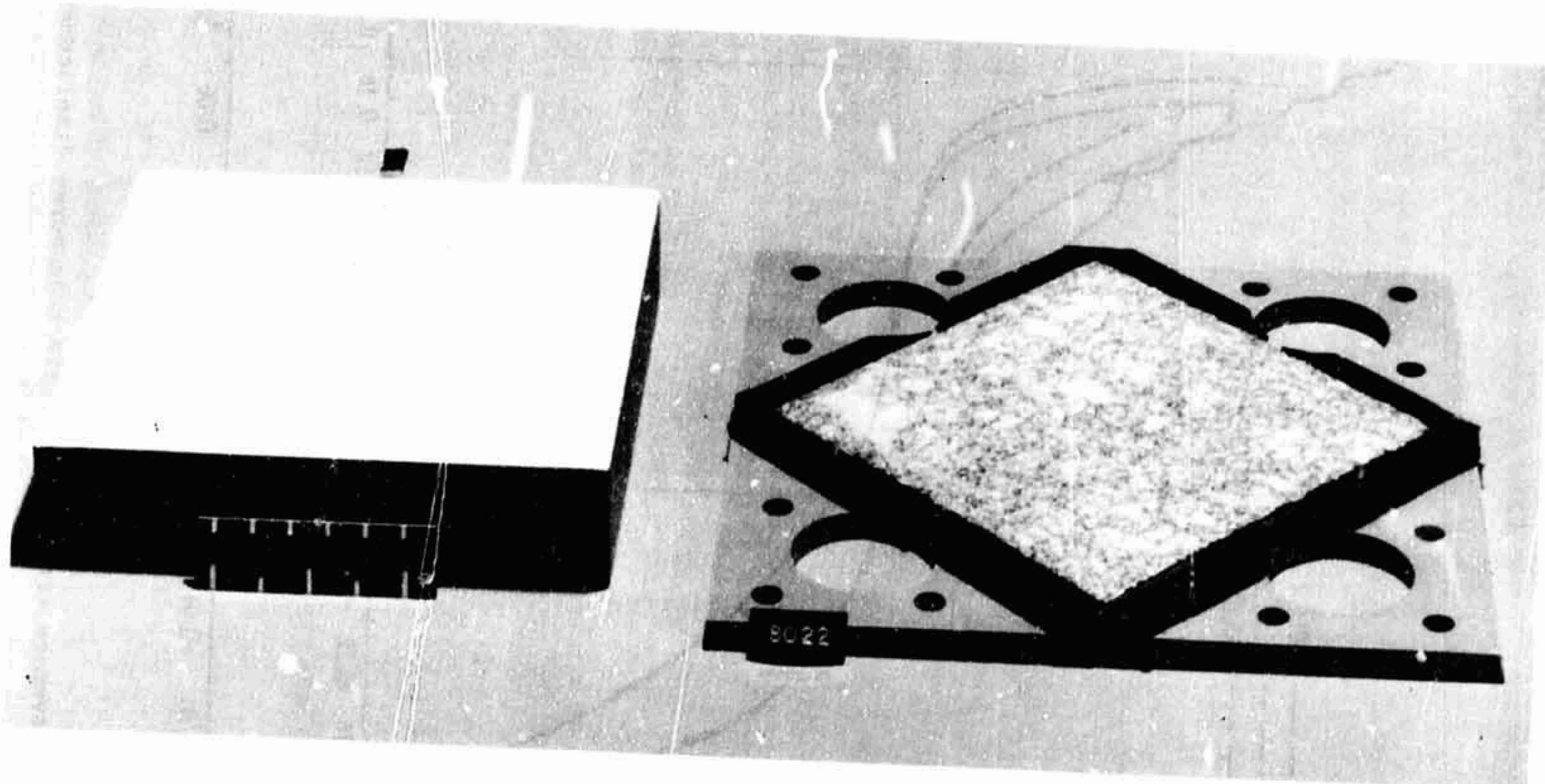


Figure 13. - Failure surface following transverse tension loading of specimen failing proof test acoustic criteria.

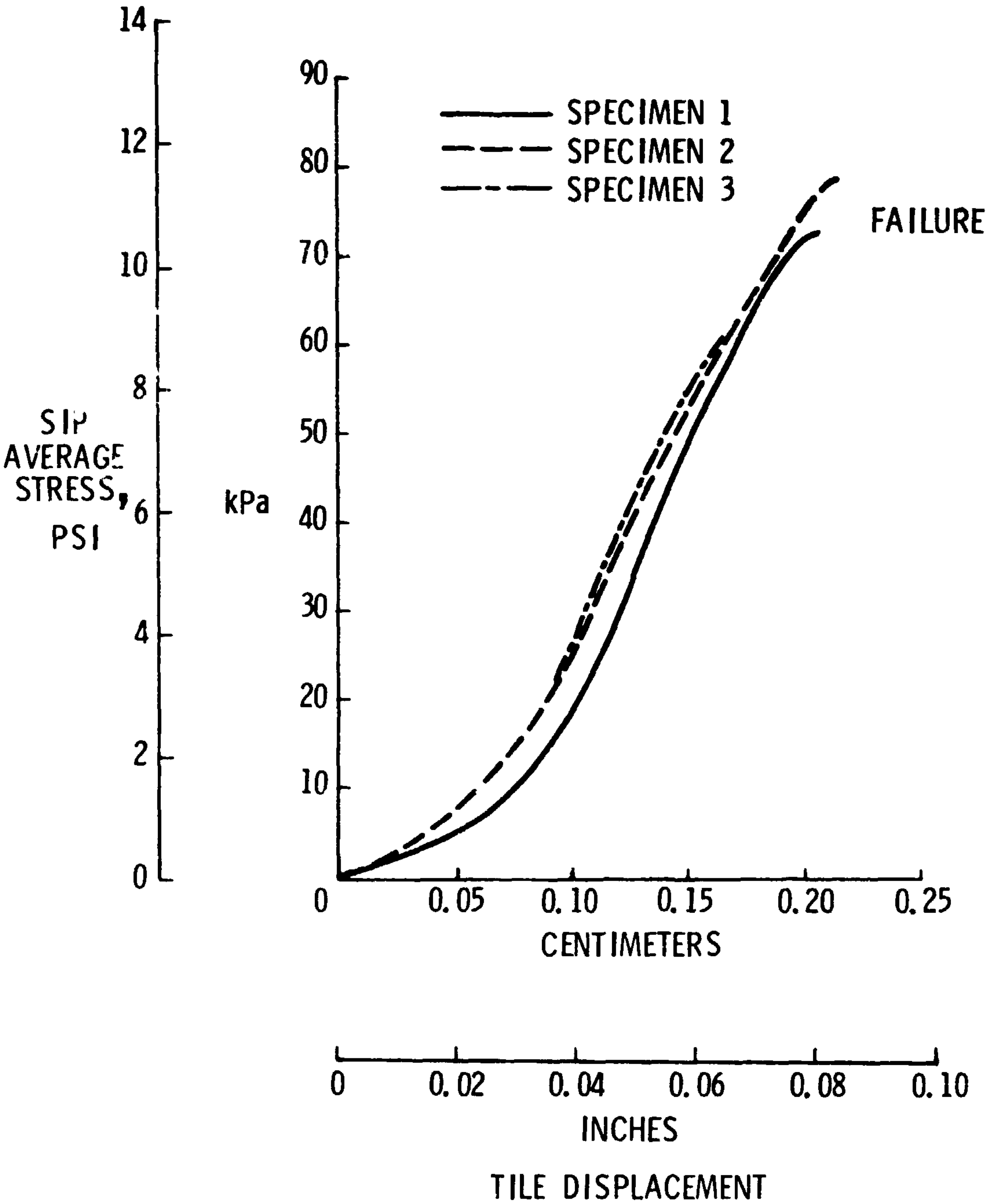


Figure 14. - SIP average stress versus tile displacement for three specimens loaded to failure in transverse tension using constant displacement rate load machine.

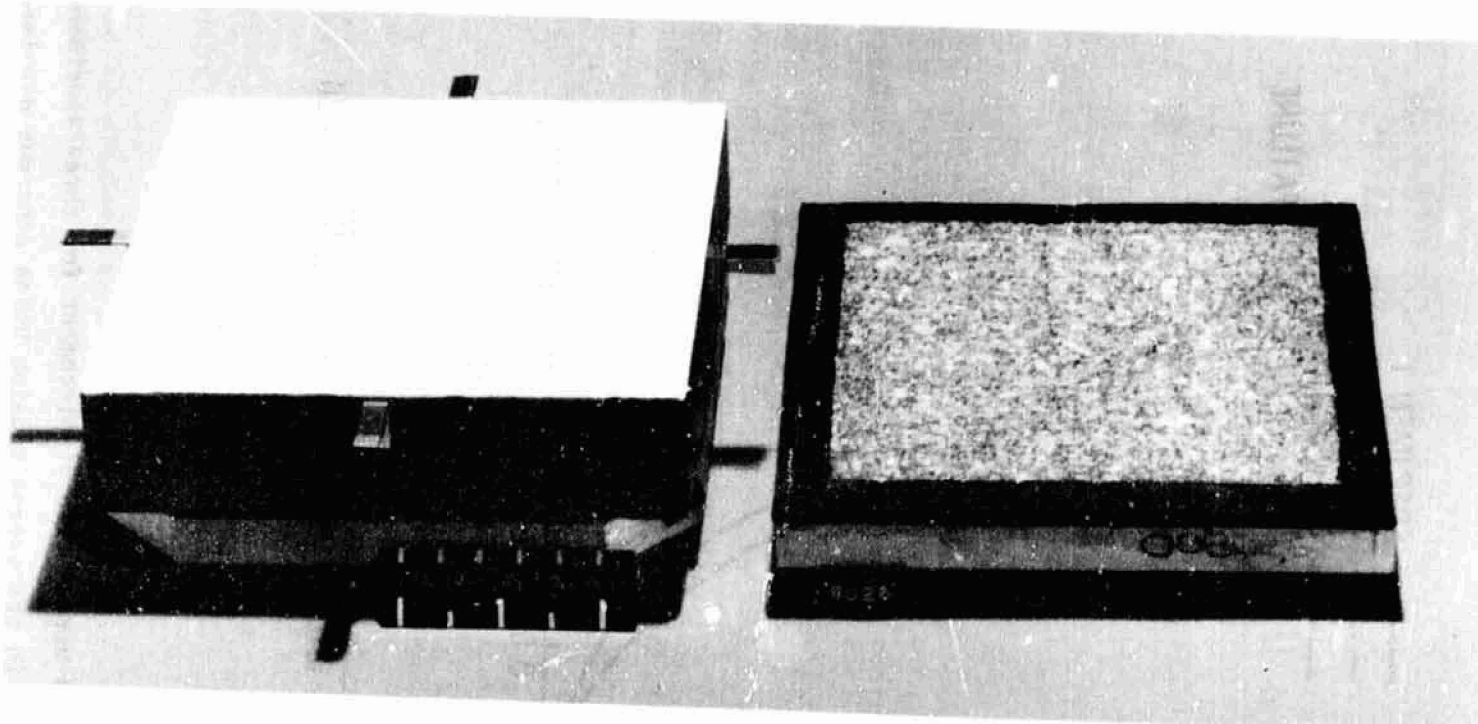


Figure 15. - Failure surface of specimen loaded by transverse tension in constant displacement rate loading machine.

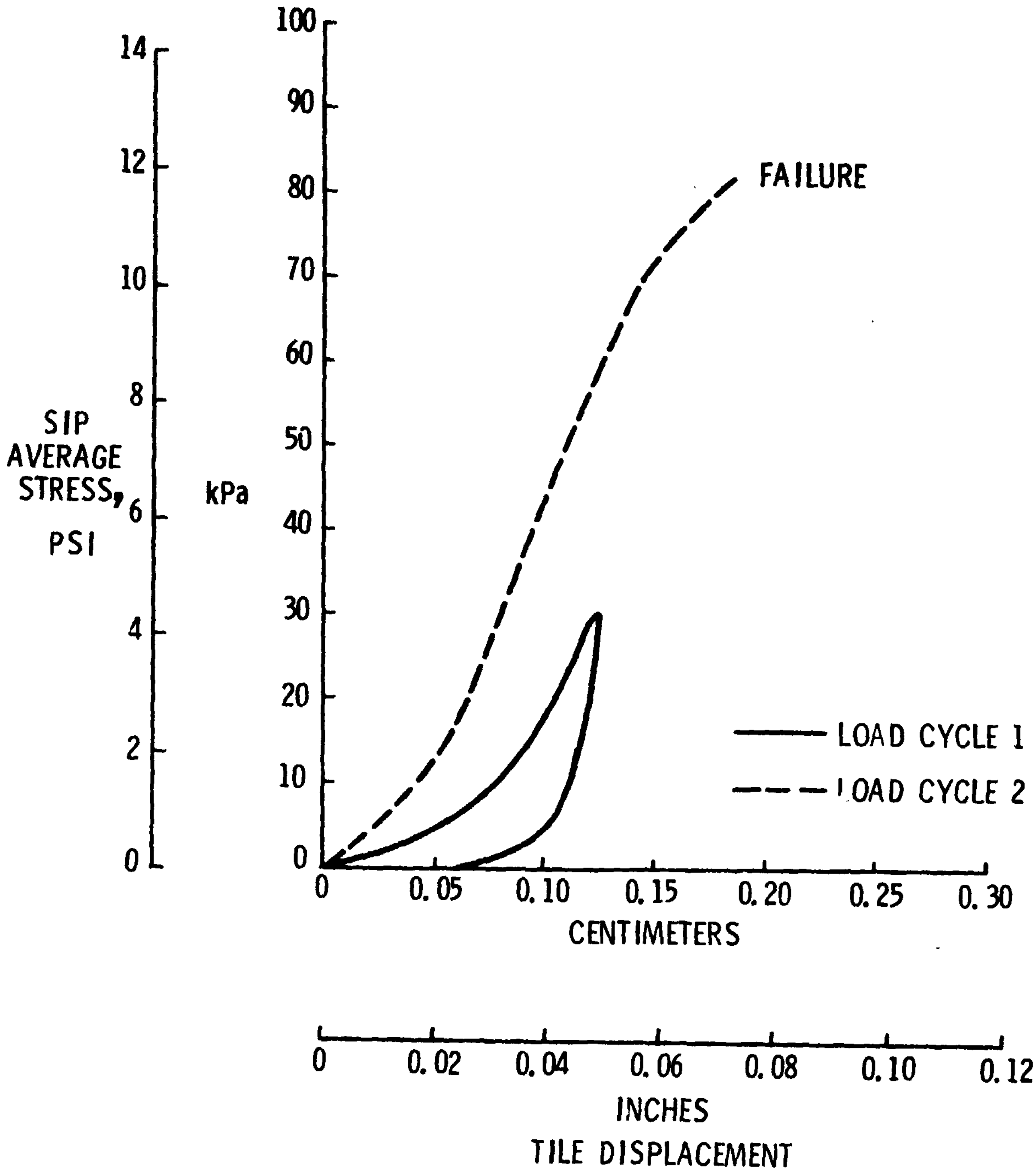


Figure 16. - SIP average stress versus tile displacement for specimen loaded to failure in transverse tension. Load applied by pressure.

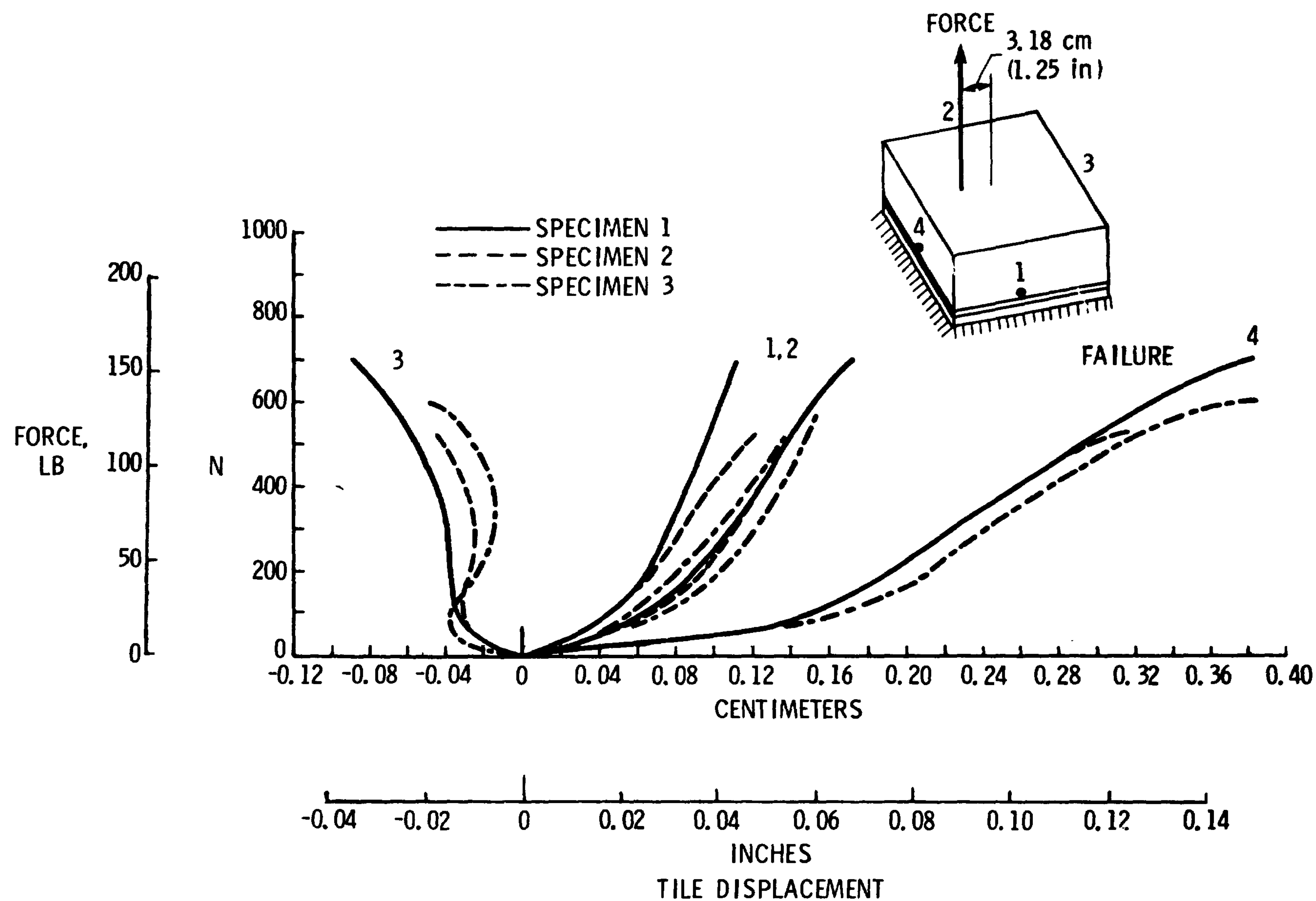


Figure 17. - Tile displacement response for eccentrically applied tension loading.

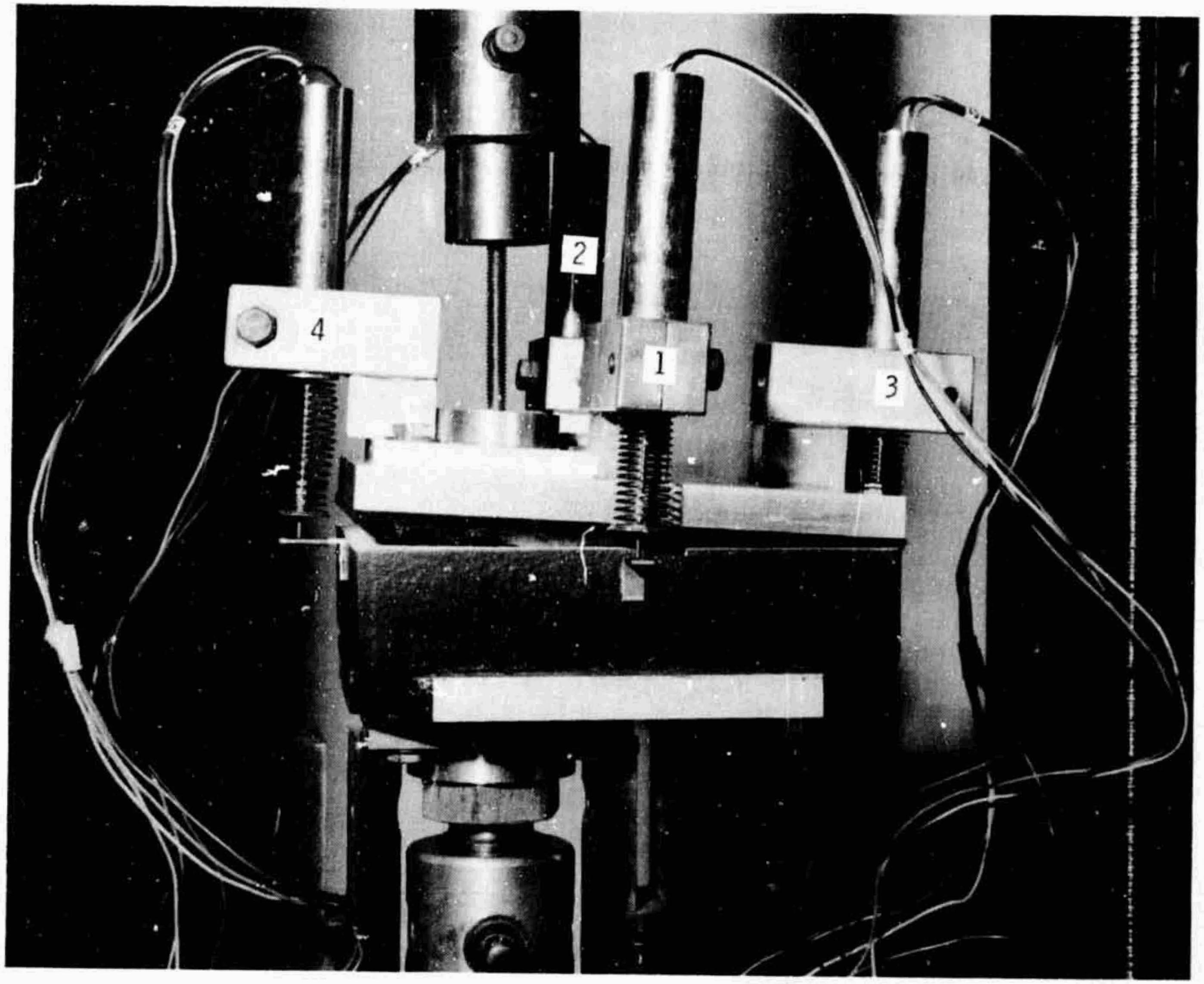


Figure 18. - Photograph illustrating tile rotation and failure in region of maximum stress under eccentrically applied tension loading.

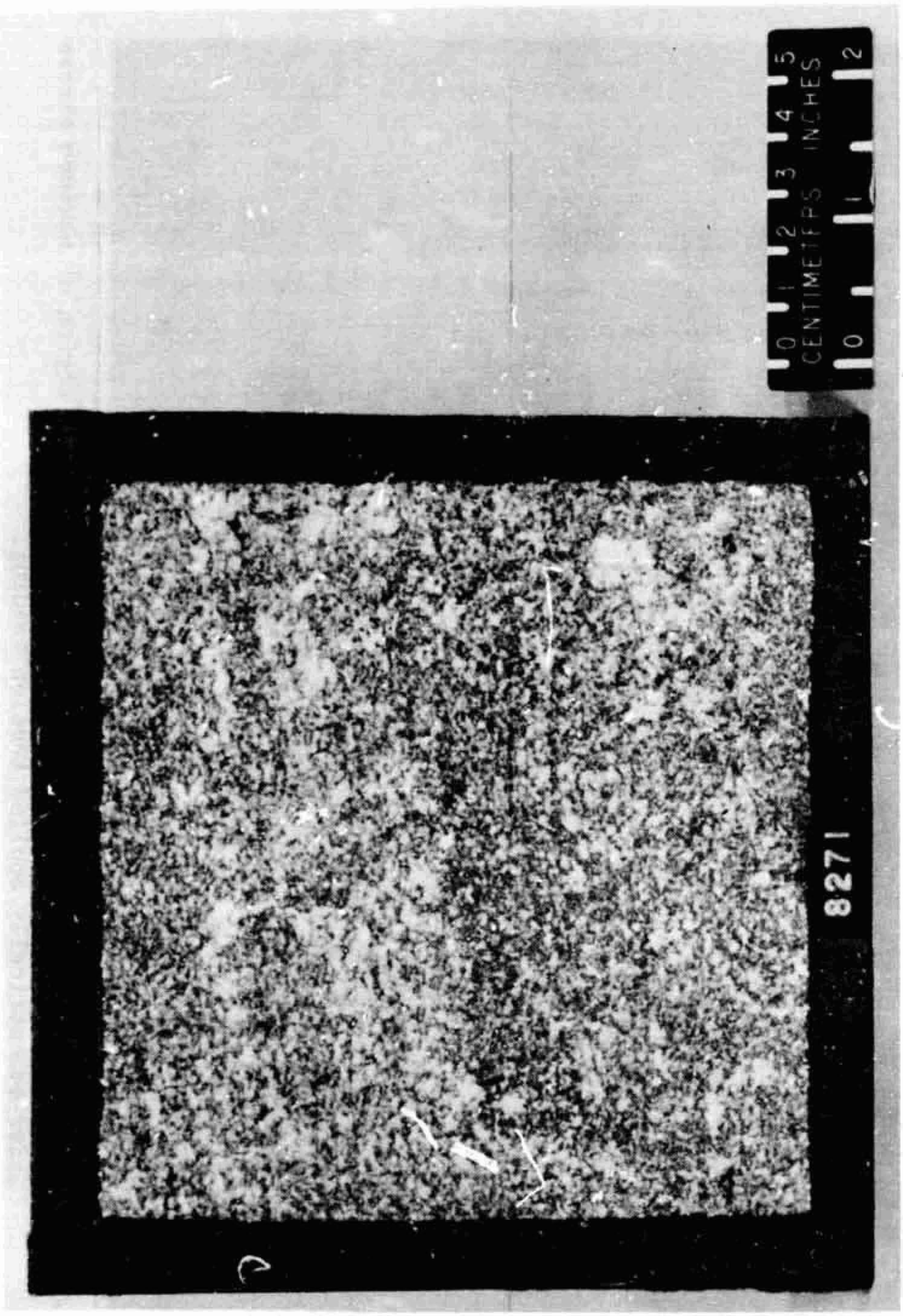


Figure 19. - SIP failure surface of specimen eccentrically loaded by transverse tension.

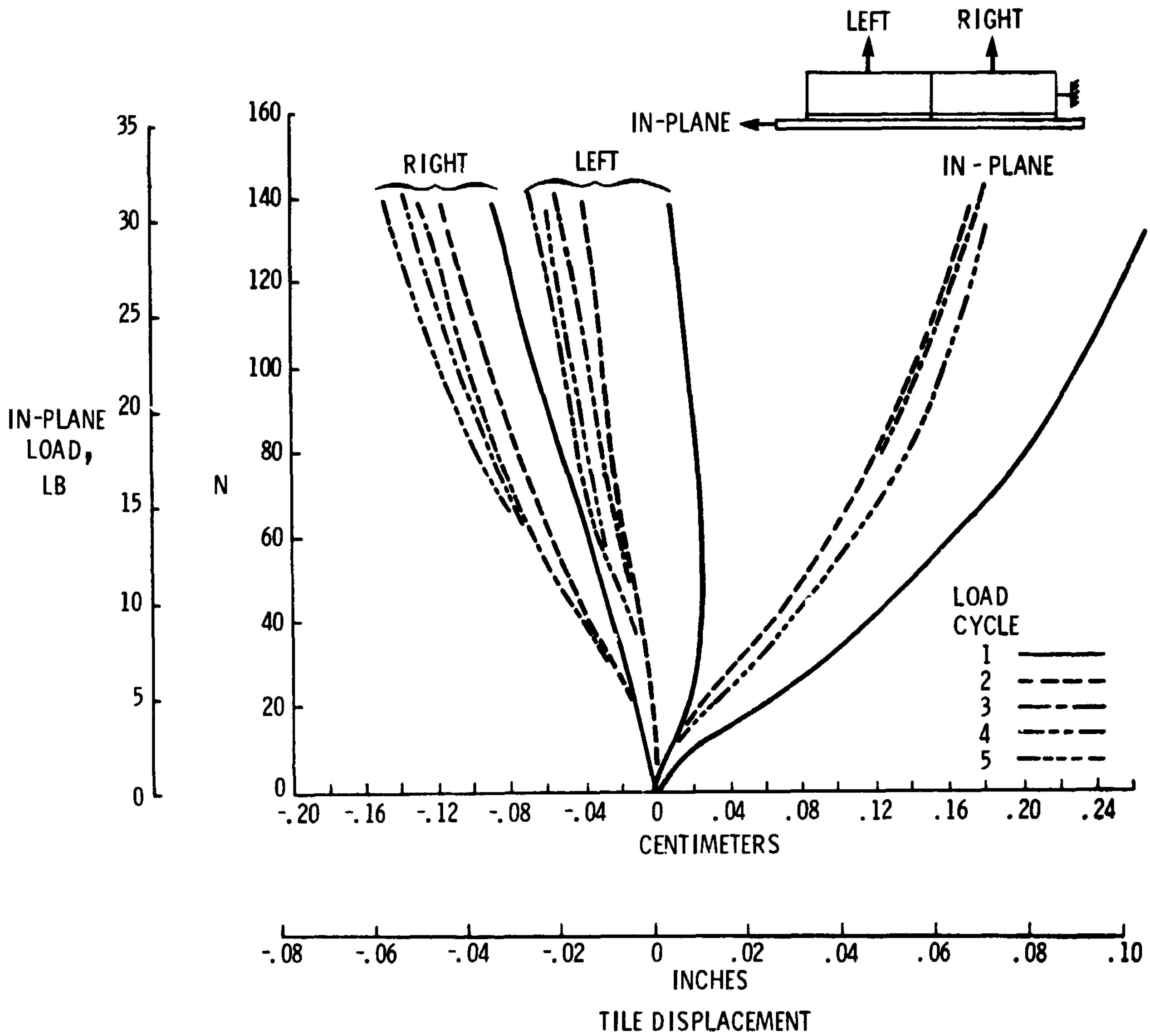


Figure 20. - Displacement response to in-plane loading only for load cycles 1 thru 5. Table III.

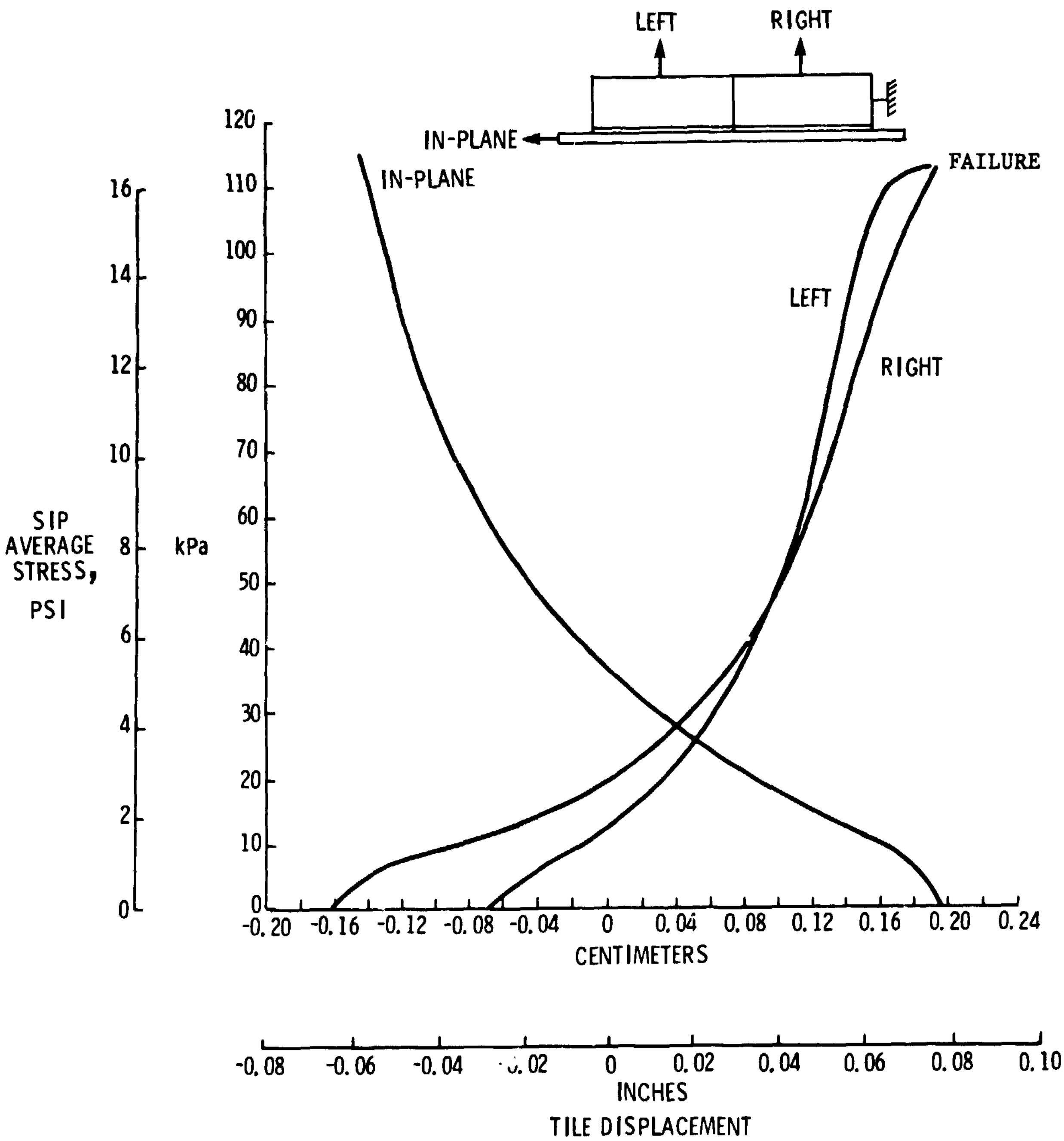
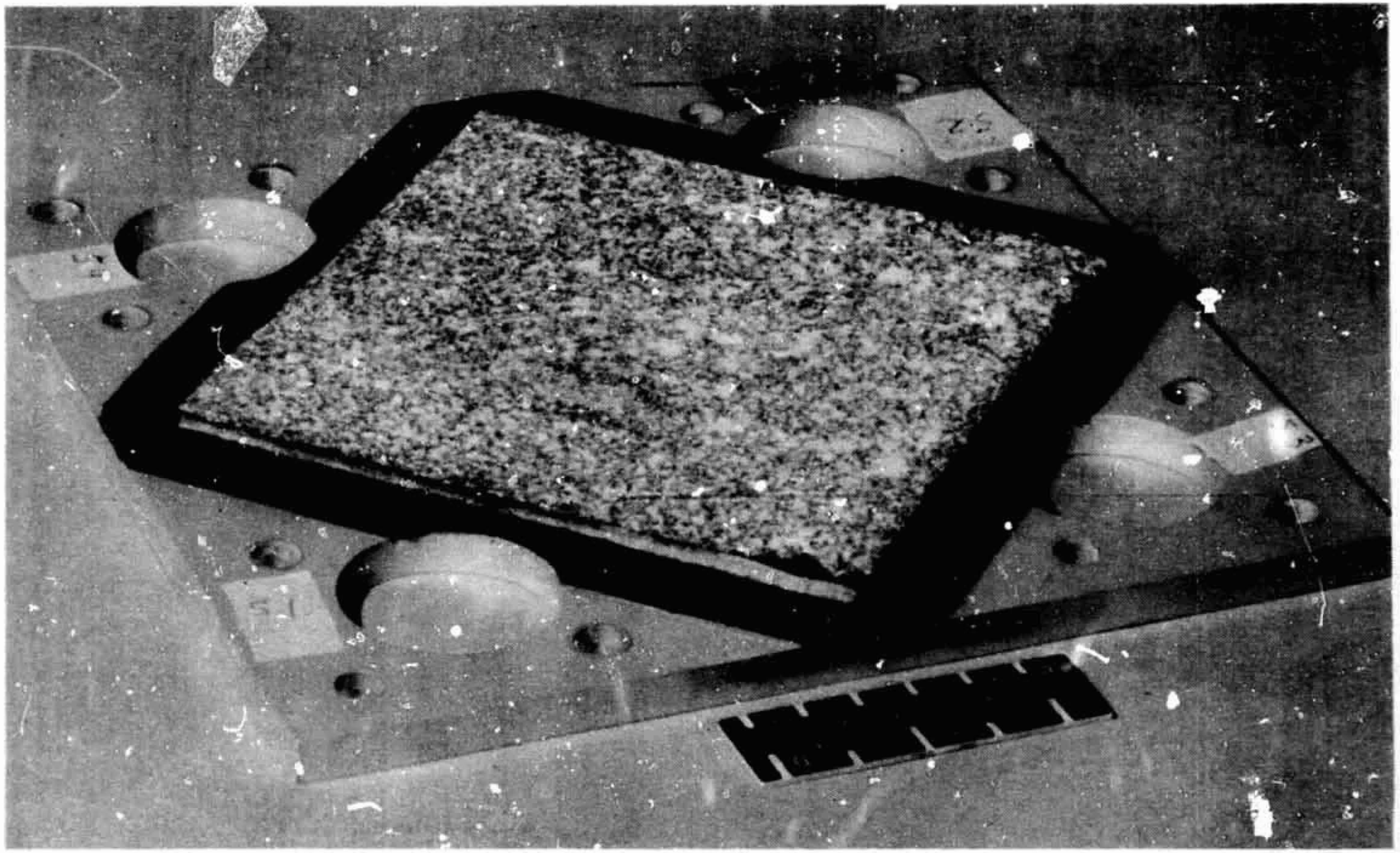
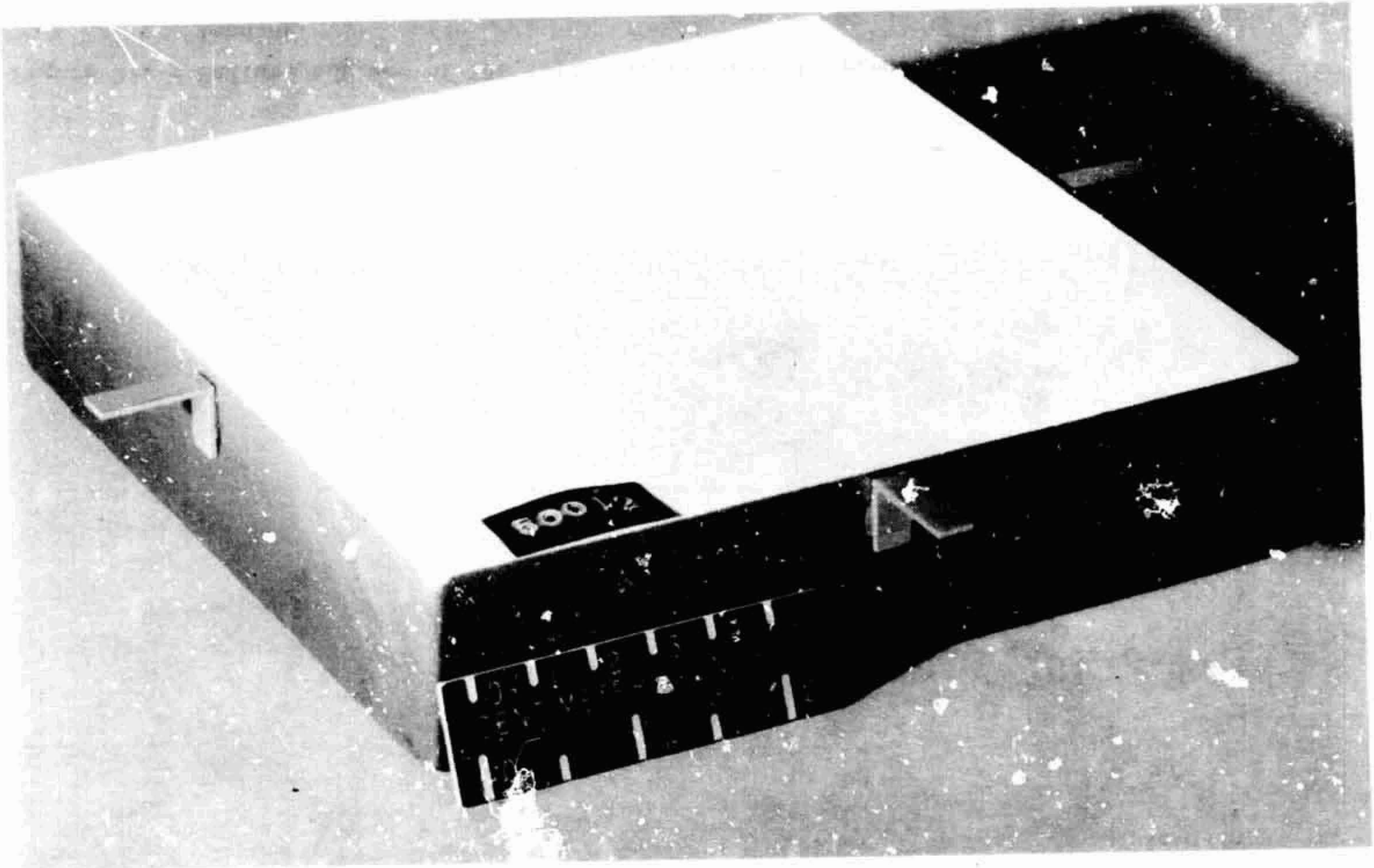


Figure 21. - Tile displacement response to pressure loading while constant in-plane load of 162N (36.5 pound) imposed on tile. Load cycle 5. Table III.



(a) SIP surface.

Figure 22. - Failure surface of TPS following combined in-plane and transverse pressure loading.



(b) Tile surface.

Figure 22. - Concluded.

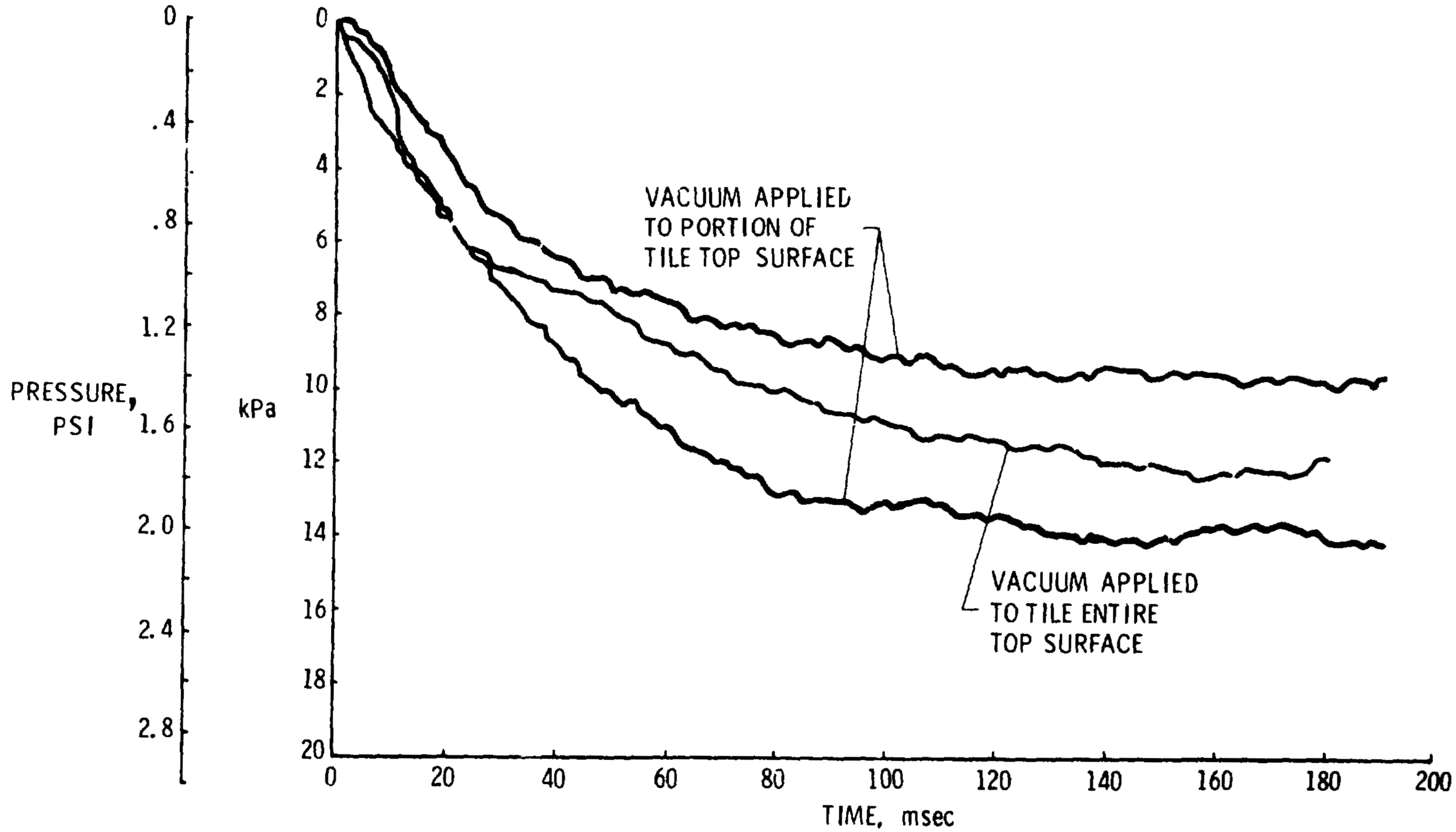


Figure 23. - Typical pressure versus time plots for shock imposed load.

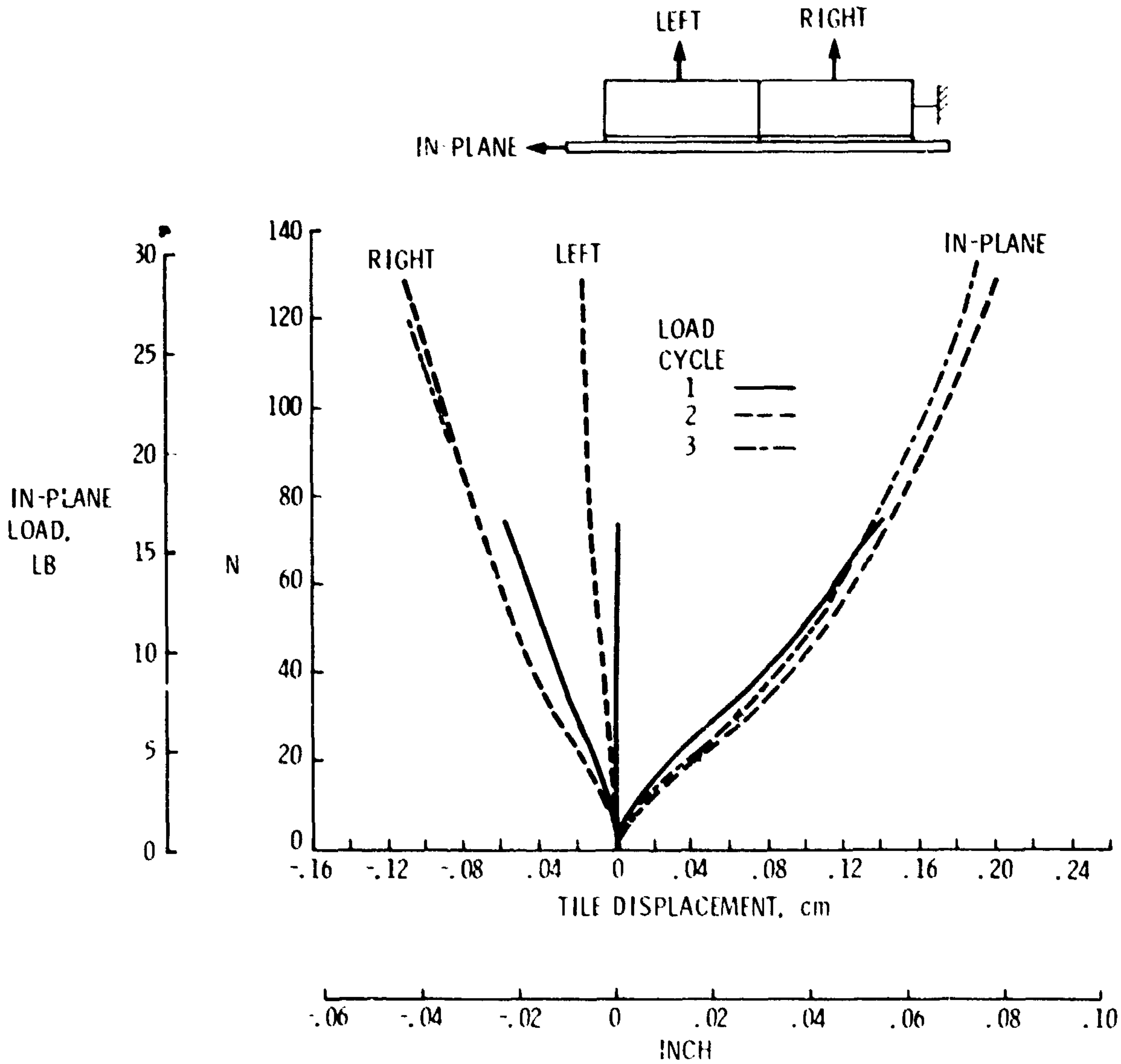


Figure 24. - Tile displacement response to in-plane loading only for load cycles 1, 2, and 3. Table IV.

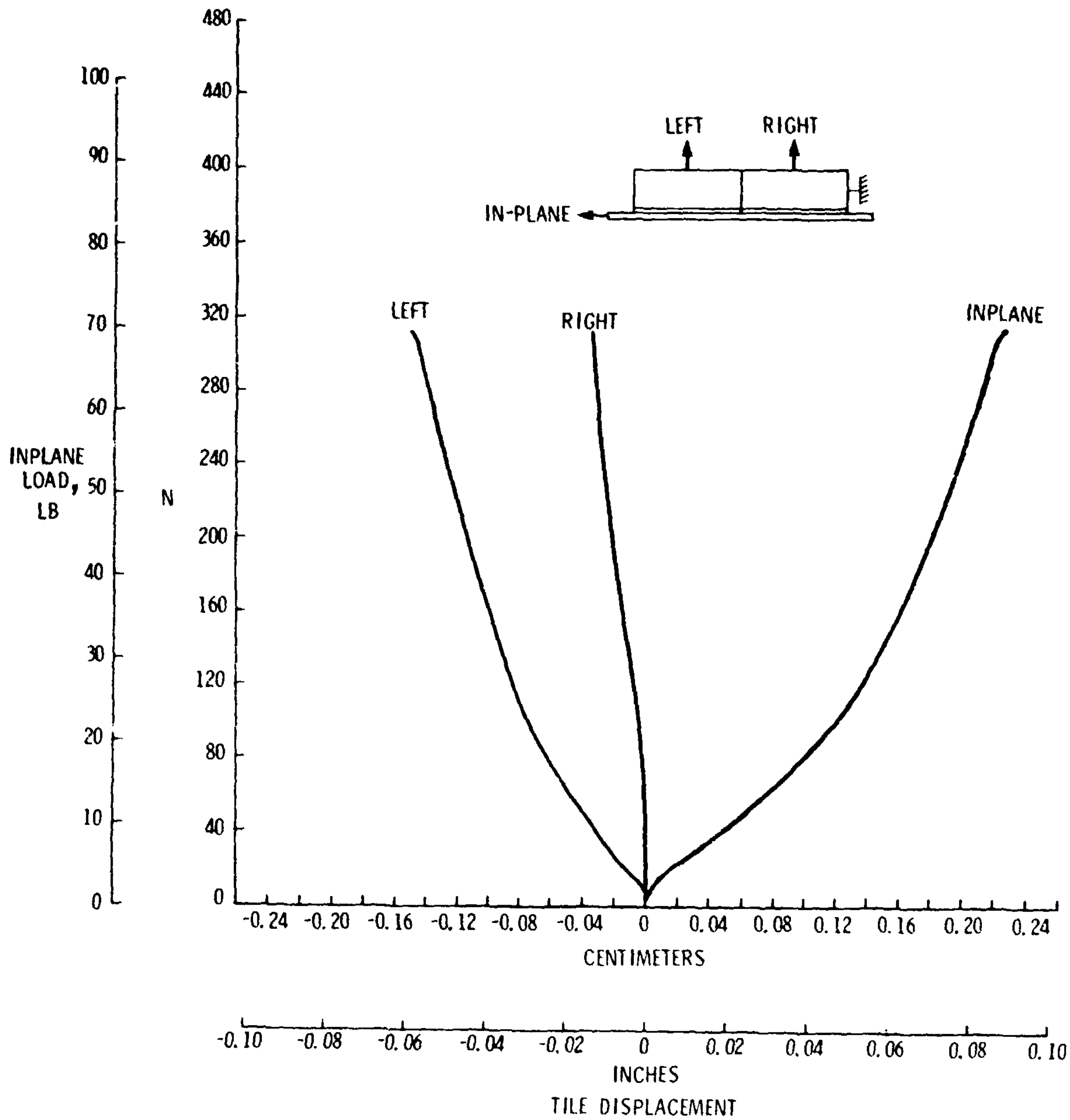


Figure 25. - Tile displacement response for in-plane loading only. Load cycle 9. Table V.

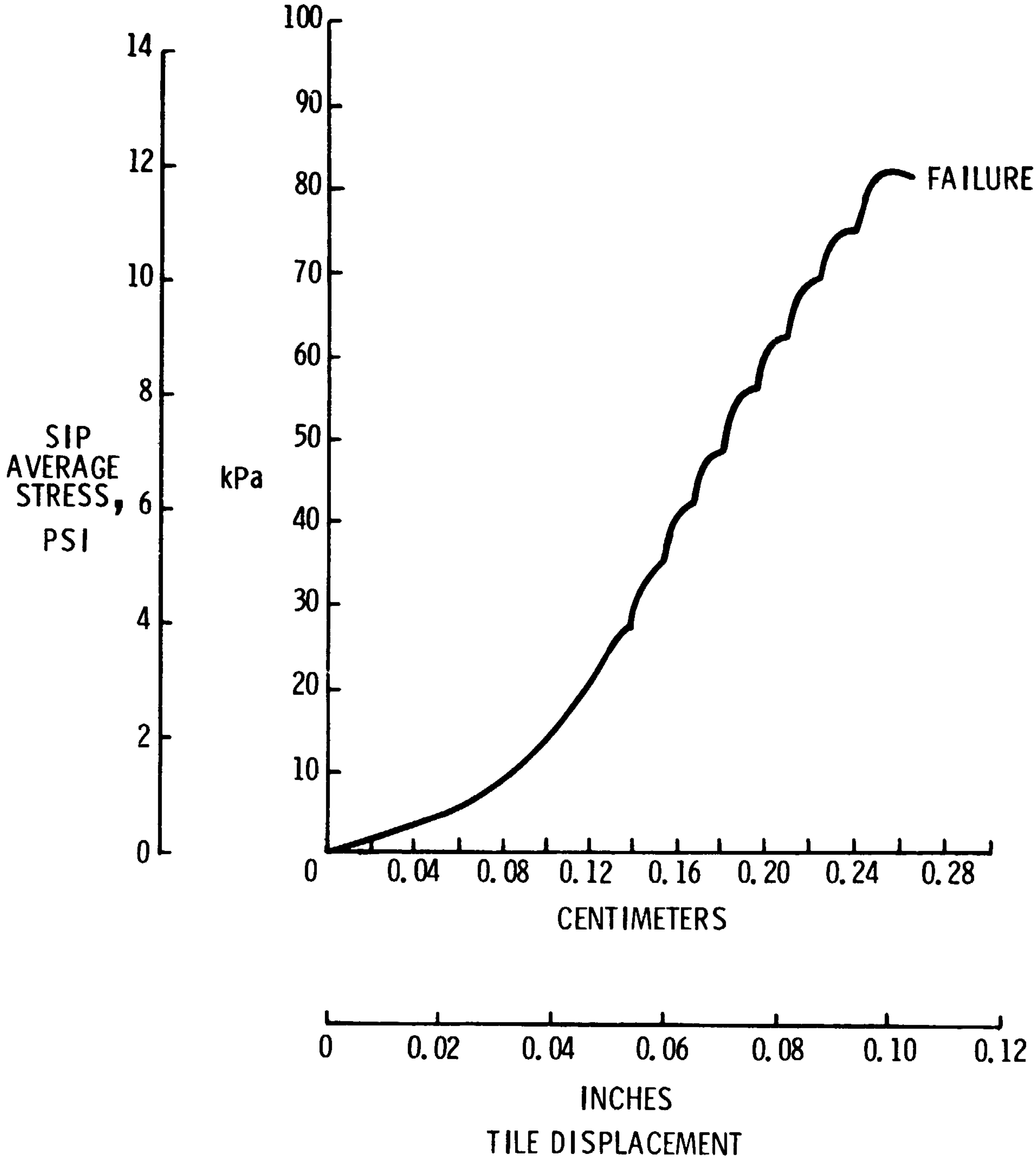


Figure 26. - SIP average stress versus tile transverse displacement for ultimate failure load cycle of specimen previously loaded by selected combinations of in-plane load and negative pressure shock (See Table V).