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STRUCTURAL TESTS ON SPACE SHUTTLE THERMAL PROTECTION SYSTEM CONSTRUCTED WITH NONDENSIFIED AND DENSIFIED LI 900 AND LI 2200 TILE

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SUMMARY

Structural tests were conducted on thermal protection systems (TPS) including LI 900 and LI 2200 tiles and .41 cm (.16 in.) and .23 cm (.09 in.) thick strain isolation pads (SIP). In addition, the bond surface of selected tiles was densified to obtain improved strength. Four basic types of experiments were conducted including tension tests, substrate mismatch (initial imperfection) tests, tension loads eccentrically applied, and pressure loads applied rapidly to the tile top surface. A small initial imperfection mismatch (2.29 m (90 in.) spherical radius on the substrate) did not influence significantly the ultimate failure strength. Densification of the tile bond region improved the strength of TPS constructed both of LI 900 tile and of LI 2200 tile. Pressure shock conditions studied did not significantly affect the TPS strength.

INTRODUCTION

The Space Shuttle aluminum skin is protected against high temperatures by a covering consisting of several thousand low density Reusable Surface Insulation (RSI) tiles. The 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 tiles instead are bonded using silicone rubber to a matted-felt material called Strain Isolation Pad (SIP), and the SIP is bonded to the aluminum skin, also using silicone rubber adhesive. Several different thermal protection systems (TPS) are used including tiles with two different densities and SIP materials with two different thicknesses. In addition, selected tiles are strengthened in the bond surface region through a local densification process.

The results of an investigation to study the structural characteristics of LI 900 tile bonded to a 0.41 cm (0.16 in.) SIP are reported in reference 1. That investigation has been expanded and is reported herein to include non-densified LI 2200 tile and both LI 900 and LI 2200 tile treated to provide a densified bond surface. Four basic types of experiments were conducted: (1) tension tests, (2) initial imperfection mismatch (deviation between the exact surface contour of the tile and the aluminum substrate) tests, (3) eccentrically applied tension loads, and (4) vacuum pressure loads applied rapidly to the top surface of the tile. Prior to conducting experiments, all specimens were subjected to a proof test tension/compression load cycle.

SPECIMEN DESCRIPTION

Specimens used in this investigation were constructed in accordance with accepted fabrication procedures approved for Space Shuttle. All tiles were rectangular parallelepipeds, 15.2 cm (6 in.) square with a density of either

144 kg/m^3 (9 lb/ft^3), "LI 900," or 352 kg/m^3 (22 lb/ft^3), "LI 2200." SIP material 0.41 cm (0.16 in.) thick was used with LI 900 tile while 0.23 cm (0.090 in.) thick SIP was used with LI 2200 tile as is common on the orbiter. The SIP bonded surface dimensions were 12.7 cm (5 in.) by 12.7 cm (5 in.). A filler bar material 0.95 cm (0.38 in.) wide of composition similar to the SIP was bonded to the aluminum plate around the perimeter of the SIP. In preparation for bonding, the 1.27 cm (0.5 in.)-thick plate was primed with Koropon. The densification of tile bond surface regions was accomplished in accordance with procedures approved for Space Shuttle. Additional details of the fabrication procedures are available in reference 1.

TEST DESCRIPTION

Schematic descriptions of the various test configurations are presented in Figure 1. Descriptions of the test techniques 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 for Space Shuttle. Details of the test equipment and proof test procedures are described in reference 1.

LI 900 and LI 900-densified specimens were loaded in tension to a maximum average stress in the SIP of 41.4 kPa (6 PSI) while LI 2200 and LI 2200-densified specimens were loaded to a maximum average stress of 68.9 kPa (10 PSI). The tension load was followed by unloading and the immediate application of compression loading (978N (220 lb) for LI 900 and LI 900-densified specimens and 1330N (300 lb) for LI 2200 and LI 2200-densified specimens). In addition to carrying the proof test loads, LI 900 tiles were also required to meet the acoustic emission criteria defined in reference 1.

Tension loading was applied in step increments with the pressure held at intermediate levels. For LI 900 and LI 900-densified specimens, the tension load was held for 30 seconds at the 27.6 kPa (4 PSI) and 34.5 kPa (5 PSI) stress levels and for 60 seconds at the 41.4 kPa (6 PSI) stress level. For LI 2200 and LI 2200-densified specimens, the tension load was held for 30 seconds at the 48.3 kPa (7 PSI), 55.2 kPa (8 PSI), 62.0 kPa (9 PSI) stress levels and for 60 seconds at the 68.9 kPa (10 PSI) stress level. Typical stress versus displacement responses from proof test data for the four tile/SIP material systems are presented in Figure 2. Variations in the response between LI 900 and LI 900-densified and between LI 2200 and LI 2200-densified specimens are primarily due to variations in properties of the SIP material used to fabricate specimens.

Tension Tests

Constant Displacement Rate.- Specimens were loaded to failure in transverse tension in a constant displacement rate test machine. Load transfer into the tile was accomplished through a 1.27 cm (0.5 in.) thick aluminum plate bonded to the top surface of the tile. A displacement rate of 0.13 cm/minute (0.05 inch/minute) was used. The SIP displacement response to loading was measured at the midpoint of the four sides of the tile.

Pressure Applied Tension.- Transverse tension loading of the specimen was also accomplished by loading the tile with pressure, thus eliminating the restraint imposed by the aluminum loading plate required in displacement controlled tests. A flexible bellows was used to form an enclosure around the top surface of the tile. The bellows was attached to the impervious tile coating with tape and tension loading of the tile was accomplished by reducing the pressure within the chamber. The experimental setup to accomplish this loading is shown in Figure 3. 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.

Substrate Initial Imperfection Mismatch Tests

Specimens bonded to a 1.27 cm (0.5 in.) thick aluminum plate with a 2.29 m (90 in.) spherical radius were loaded to failure in tension. This configuration imposes an initial imperfection amplitude of 0.18 cm (0.069 in.) at the SIP corners. These tests were conducted to simulate dimensional differences between the tile and aluminum substrate which may exist initially or which slowly develop during flight.

Eccentrically Applied Tension

Specimens were loaded to failure by an eccentrically applied tension load. The experimental setup is shown in Figure 4. 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 caused by the eccentric loading. These tests were performed to simulate load conditions which might occur as a shock wave passes across a tile or as aerodynamic pressure gradients occur during flight.

Combined In-Plane Force and Transverse Pressure Tests

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 schematically in Figure 5. 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 5, 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. 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 vacuum pressure loads to be imposed on either all or part of the tile top surface. The flexible bellows vertical 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 bellows.

In-plane loads were applied at the rate of 67 N/min. (15 lb/min) and pressure was applied at the rate of 28 kPa/min (4 psi/min). For some tests, the pressure was applied rapidly to simulate a shock. The technique for applying pressure shock involved pumping down a large pressure bottle to the desired pressure and releasing a solenoid valve connecting the bottle to the bellows chamber to reduce rapidly the pressure in the desired chamber. Measurements obtained during tests included 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. These tests were performed to investigate in-plane and transverse displacement coupling and failure interactions and to determine the effect of pressure shock loading.

RESULTS AND DISCUSSION

A summary of the ultimate loads carried by specimens for various test conditions is presented in Table 1. Details of test results are described below.

Tension and Substrate Initial Imperfection Mismatch Tests

A graph of the SIP average stress versus tile displacement for the first load cycle following proof test for LI 900, LI 900-densified, LI 2200, and LI 200-densified specimens loaded in tension (with and without substrate mismatch) are presented in Figures 6, 7, 8, and 9. A discussion of results for each type of specimen is presented below.

LI 900 - Specimens loaded in tension failed at average stresses ranging from 63.4 kPa (9.2 PSI) to 84.1 kPa (12.2 PSI) and the two specimens with 2.29 m (90 in.) spherical mismatch failed at average stress in the same range, 73.8 kPa (10.7 PSI) and 80.0 kPa (11.6 PSI).

No significant differences in results were observed between specimens in which load was introduced through a metal plate bonded to the tile top surface and in which load was imposed by reducing the pressure on the top surface of the tile. The typical failure mode for LI 900 specimens loaded in tension is illustrated in Figure 10. The failure occurred in the bond between the tile and the SIP in which small particles of the tile remain distributed over the silicone rubber surface. The tile thickness of one specimen loaded through pressure was only 0.97 cm (0.38 in.). This specimen at failure carried an average stress of 84.1 kPa (12.2 PSI). Failure for the 0.97 cm (0.38 in.)-thick tile loaded by pressure initiated at one corner in the typical peel mode and propagated until the bending stresses on the thin tile were sufficient to cause the tile to fracture in the manner shown in Figure 11.

A set of tension tests were also conducted in which the SIP size was varied. These tests designed to address the effect bond area has on the specimen failure stress had SIP area ranging from 161 cm^2 (25 in^2) to 40.3 cm^3 (6.25 in^3). Results are listed in Table II. For the range of sizes considered, reducing the SIP area did not significantly change the average stress at failure. The failure mode was also unchanged as seen by comparing the failure surface for one of the reduced SIP area specimens (Figure 12) with that for the 161 cm^2 (25 in^2) SIP (Figure 10).

<u>LI 900-Densified</u> - The average SIP stress at failure was 179 kPa (25.9 PSI) for one LI 900-densified specimen loaded in tension and 171 kPa (24.8 kPa) for one specimen with a 2.29 m (90 in.) radius spherical imperfection mismatch. Beyond the 27.6 kPa (4 PSI) stress level, tension stress as a function of tile displacement response is almost linear as shown in Figure 7. Failure occurred totally within the tile above the densified region as shown in Figure 13.

<u>LI 2200</u> - The average SIP stress at failure was 170 kPa (24.6 PSI) and 175 kPa (25.4 PSI) for two LI 2200 tension specimens and 136 kPa (19.7 PSI) for one specimen with a 2.29 m (90 in.) radius spherical imperfection mismatch. The stress versus displacement response for the mismatch specimen plots between the response for the two tension specimens (Figure 8). The failure mode for LI 2200 specimens involved peel separation at the tile/SIP bond surface similar to that experienced by LI 900 specimens as illustrated in Figure 14.

<u>LI 2200-Densified</u> - The SIP average stress at failure was 210 kPa (30.4 PSI) and 213 kPa (30.9 PSI) for two LI 2200-densified tension specimens and 199 kPa (28.8 PSI) for one specimen with a 2.29 m (90 in.) radius spherical imperfection

mismatch. The stress versus displacement response curves are highly nonlinear especially near the ultimate load (Figure 9). This response is related to the mode of failure illustrated by the photograph in Figure 15. As the specimen load approached the ultimate, the SIP fibers adjacent to the aluminum plate experienced large deformations leaving most of the SIP attached to the tile.

Eccentrically Applied Tension Tests

LI 900 - The displacement response for three specimens with a 3.18 cm (1.25 in.) eccentrically applied load as a function of the applied force is presented in Figure 16. The failure load for the three specimens was 519, 586, and 694 N (117, 132, and 156 lb.). A comparison of the displacement responses for specimens with load eccentricities of 1.91 cm (0.75 in.), 3.18 cm (1.25 in.), and 4.32 cm (1.7 in.) is presented in Figure 17. The failure loads for the specimens with eccentricities of 1.91 cm (0.75 in.) and 4.32 cm (1.7 in.) were 809 N (182 lb.) and 654 N (147 lb), respectively. Two tests were also conducted in which specimens with a 2.29 m (90 in.) radius spherical imperfection mismatch of the aluminum plate to which the SIP was bonded were loaded eccentrically. The displacement responses for specimens with mismatch plus 3.18 cm (1.25 in.) or 4.32 cm (1.7 in.) load eccentricities are presented in Figure 18. Ultimate loads for these two specimens were 547 N (123 lb.) for the mismatch specimen with 3.18 m (1.25 in.) eccentricity and 538 N (121 lb.) for the mismatch specimen with 4.32 cm (1.7 in.) eccentricity.

Failure for eccentrically loaded LI 900 specimens initiated in the region of maximum tensile stress and propagated by peeling of the tile-SIP interface until complete separation resulted. A photograph showing the rotation of the plate and disbond failure of the SIP to tile in this region is presented in Figure 19. The appearance of the failure surface was similar to that observed for pure tension tests. Failure for specimens with mismatch and load eccentricity occurred initially near the center of the edge of maximum tension as illustrated in Figure 20 rather than at the corners of this edge where the maximum warpage displacement amplitude occurs.

LI 900-Densified - The displacement response for an LI 900-densified specimen loaded in tension with a 3.18 cm (1.25 in.) load eccentricity is presented in Figure 21. The load at failure was 1.67 kPa (375 lb.). A photograph of the failure surface is presented in Figure 13. Failure was by instantaneous fracture of the tile in which a cavity developed on the half of the tile loaded by maximum tension.

LI 2200 - The displacement responses for two LI 2200 specimens loaded in tension with a 3.18 cm (1.25 in.) load eccentricity are presented in Figure 22. The loads at failure were 1.74 kN (392 lb.) and 1.81 kN (407 lb.). The failure mode involved peeling of the tile from the SIP at the bond interface similar to that observed for pure tension tests.

LI 2200-Densified - The displacement responses for two LI 2200-densified specimens loaded in tension with a 3.18 cm (1.25 in.) load eccentricity are presented in Figure 23. The loads at failure were 2.38 kN (534 lb.) and 2.41 kN (541 lb.). The failure mode was similar to that observed for specimens loaded in pure tension, i.e., large displacements of SIP fibers adjacent to the aluminum plate leaving most of the SIP attached to the tile.

Rapidly Applied Pressure Loads

The LI 900 specimens were subjected to load sets involving the rapid application of reduced pressure to part or all of the tile top surface. Results of the three specimens are described below.

Pressure Shock Applied to Half of Tile Top Surface. - Pressure shock loads were applied to the half of the tile top surface bounded by the tile diagonal and two edges. The history of loading and the tile displacement responses are summarized in Table III. Prior to conducting the shock tests, an in-plane load of 407 N (91.6 lb.) was imposed on the specimen and released before shock pressures were applied. A plot of the pressure versus time response for several shock loadings is presented in Figure 24. The pressure recorded in Table III is slightly greater than the maximum pressure recorded in Figure 24 because the pressure had not stabilized in the time frame shown. Pressure shocks were applied without failure in increasing steps up to a magnitude of 66.9 kPa (9.7 PSI). A shock load of 75.3 kPa (10.92 PSI) caused the specimen to fail by disbond at the tile/SIP interface at the corner of maximum tension loading.

Pressure Shock Applied to Entire Tile Top Surface. - Fifty cycles of pressure shock were applied to the entire top surface of one LI 900 specimen. The peak pressure ranged from 27.6 kPa (4.0 PSI) to 31.0 kPa (4.5 PSI). The pressure and the tile displacement time history response for the fiftieth cycle are presented in Figure 25. The specimen survived this sequence of shock loads and was loaded slowly in tension to failure. The specimen failed in the peel mode at the tile-SIP interface at an average SIP stress of 76.5 kPa (11.1 PSI).

Combined Loading: In-Plane, Pressure and Shock. - One LI 900 specimen was subjected to shock loading while already loaded by an in-plane load as well as by vacuum pressure applied to the entire top surface of the tile. The sequence of loads applied to the specimen is described in Table IV. An in-plane load of 178 N (40 lb) was imposed at the start of the test and was held during the remainder of the shock test. Increasing vacuum pressure was slowly imposed on the entire top surface of the tile ($P_2 = P_3$) and the shock pressure difference was superimposed by rapidly reducing the pressure in chamber P_3 by approximately 17.2 kPa (2.5 PSI). The shock load was applied to approximately 72 percent of the tile top surface. Shock pressures were imposed at the rate of approximately 462 kPa/sec (67 PSI/sec) for the first 13.8 kPa (2 PSI) of pressure reduction. Following application of the shock, the pressures were allowed to equalize in the two chambers ($P_2 = P_3$) yielding the maximum recorded pressure. The SIP average stress is based on a load calculated using the maximum pressure applied to the top surface of the tile and the 161 cm^2 (25 in^2) area of the SIP.

The strength measured for this specimen is in excess of that measured for specimens loaded purely in tension. The specimen carried a 17.6 kPa (2.55 PSI) shock pressure superimposed on a 62.5 kPa (9.06 PSI) initial uniform pressure. Disbond failure initiated in a corner at a SIP average stress of 126 kPa (18.22 PSI). The test was terminated and the specimen was subsequently loaded to failure in the proof test fixture. The specimen carried an ultimate average stress of 89.24 kPa (12.95 PSI) at which the corner disbond grew resulting in the separation at the tile/SIP interface.

CONCLUDING REMARKS

A limited number of structural tests have been conducted on LI 900 and LI 2200 tiles with and without a densified tile bond surface. Test results show that densification improved the ultimate strength of the LI 900 tile/ .41 cm (.16 in.) SIP specimens by a factor greater than two. Densification improved the ultimate strength of the LI 2200 tile/.23 cm (.09 in.) SIP specimens by about 30 percent. LI 900 nondensified specimens failed in the SIP-to-tile bond region while the failure for LI 900 densified specimens occurred in the tile. The failure mode for LI 2200 nondensified specimens was in the bond between the tile and the SIP. Densified LI 2200 specimens failed by excessive extension of SIP fibers. A 2.29 m (90 in.) spherical radius imperfection mismatch had negligible effect in reducing the strength in any of the tests conducted. Several tests were conducted in which specimens were subjected to rapidly applied pressure to simulate aerodynamic shock. Failures were experienced only after very high pressure conditions were imposed.

REFERENCES

1. Williams, Jerry G.: Structural Tests On A Tile/Strain Isolation Pad Thermal Protection System. NASA TM 80226, March 1980.

TABLE I. - TPS TEST RESULTS.[a]

TEST	FAILURE LOAD, N(LBS)			
	LI 900	LI 900D	LI 2200	LI 2200D
TENSION	1020(230), 1180(265), 1190(268), 1270(285), 1290(290), 1310(295), 1360(305)	2880(647)	2740(615), 2820(635)	3380(759), 3440(773)
Mismatch[b]	1190(267), 1290(290)	2760(620)	2190(492)	3210(721)
1.9 cm (0.75 In.) Eccentrically Applied Load	809(182)	--	--	--
3.18 cm (1.25 In.) Eccentrically Applied Load	520(117), 587(132) 694(156)	1670(375)	1810(407), 1740(392)	2410(541), 2380(534)
4.32 cm (1.7 In.) Eccentrically Applied Load	654(147)	--	--	--
Combined In-Plane Load, Pressure and Pressure Shock	1350(304), 1330(298), 1450(325), 1790(402), 1810(407)			
Mismatch[b] and 3.18 cm (1.25 In.) Eccentrically Applied Load	547(123)	--	--	--
Mismatch[b] and 4.32 cm (1.7 In.) Eccentrically Applied Load	538(121)	--	--	--

(a) 12.7 cm (5 In.) x 12.7 cm (5 In.) SIP area.
(b) 2.3 m (90 In.) spherical radius.

TABLE II.- EFFECT OF SIP AREA ON TPS ULTIMATE TENSILE STRENGTH.

SIP AREA cm^2 (in^2)	AVERAGE STRESS AT FAILURE kPa (PSI)
161 (25)	63 to 84 (9.2 to 12.2)
121 (18.75)	88 (12.8)
81 (12.5)	94 (13.6)
40 (6.25)	83 (12.0)

TABLE III.- SPECIMEN DISPLACEMENT RESPONSE TO NEGATIVE PRESSURE SHOCK APPLIED TO TRIANGULAR ONE-HALF OF TILE TOP SURFACE.

LOAD CYCLE	IN-PLANE LOAD, N (lb)	PRESSURE SHOCK, P_3, kPa (PSI)	DISPLACEMENT, CM (IN.)		
			IN-PLANE	VERTICAL LEFT	VERTICAL RIGHT
1	407 (91.6)	0 (0)	-0.266 (-0.105)	0.036 (0.014)	0.175 (0.069)
	0 (0)	0 (0)	-0.126 (-0.050)	-0.004 (-0.002)	0.031 (0.012)
2	0 (0)	9.03 (1.31)	0.033 (0.013)	0.004 (0.002)	-0.044 (-0.017)
	0 (0)	0 (0)	0.006 (0.002)	0.000 (0.000)	-0.000 (-0.001)
3	0 (0)	19.0 (2.76)	0.053 (0.021)	0.006 (0.002)	-0.070 (-0.027)
	0 (0)	0 (0)	0.012 (0.005)	0.001 (0.001)	-0.010 (-0.004)
4	0 (0)	30.6 (4.44)	0.066 (0.026)	0.010 (0.004)	-0.098 (-0.039)
	0 (0)	0 (0)	0.020 (0.008)	0.005 (0.002)	-0.026 (-0.010)
5	0 (0)	49.9 (7.24)	0.078 (0.031)	0.022 (0.009)	-0.147 (-0.058)
	0 (0)	0.14 (0.02)	0.038 (0.015)	0.018 (0.007)	-0.074 (-0.029)
6	0 (0)	56.9 (8.25)	0.083 (0.033)	0.035 (0.014)	-0.180 (-0.071)
	0 (0)	0.14 (0.02)	0.041 (0.016)	0.025 (0.010)	-0.097 (-0.038)
7	0 (0)	66.9 (9.70)	0.089 (0.035)	0.047 (0.019)	-0.215 (-0.085)
	0 (0)	1.45 (0.21)	0.053 (0.021)	0.040 (0.016)	-0.143 (-0.056)
8[a]	0 (0)	75.3 (10.9)	0.125 (0.049)	0.099 (0.039)	-0.309 (-0.122)

(a) Specimen failure, disbond of tile from SIP at tension corner.

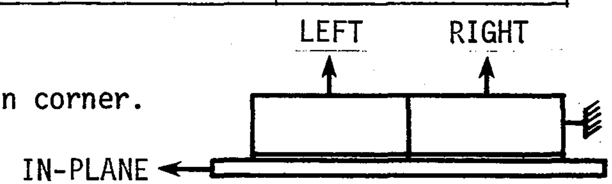
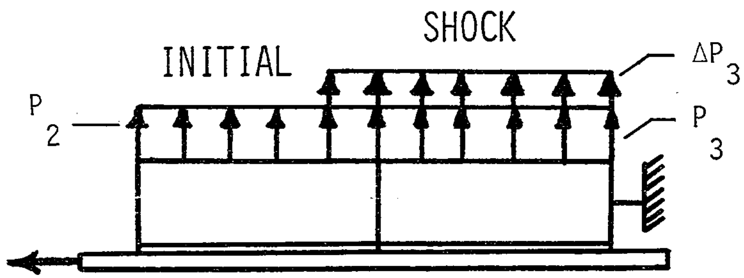
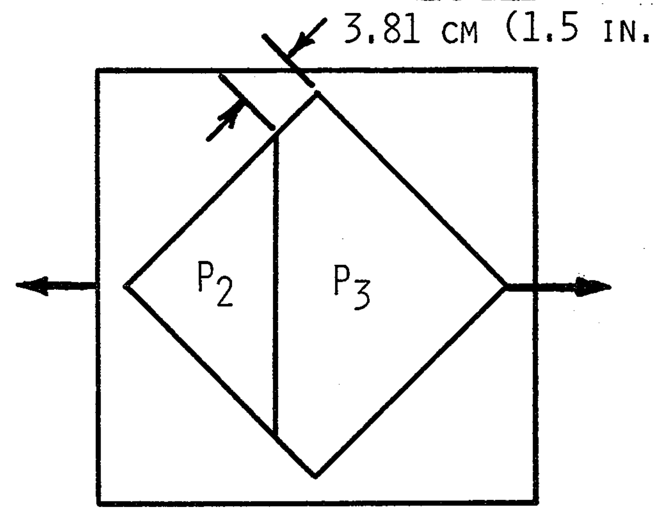


TABLE IV.- COMBINED LOADING INCLUDING PRESSURE, SHOCK AND IN-PLANE LOADS.





LOAD CYCLE	INITIAL PRESSURE[a] P_2=P_3, kPa (PSI)	SHOCK PRESSURE ΔP_3, kPa (PSI)	MAXIMUM UNIFORM LOAD P_2=P_3, kPa (PSI)	MAXIMUM UNIFORM LOAD SIP AVERAGE STRESS, kPa (PSI)
1	13.79 (2.00)	17.72 (2.57)	30.89 (4.48)	44.47 (6.45)
2	20.68 (3.00)	16.89 (2.45)	35.78 (5.19)	51.50 (7.47)
3	27.99 (4.06)	17.44 (2.53)	43.37 (6.29)	62.47 (9.06)
4	34.68 (5.03)	18.06 (2.62)	50.95 (7.39)	73.36 (10.64)
5	41.64 (6.04)	17.86 (2.59)	58.05 (8.42)	83.56 (12.12)
6	48.54 (7.04)	18.13 (2.63)	64.95 (9.42)	93.49 (13.56)
7	55.50 (8.05)	16.89 (2.45)	71.36 (10.35)	102.73 (14.90)
8	62.47 (9.06)	17.58 (2.55)	78.19 (11.34)	112.52 (16.32)
9	87.22 (12.65)[a]	0 (0)	87.22 (12.65)	125.62 (18.22) (CORNER DISBOND)
10	ULTIMATE FAILURE AT SIP AVERAGE STRESS = 89.29 kPa (12.95 PSI)			

[a] UNIFORM PRESSURE WITHOUT SHOCK.

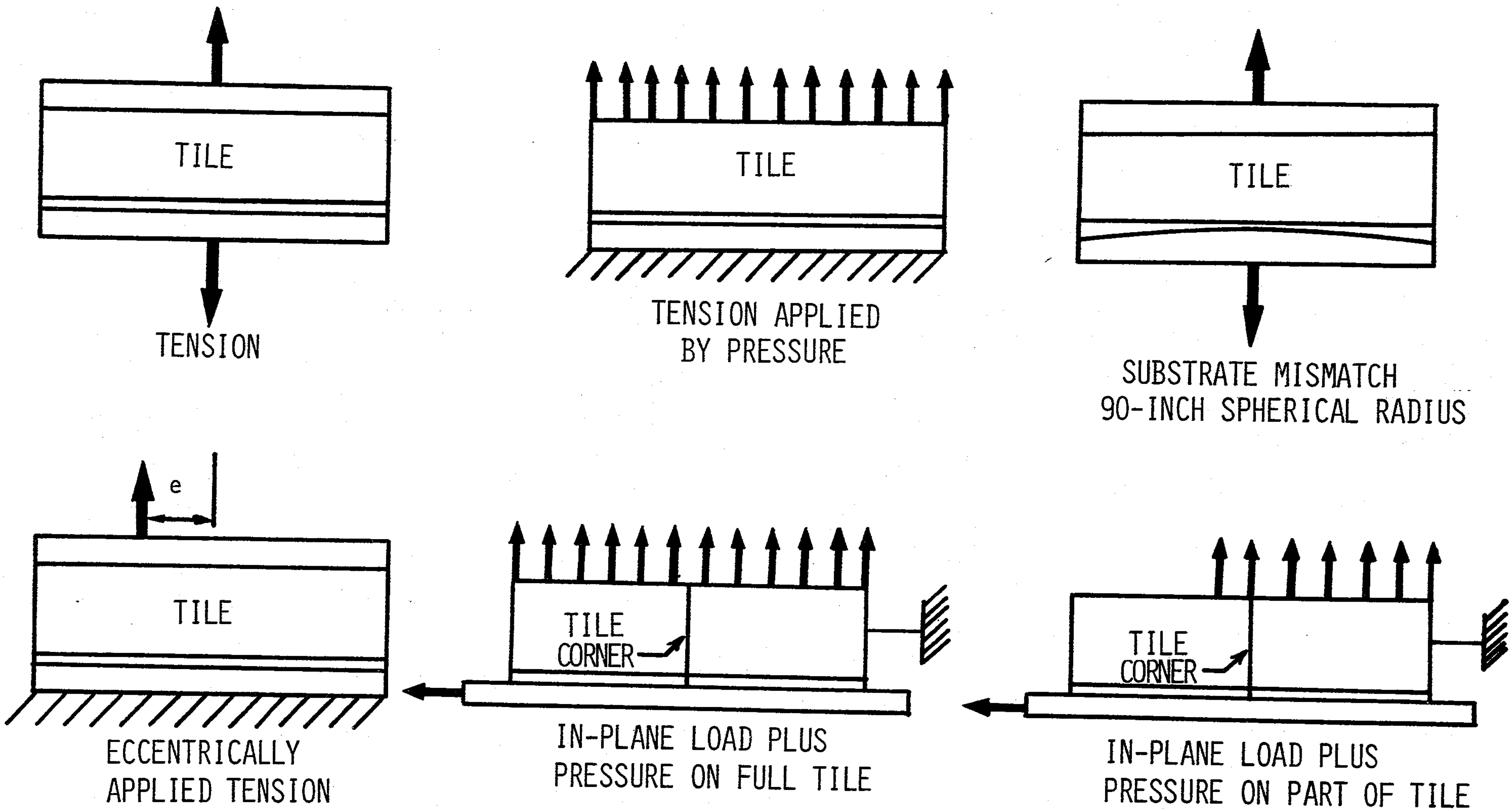


Figure 1. - Test Conditions.

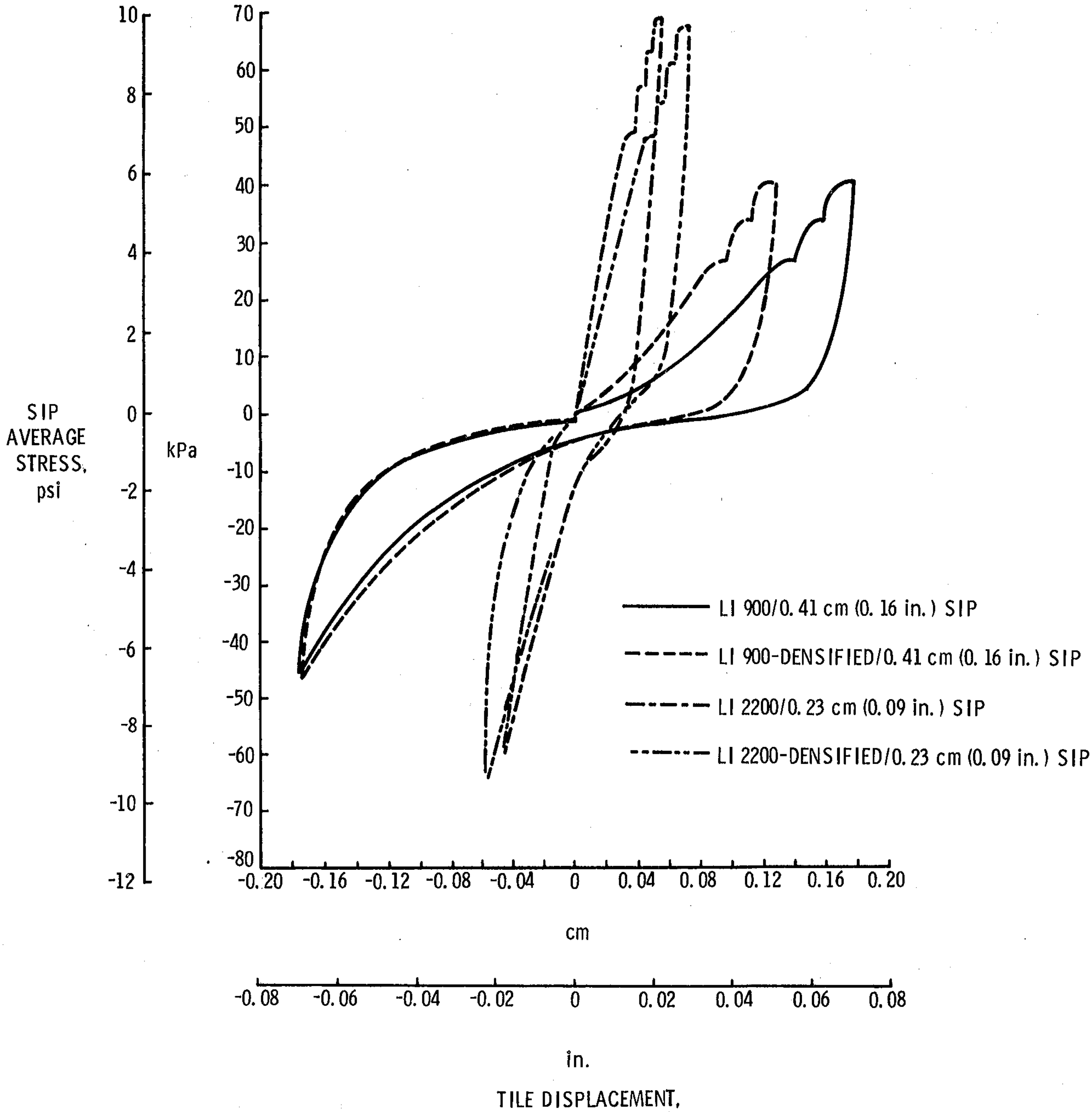


Figure 2. - SIP average stress versus tile displacement for selected tile/SIP material systems.

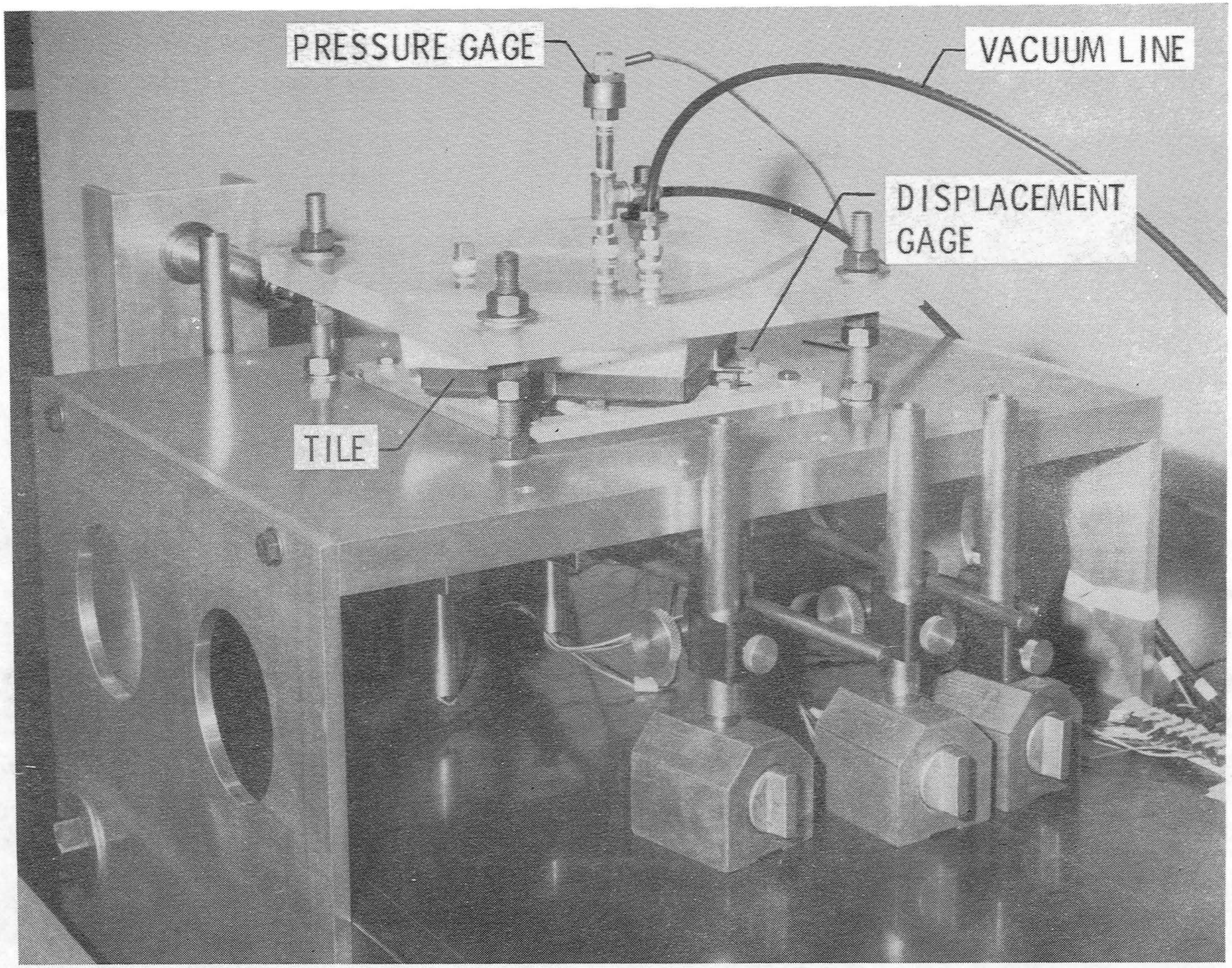


Figure 3. - Test setup for applying transverse pressure loads.

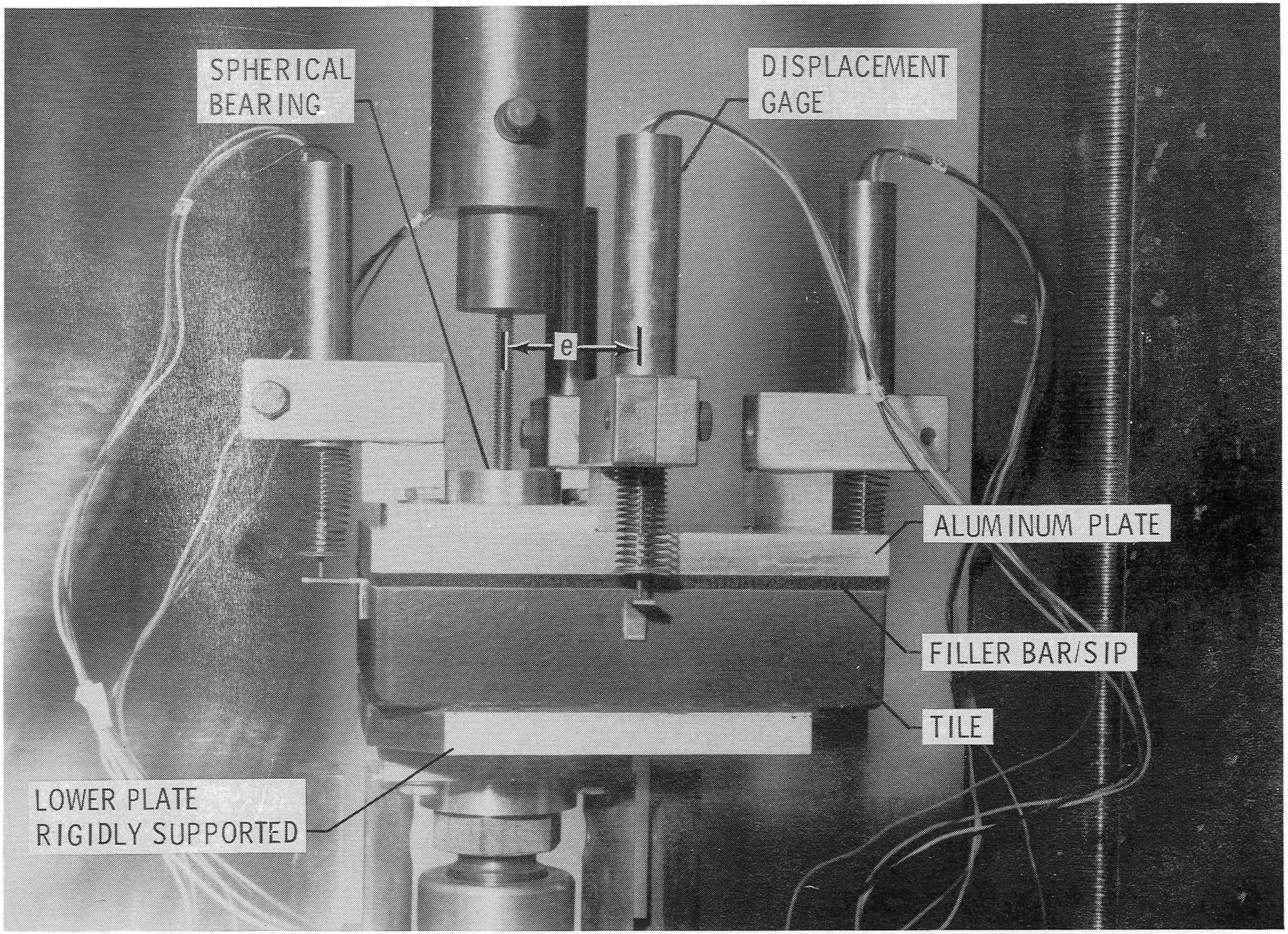


Figure 4. - Experimental setup for conducting eccentrically applied tension loads.

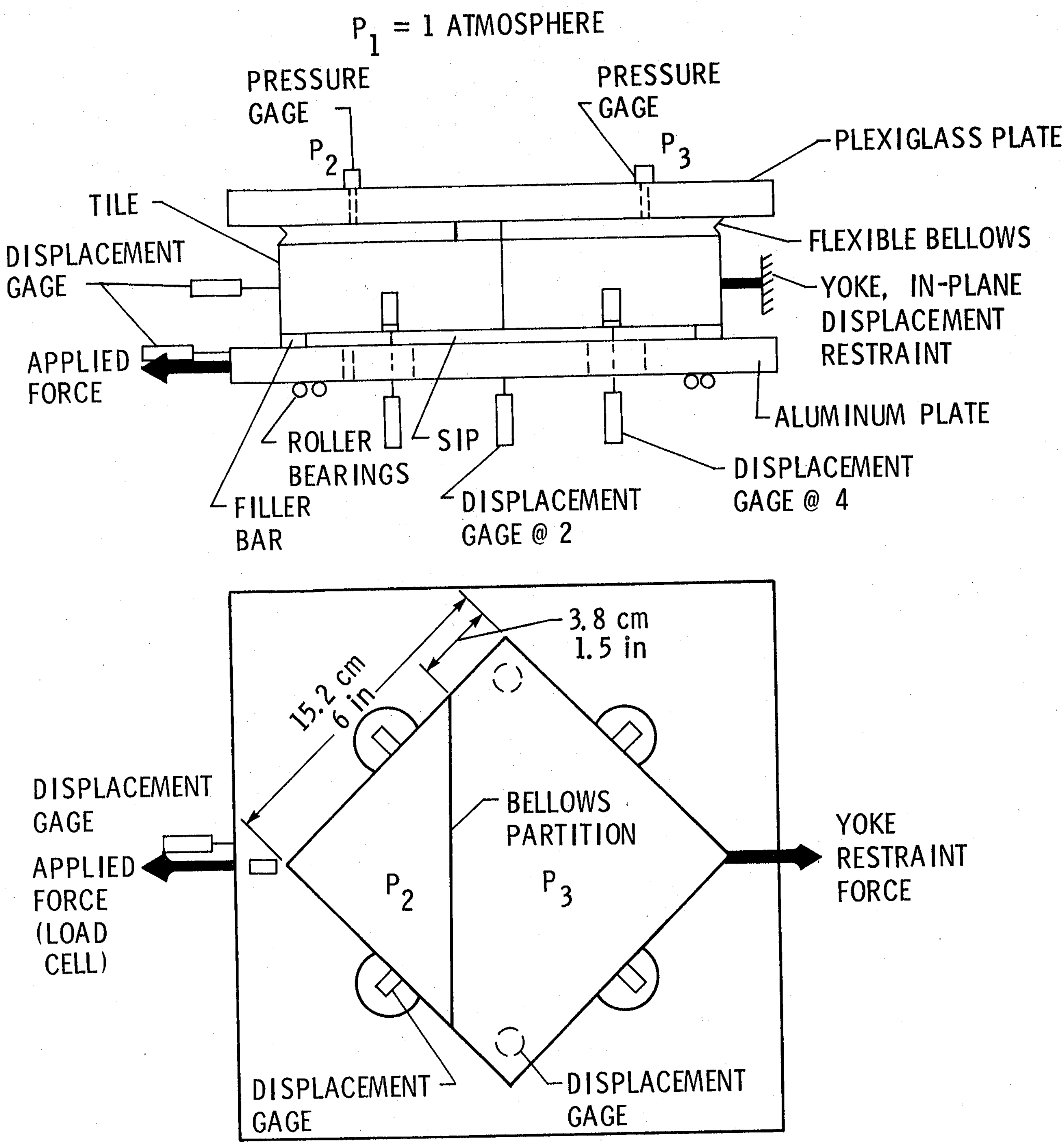


Figure 5. - Schematic of equipment and instrumentation for imposing combined in-plane and transverse pressure loads.

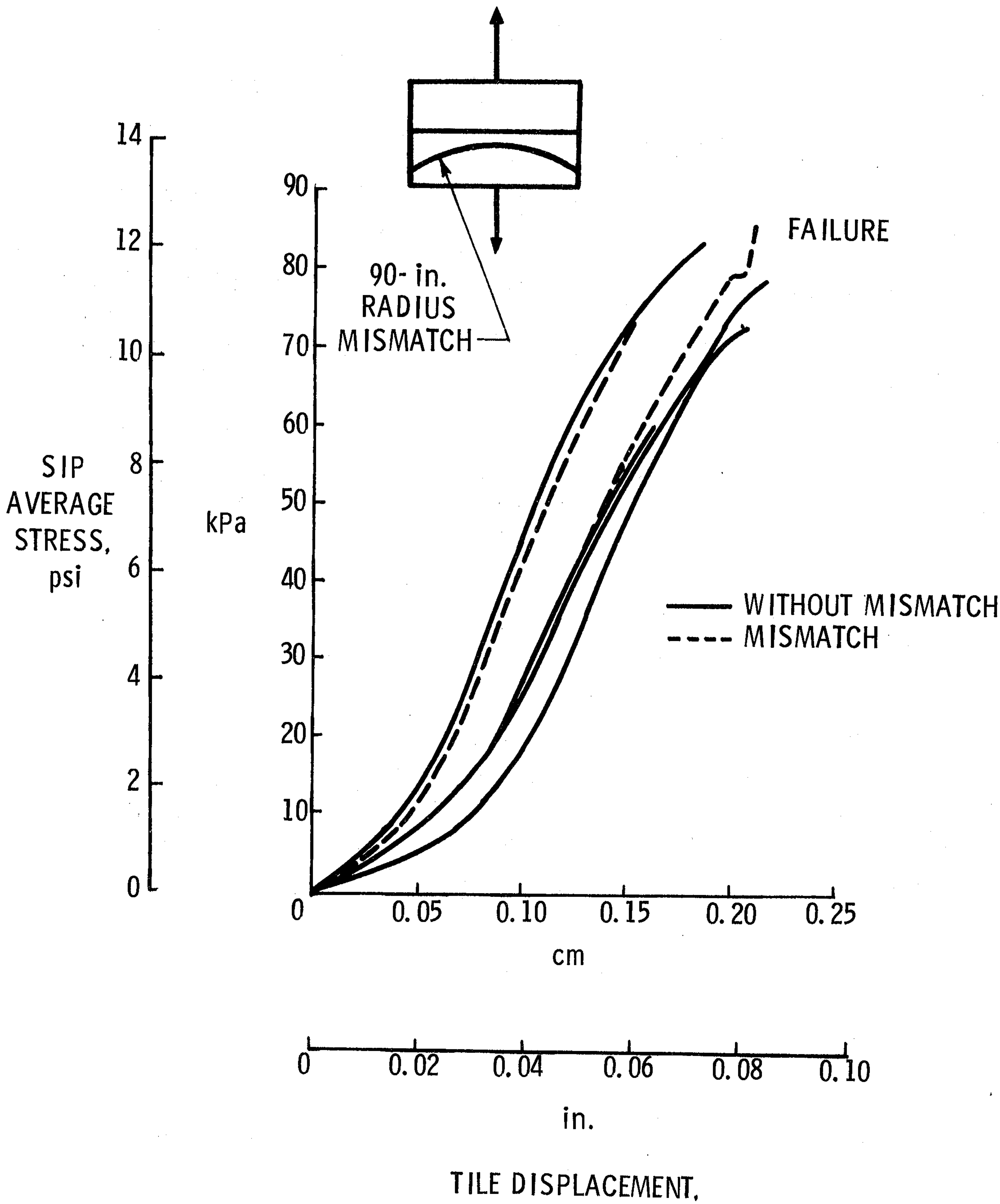


Figure 6. - SIP average stress versus tile displacement for LI 900 specimens loaded to failure in transverse tension (with and without mismatch).

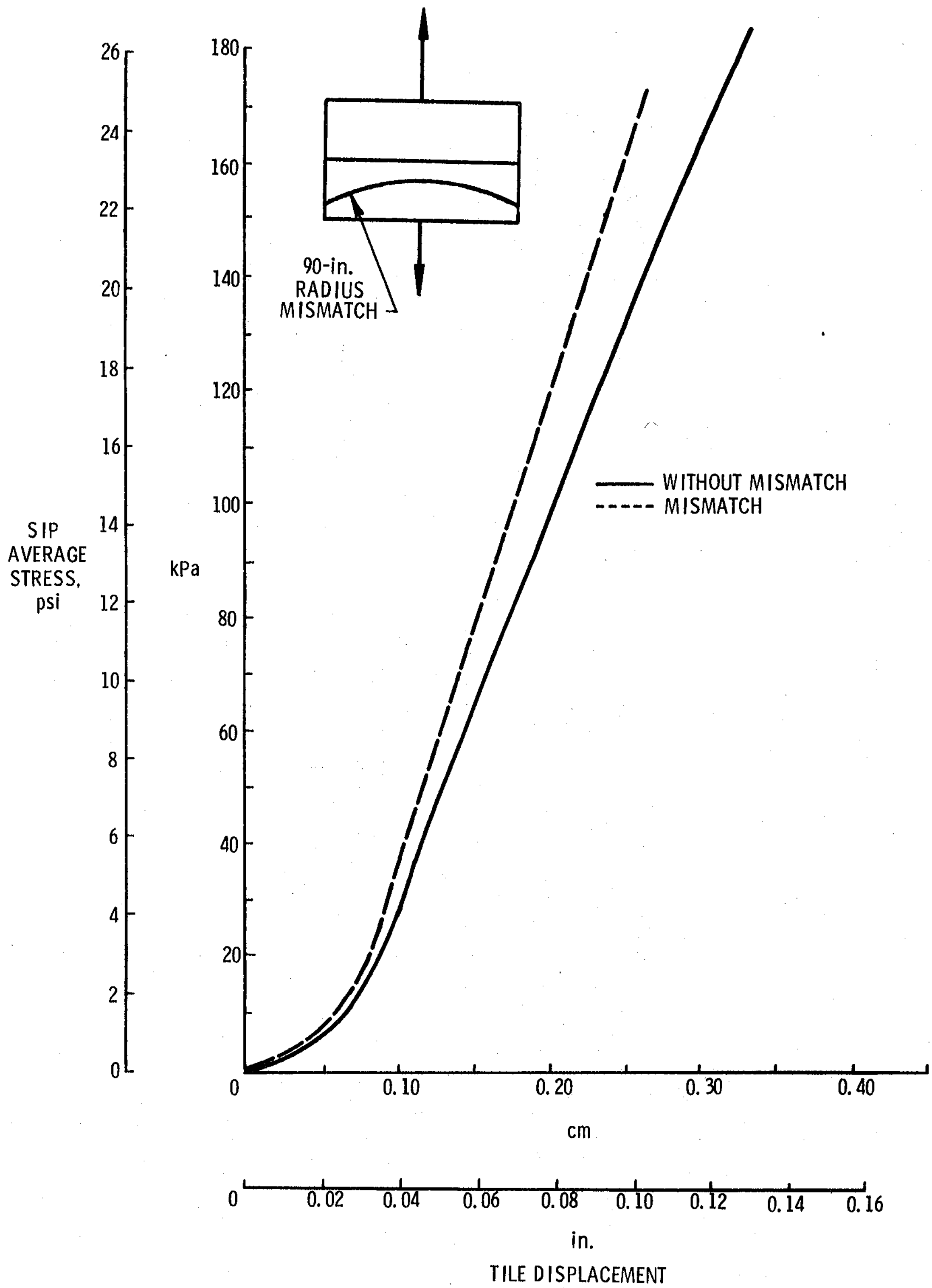


Figure 7. - SIP average stress versus tile displacement for LI 900-densified specimens loaded to failure in transverse tension (with and without mismatch).

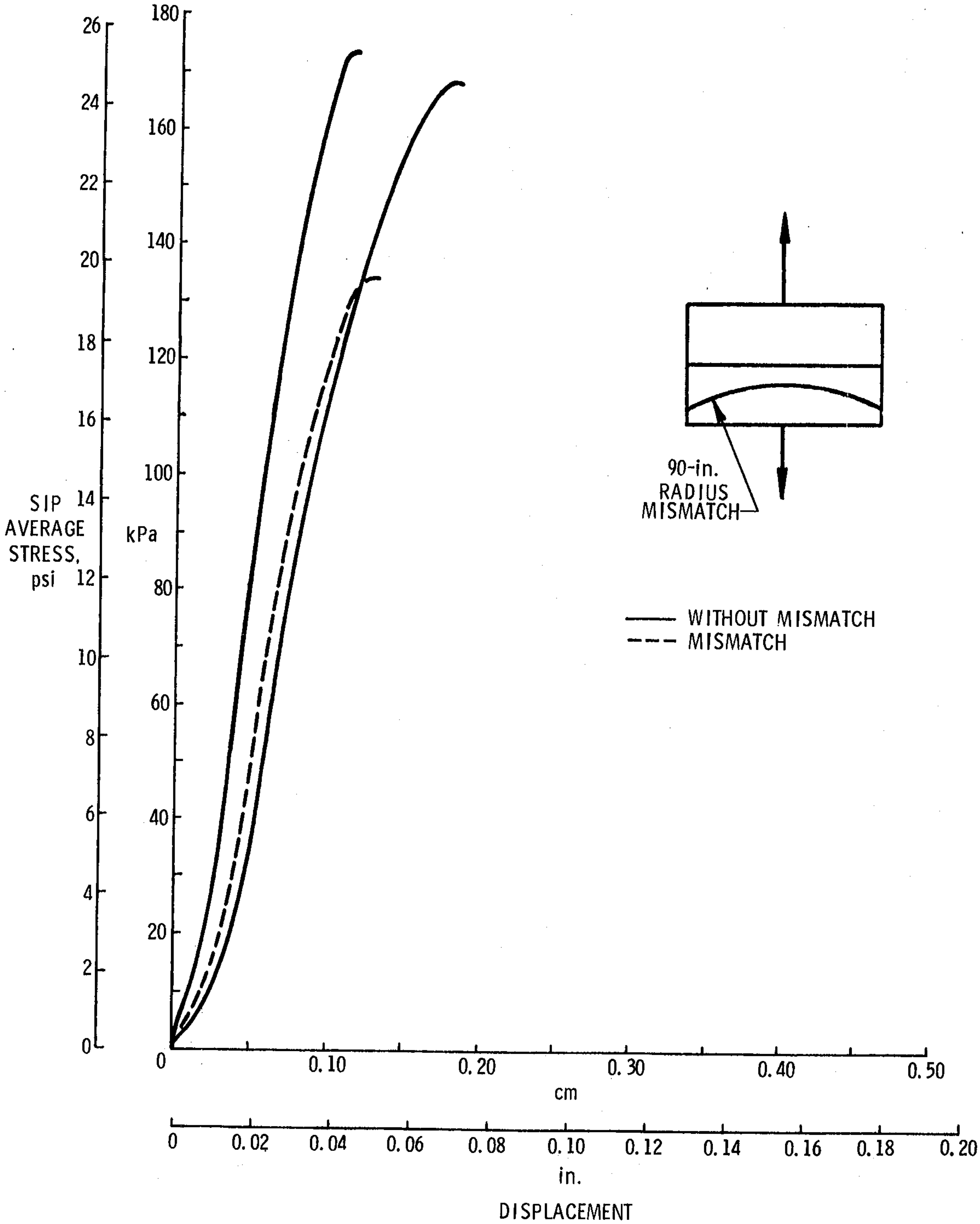


Figure 8. - SIP average stress versus tile displacement for LI 2200 specimens loaded to failure in transverse tension (with and without mismatch).

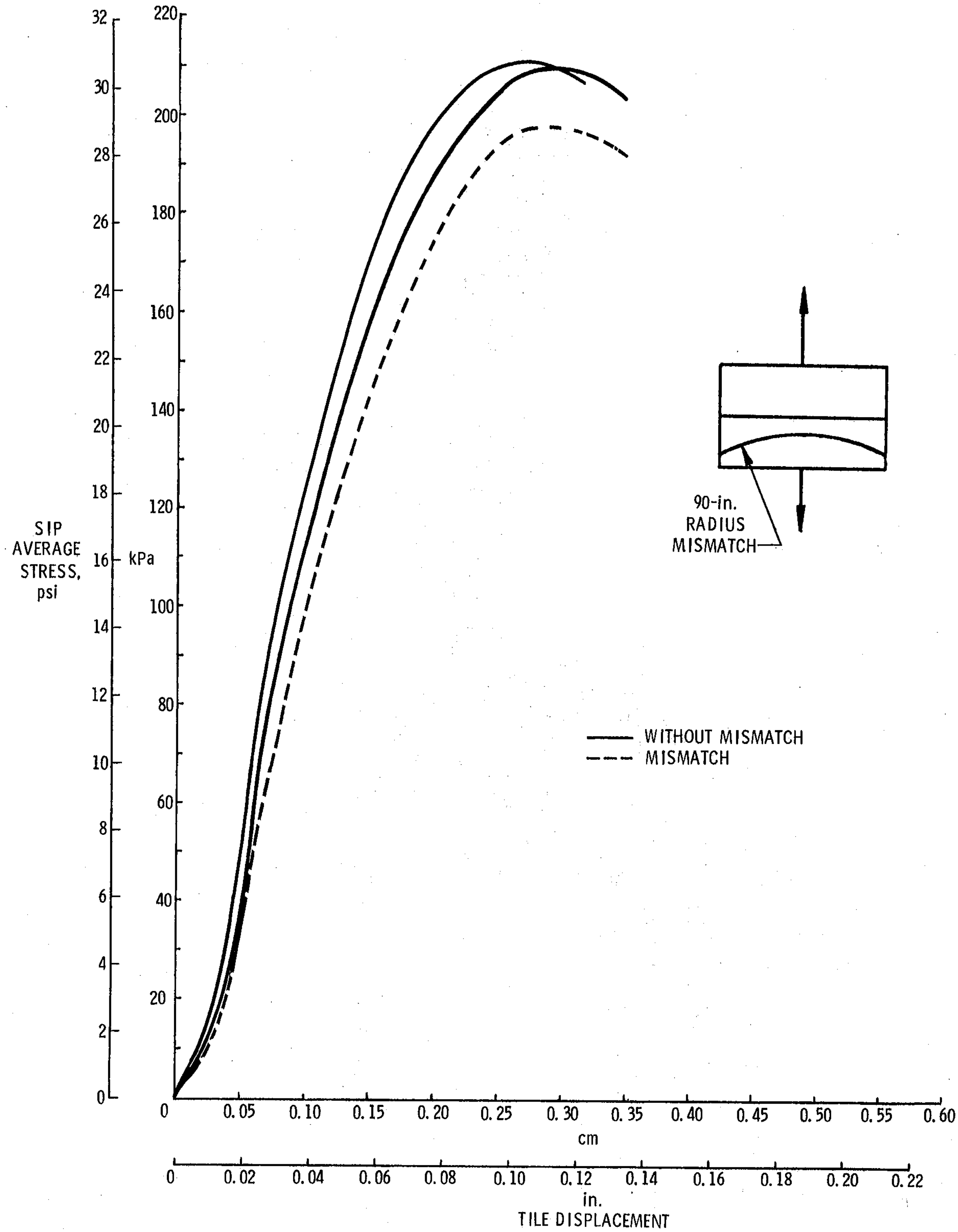


Figure 9. - SIP average stress versus tile displacement for LI 2200-densified specimens loaded to failure in transverse tension (with and without mismatch).

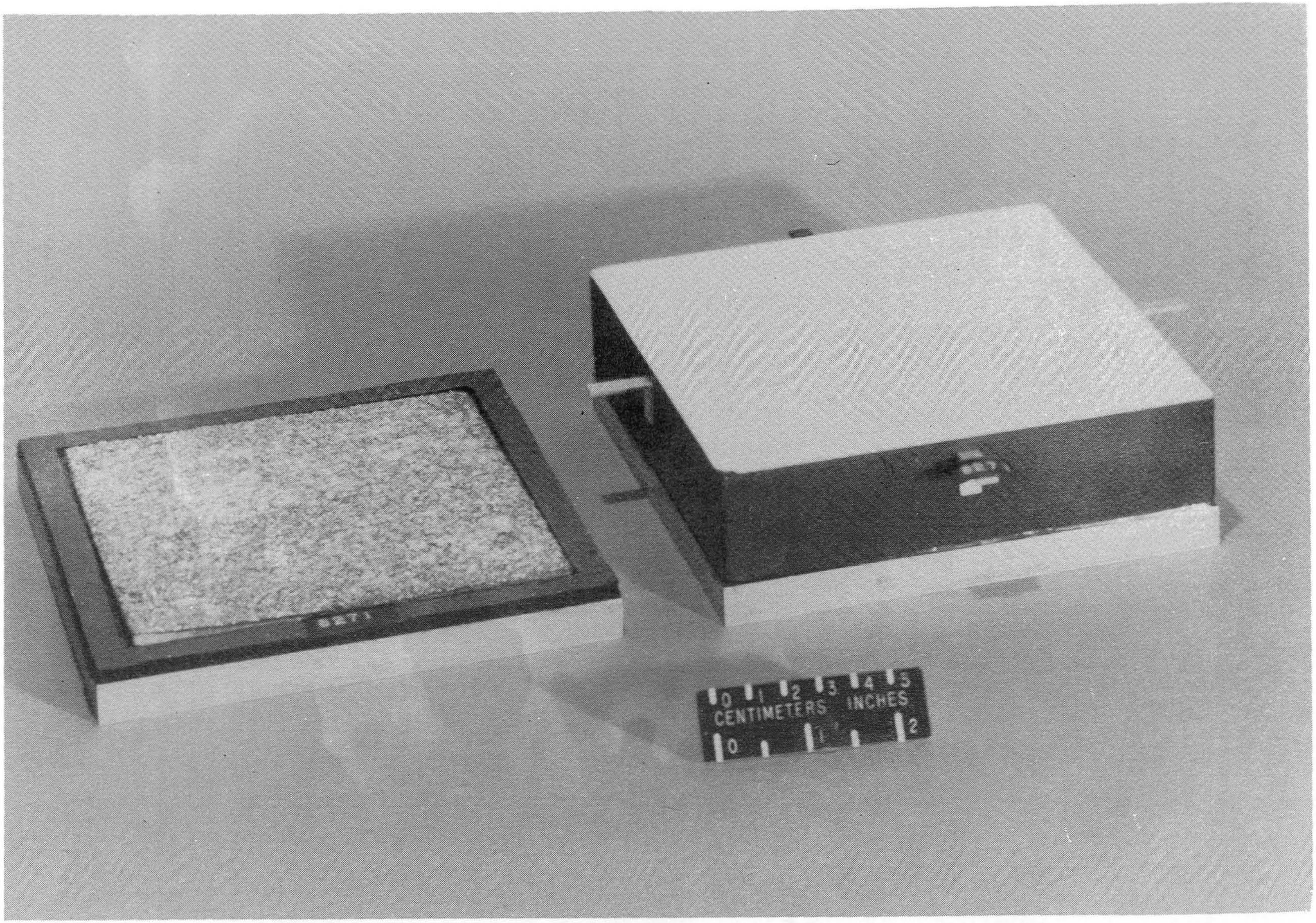


Figure 10. - Typical failure mode for LI 900 specimens.

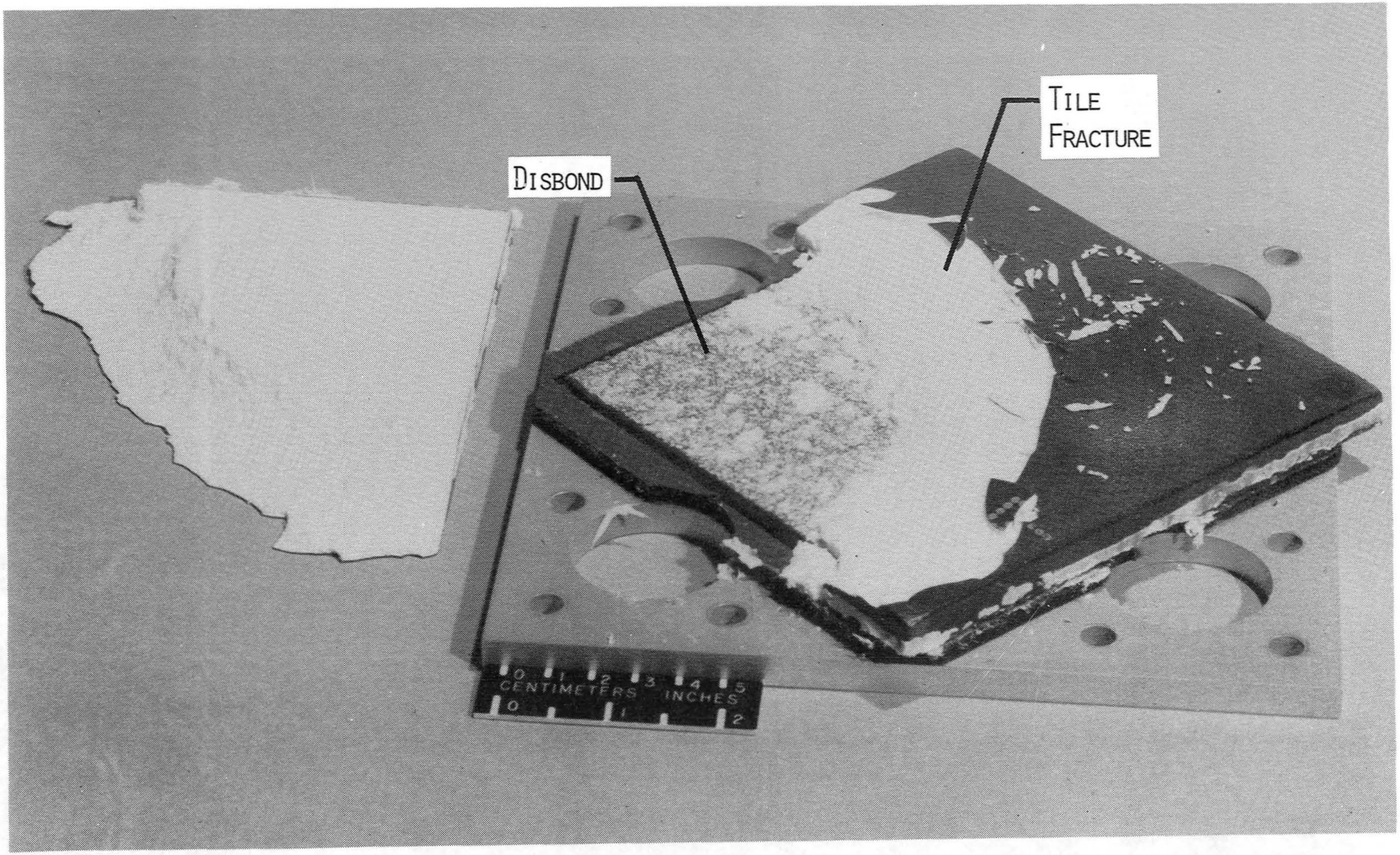


Figure 11. - Thin tile fracture following peel disbond at one corner.

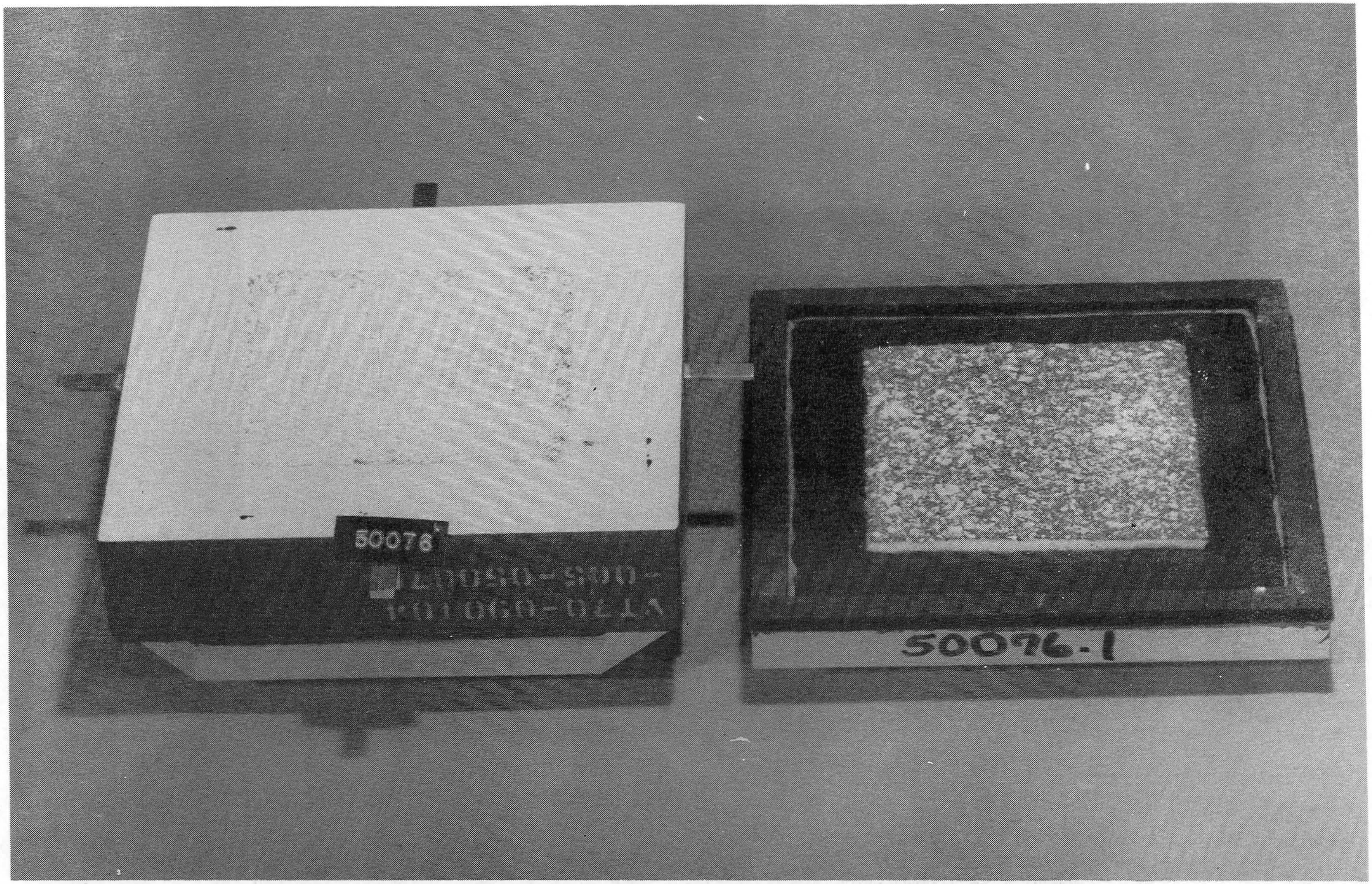


Figure 12. - Failure surface of LI 900 tile with reduced SIP area.

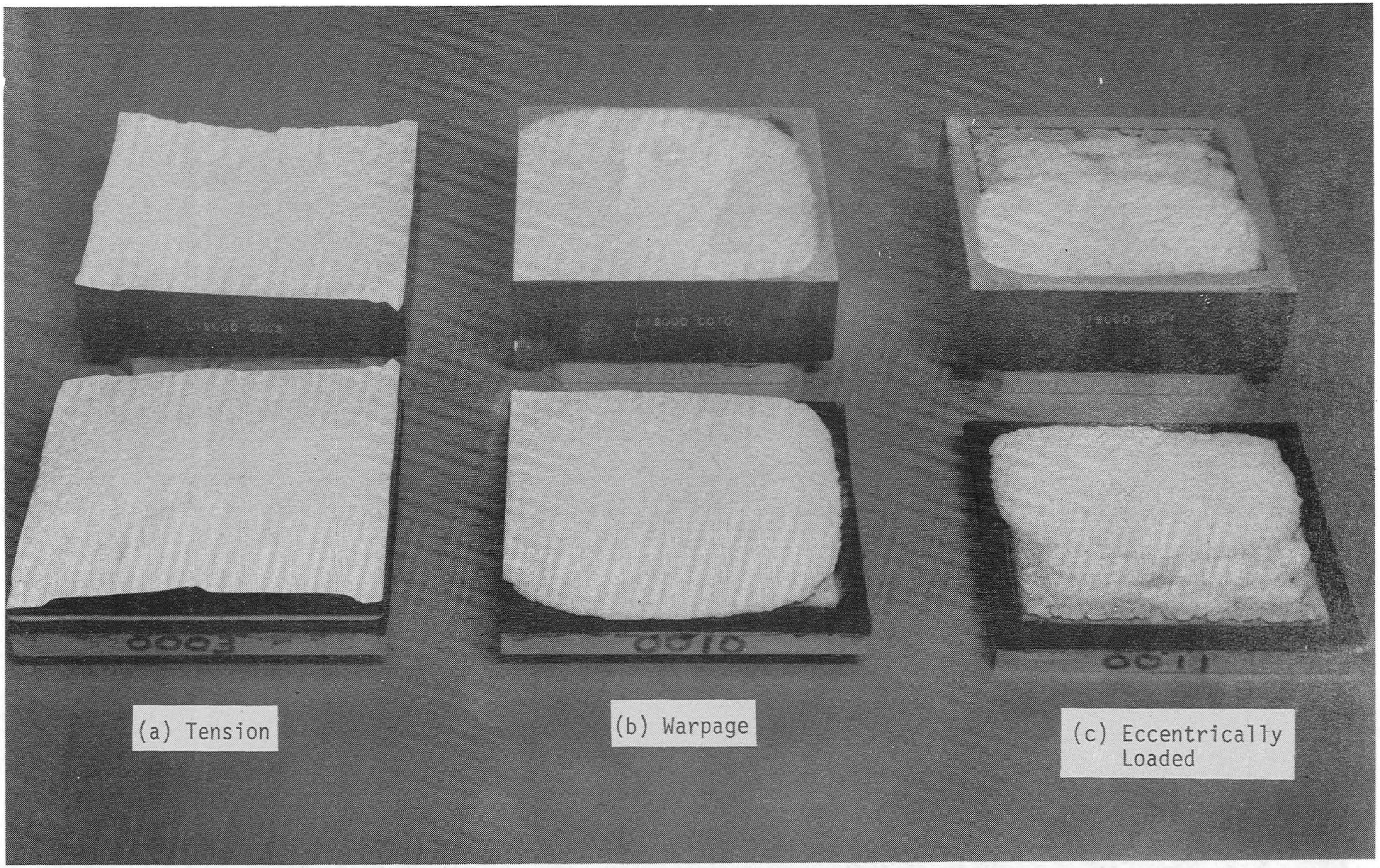


Figure 13. - Typical failure modes for LI 900-densified specimens.

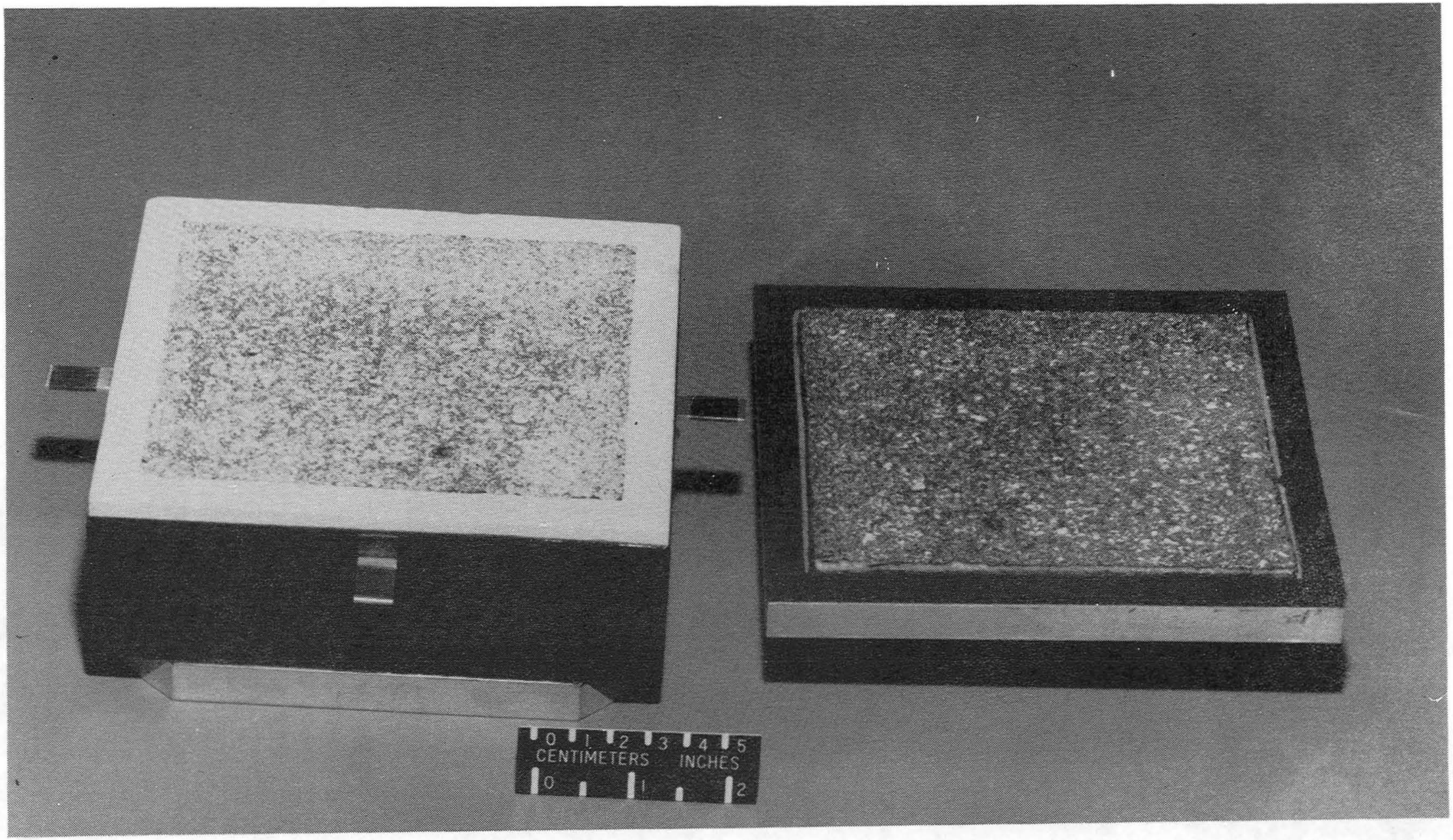


Figure 14. - Typical failure mode for LI 2200 specimens.

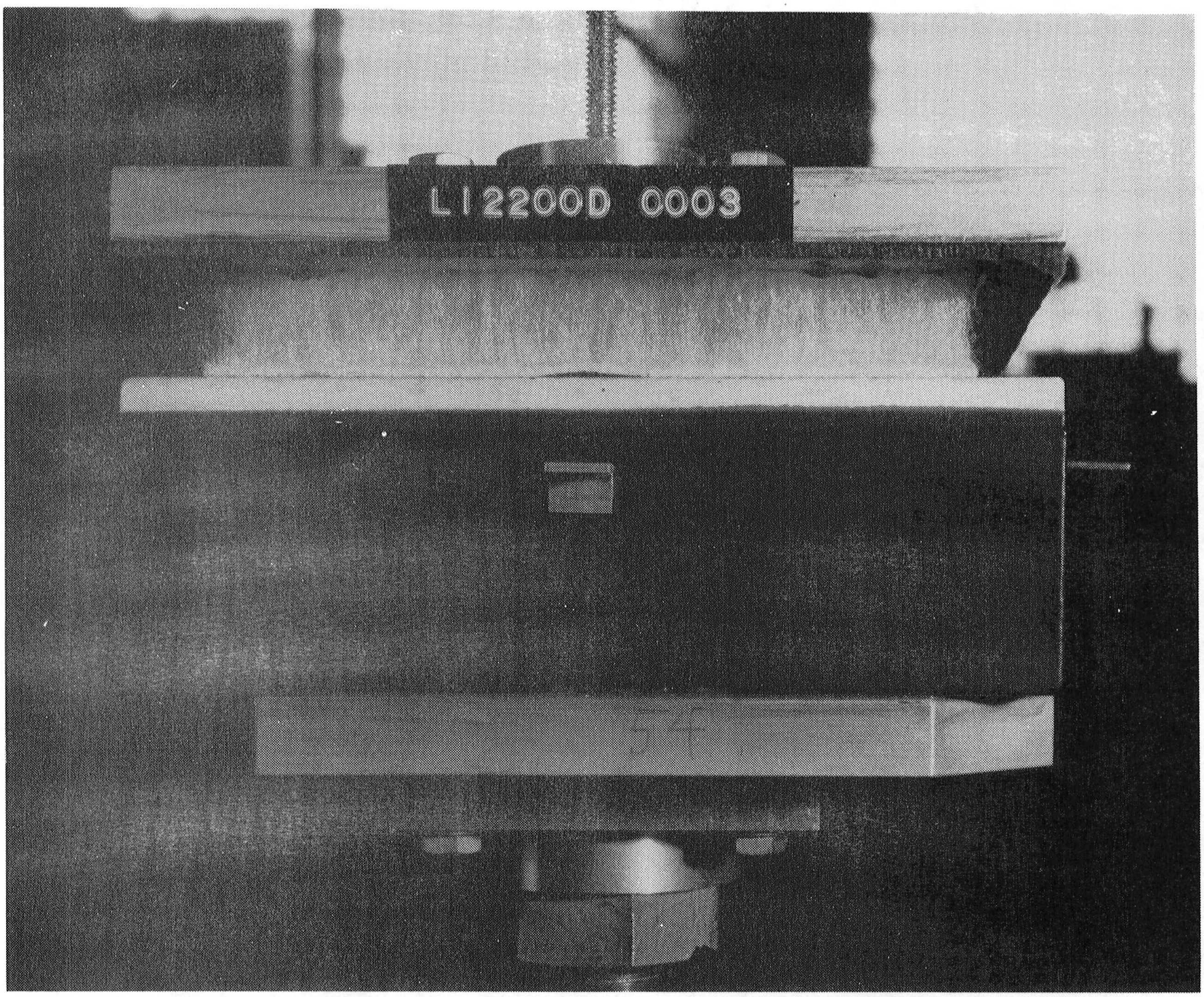


Figure 15. - Typical failure mode for LI 2200-densified specimens.

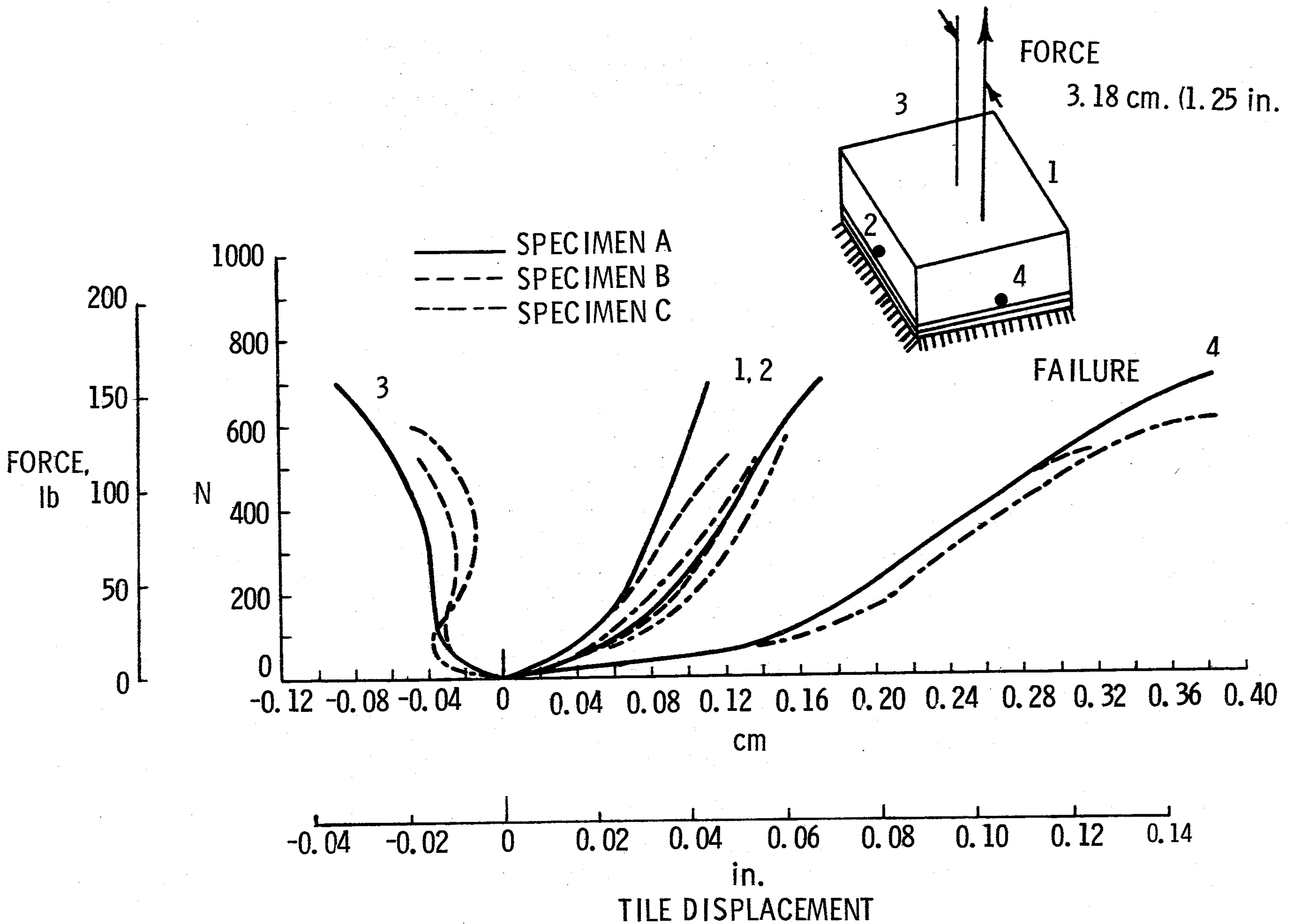


Figure 16. - Displacement response for LI 900 tile/0.41 cm (0.16 in.) SIP specimens with 3.18 cm (1.25 in.) load eccentricity.

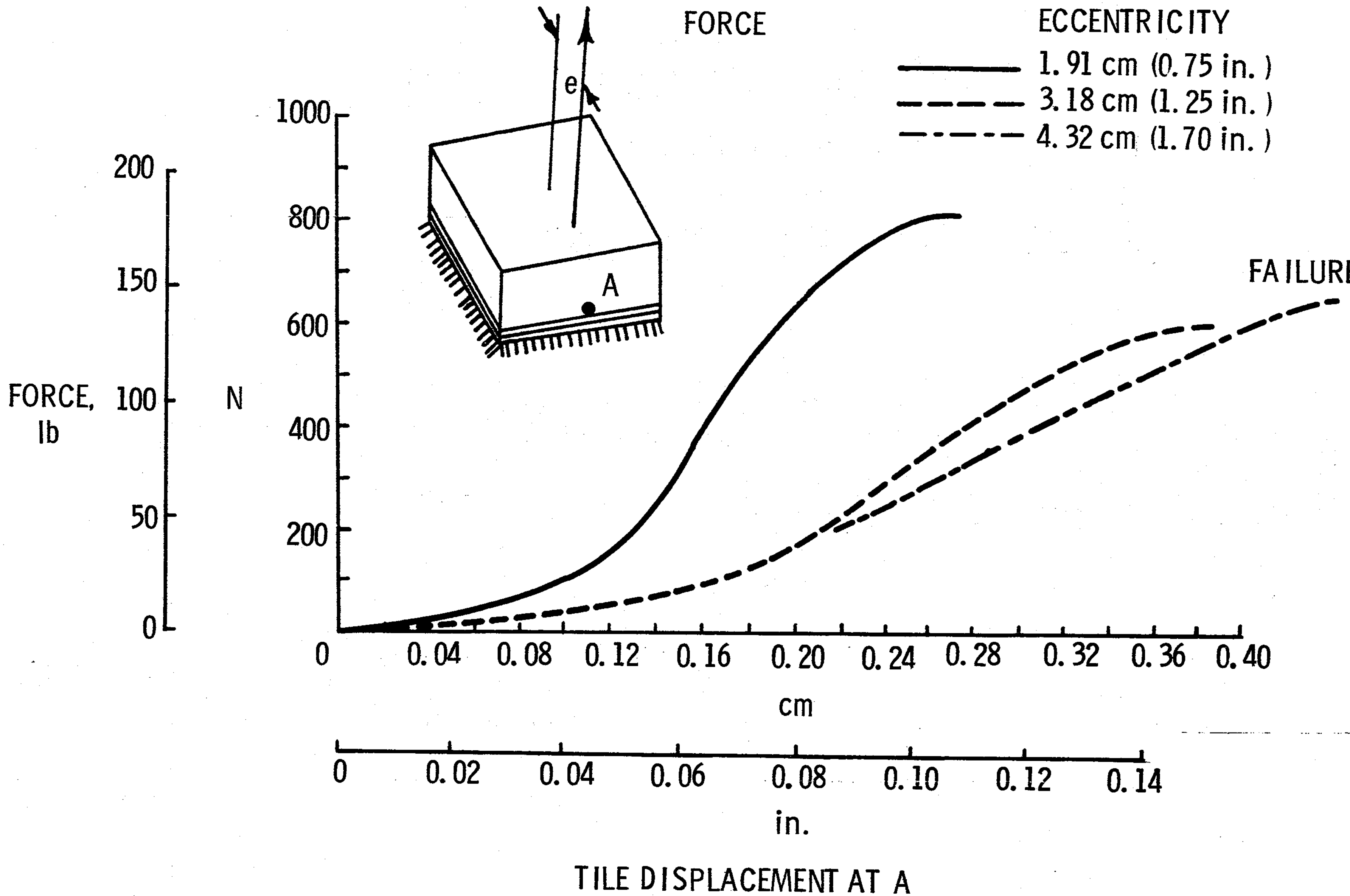


Figure 17. - Displacement response for LI 900 tile/0.41 cm (0.16 in.) SIP specimens loaded with selected magnitudes of eccentricity.

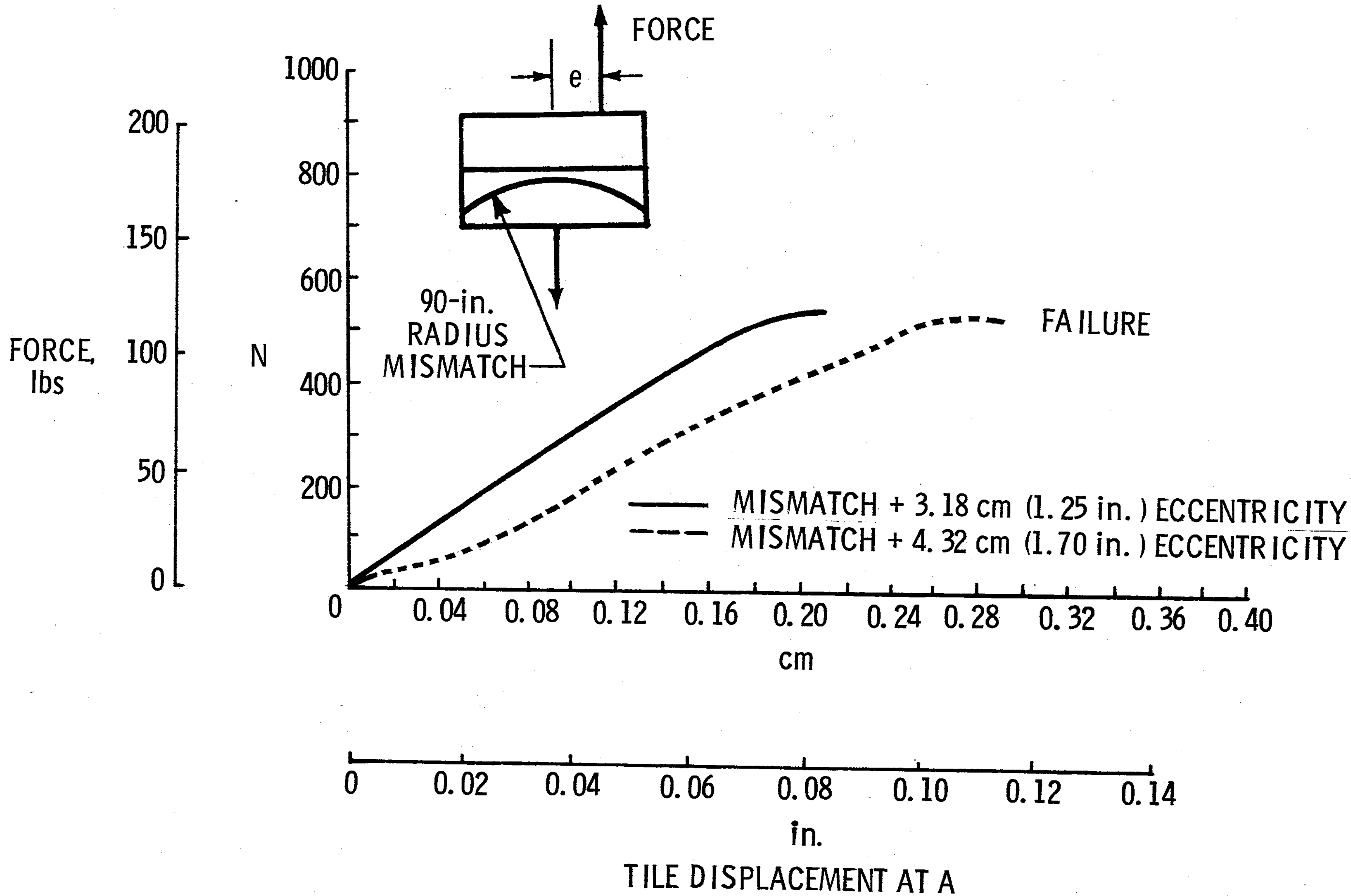


Figure 18. - Displacement response for LI 900 tile/0.41 cm (0.16 in.) SIP specimens with substrate mismatch and eccentrically loaded.

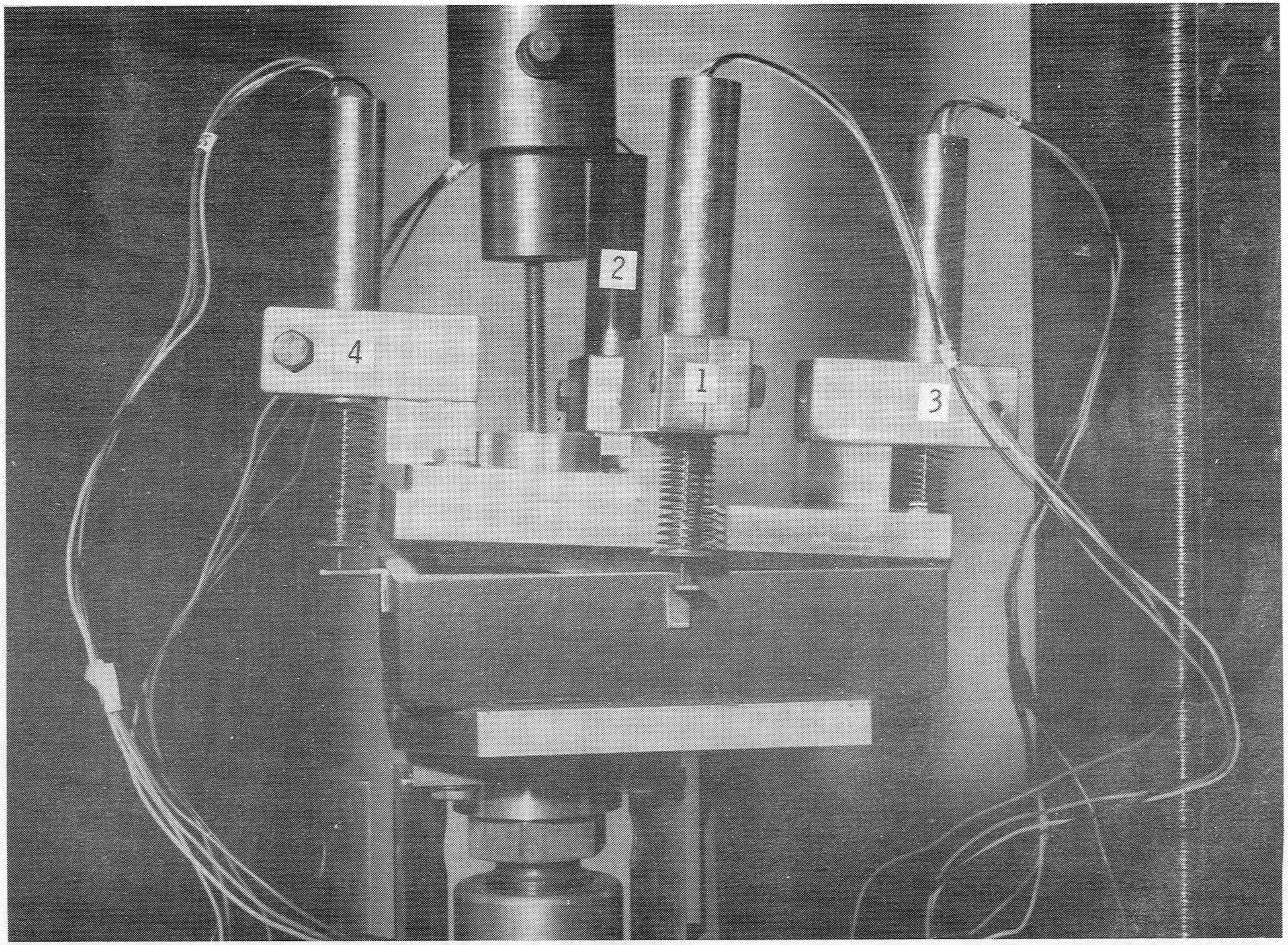


Figure 19. - Photograph illustrating tile rotation and failure in region of maximum stress under eccentrically applied tension loading. LI 900 specimen.

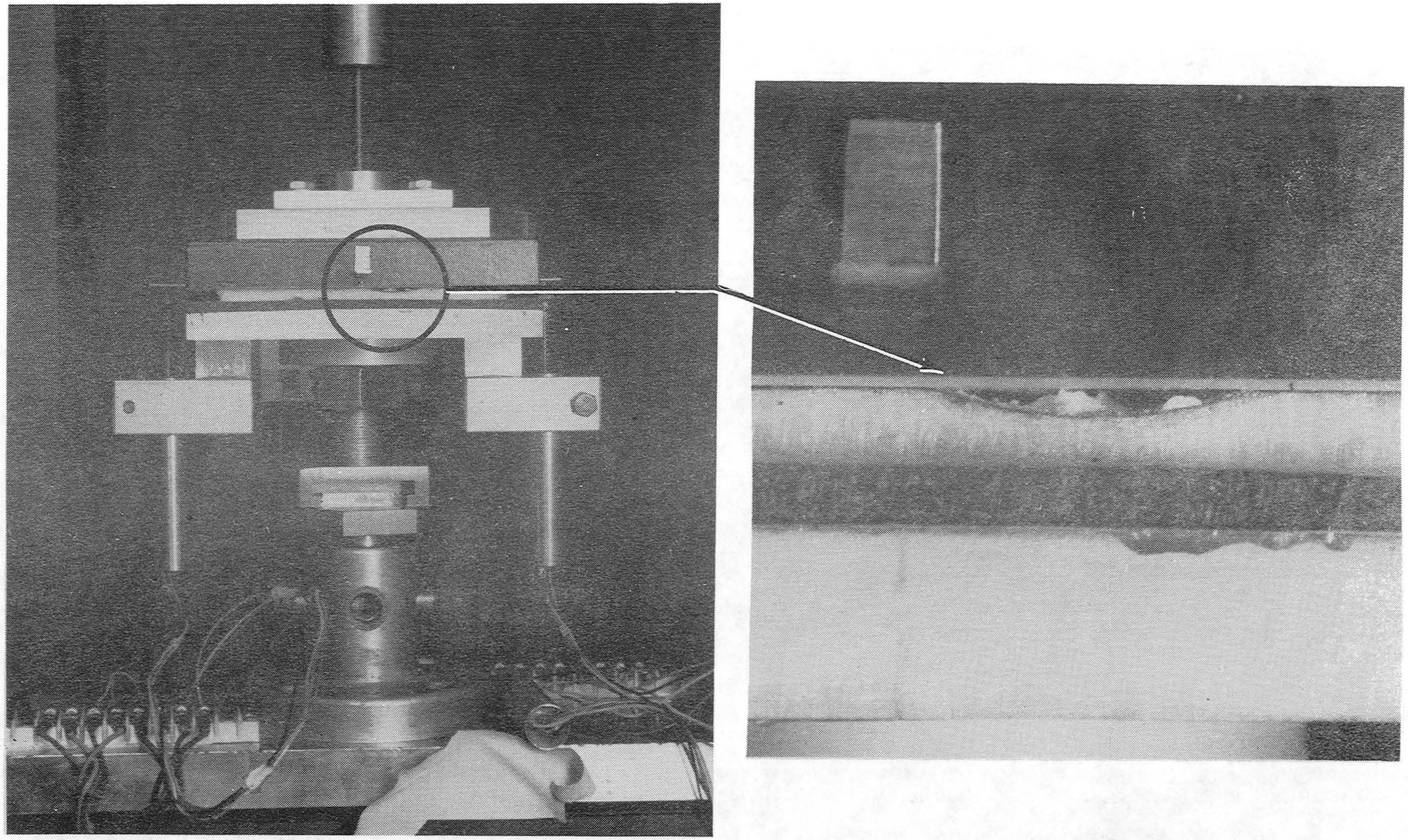


Figure 20. - LI 900 specimen with warpage showing initiation of failure near the center of the edge of maximum tension.

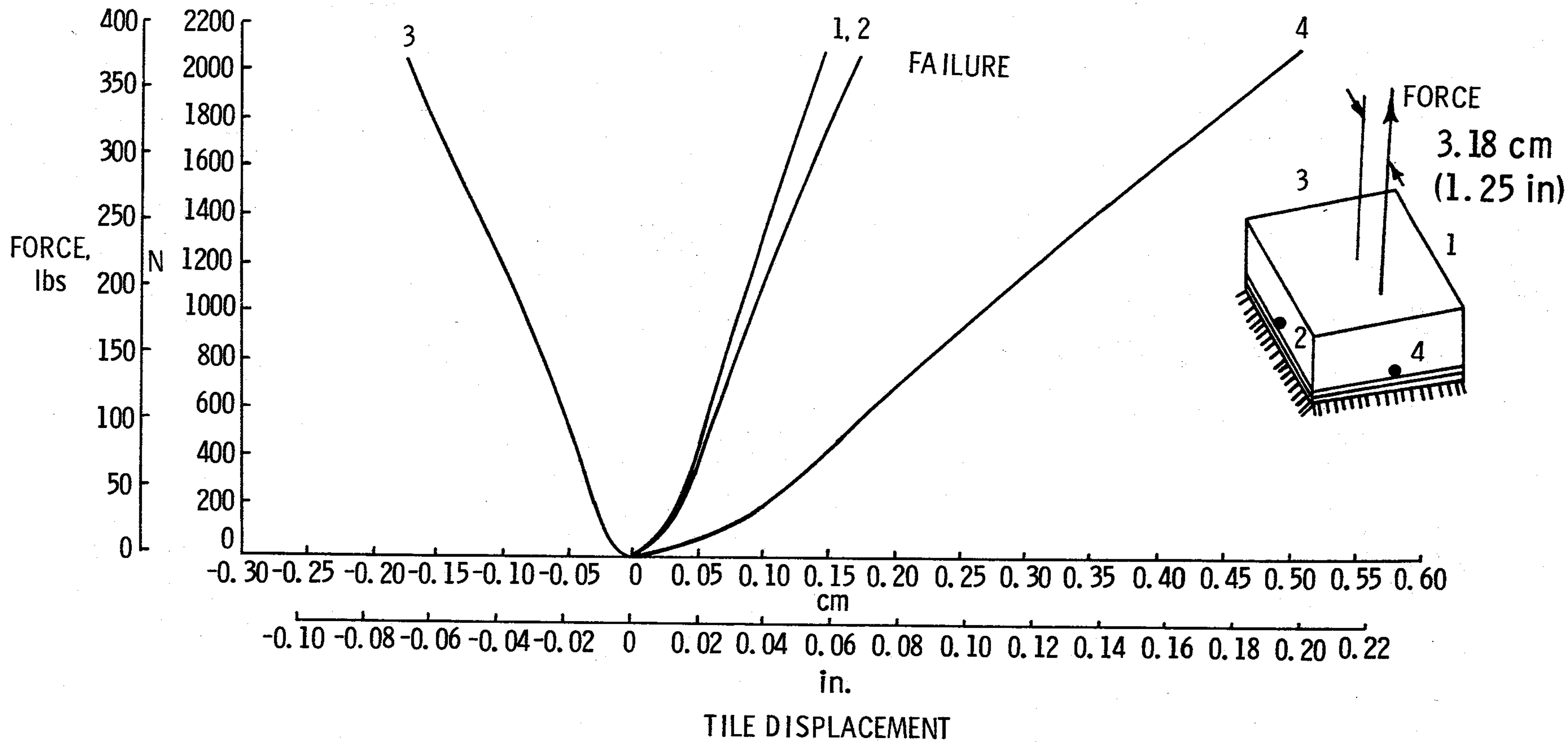


Figure 21. - Displacement response for LI 900-densified tile/0.41 cm (0.16 in.) SIP specimen with 3.18 cm (1.25 in.) load eccentricity.

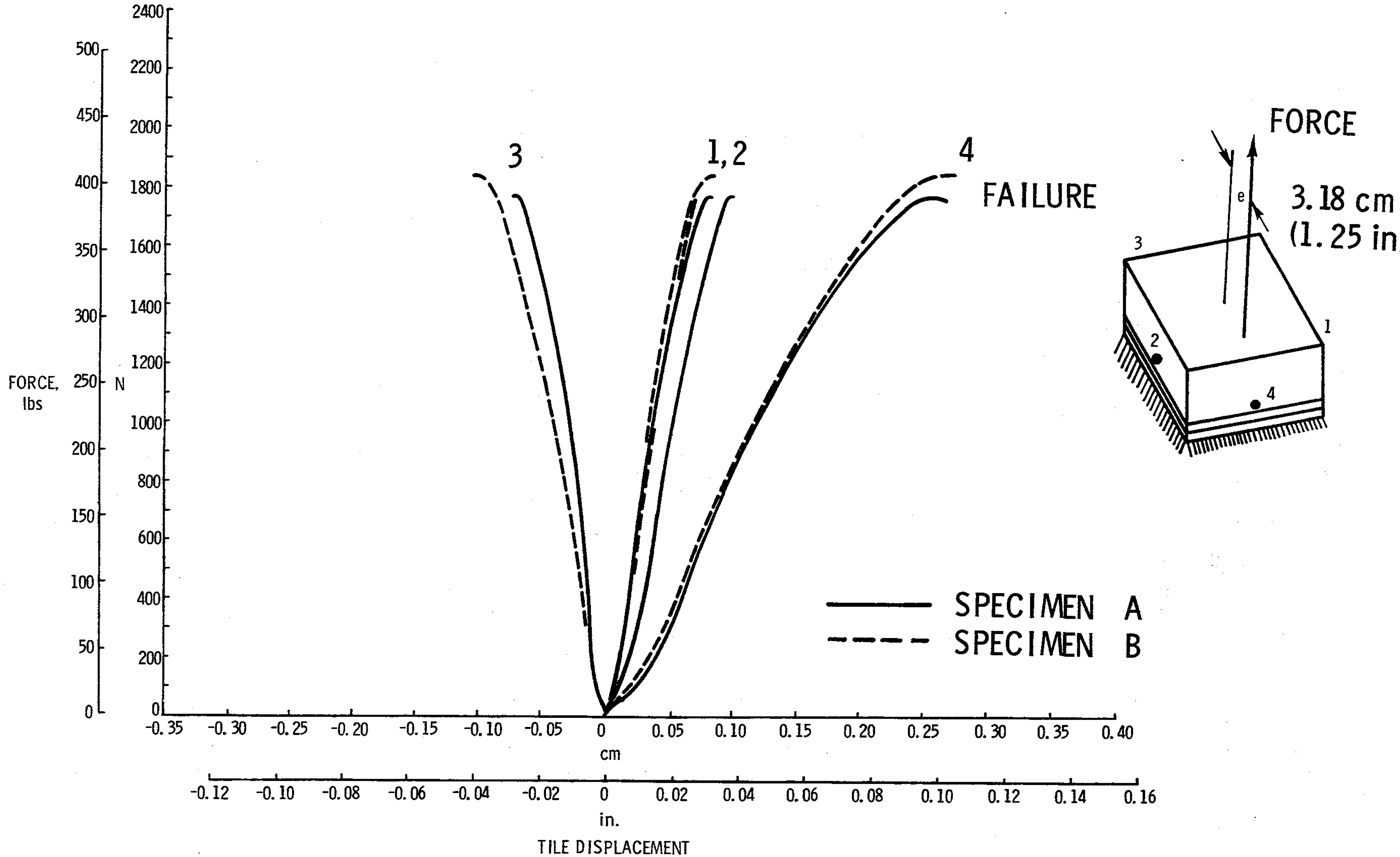


Figure 22. - Displacement response for LI 2200 tile/0.23 cm (0.09 in.) SIP specimens with 3.18 cm (1.25 in.) load eccentricity.

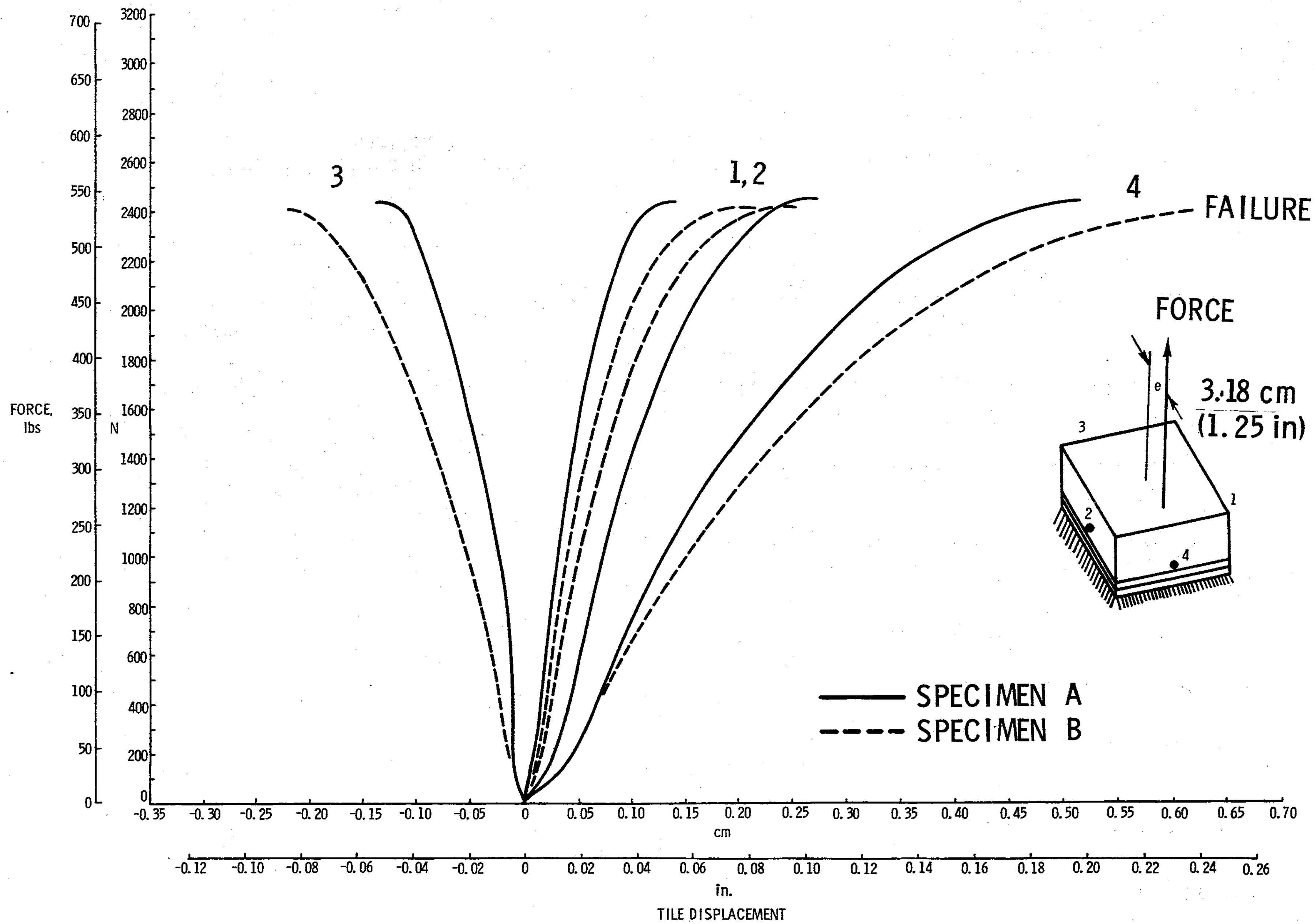


Figure 23. - Displacement response for LI 2200-densified tile/0.23 cm (0.09 in.) SIP specimens with 3.18 cm (1.25 in.) load eccentricity.

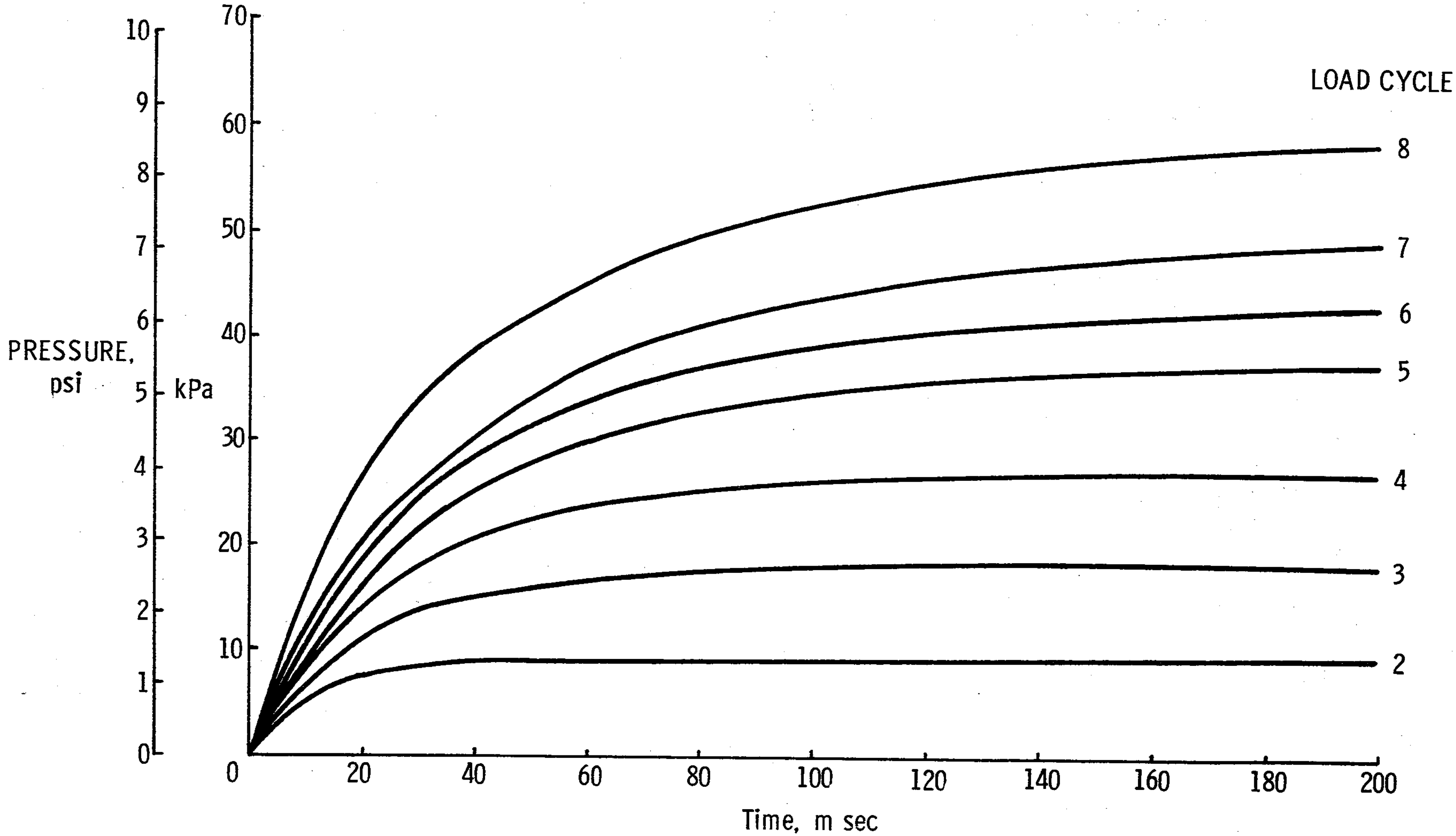


Figure 24. - Pressure response as a function of time for pressure shock loads applied to half of tile top surface.

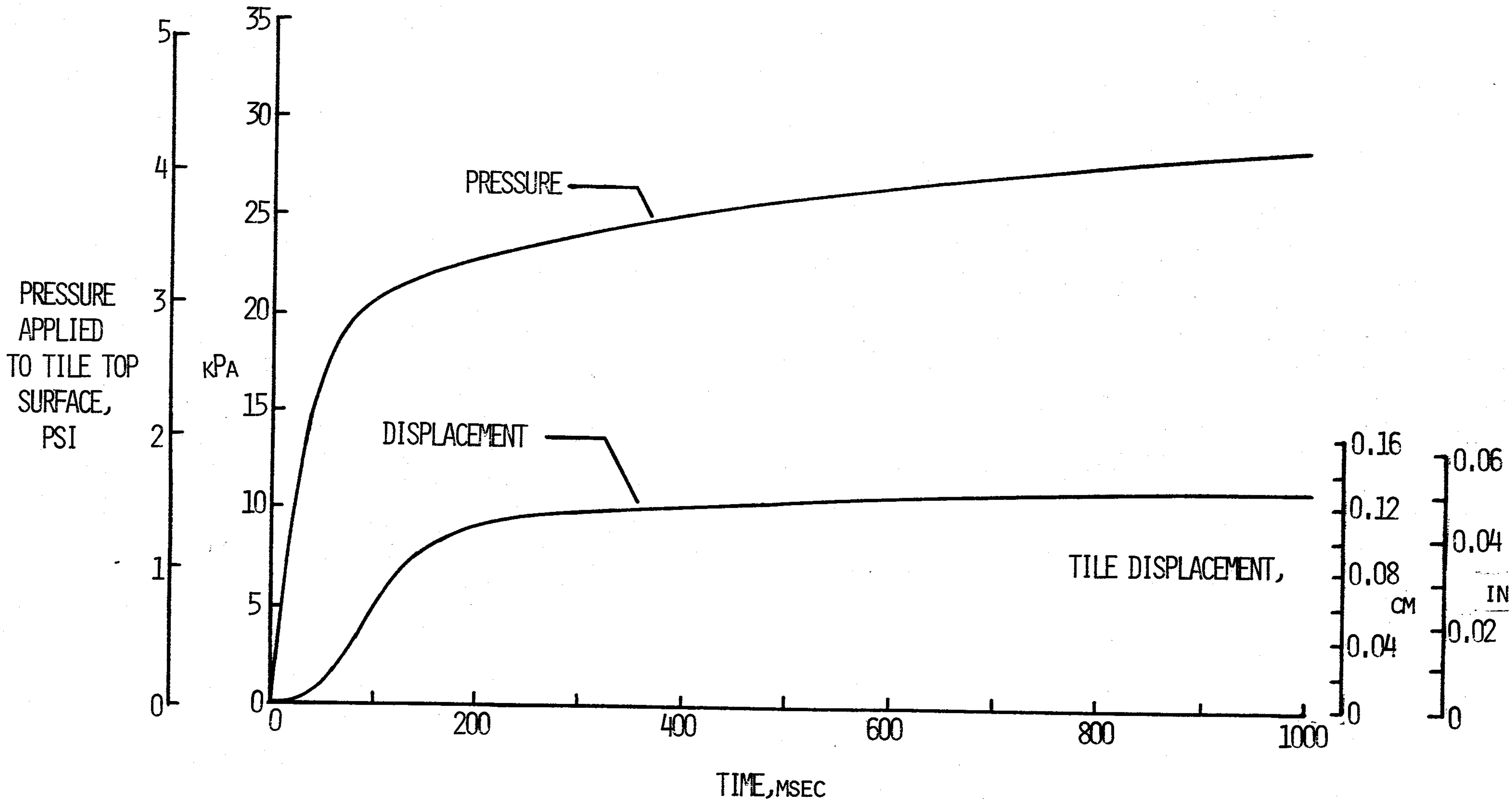


Figure 25. - Pressure and displacement time history for LI 900/0.41 cm (0.16 in.) SIP specimen loaded by transverse pressure tension shock applied to entire top surface of tile. Data presented for last cycle of 50 cycle sequence. Specimen carried shock load sequence without failure.

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16. Abstract

Structural tests were conducted on thermal protection systems (TPS) including LI 900 and LI 2200 tiles and .41 cm (.16 in.) and .23 cm (.09 in.) thick strain isolation pads (SIP). In addition, the bond surface of selected tiles was densified to obtain improved strength. Four basic types of experiments were conducted including tension tests, substrate mismatch (initial imperfection) tests, tension loads eccentrically applied, and pressure loads applied rapidly to the tile top surface. A small initial imperfection mismatch (2.29 m (90 in.) spherical radius on the substrate) did not influence significantly the ultimate failure strength. Densification of the tile bond region improved the strength of TPS constructed both of LI 900 tile and of LI 2200 tile. Pressure shock conditions studied did not significantly affect the TPS strength.

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