NASA Technical Memorandum 81899

FATIGUE PROPERTIES OF SHUTTLE THERMAL PROTECTION SYSTEM

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(NASA-TM-81899) FATIGUE PROPERTIES OF SHUTTLE THERMAL PROTECTION SYSTEM (NASA) 25 p HC A02/MF A01 CSCL 20K

N81-14346

Unclas
G3/39 29585

November 1980

National Aeronautics and
Space Administration

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Summary

Static and cyclic load tests were conducted to determine the static and fatigue strength of the RSI tile/SIP thermal protection system used on the orbiter of the Space Shuttle. The material systems investigated include the densified and undensified LI-900 tile system on the .40 cm (.160 inch) thick SIP and the densified and undensified LI-2200 tile system on the .23 cm (.090 inch) thick SIP. The tests were conducted at room temperature with a fully reversed uniform cyclic loading at 1 Hertz. Cyclic loading causes a relatively large reduction in the stress level that each of the SIP/tile systems can withstand for a small number of cycles. For example, the average static strength of the .40 cm (.160 inch) thick SIP/LI-900 tile system is reduced from 86 kPa (12.5 psi) to 62 kPa (9 psi) for a thousand cycles. Although the .23 cm (.090 inch) thick SIP/LI-2200 tile system has a higher static strength, similar reductions in the fatigue strength are noted. Densifying the faying surface of the RSI tile changes the failure mode from the SIP/tile interface to the parent RSI or the SIP and thus greatly increases the static strength of the system. Fatigue failure for the densified tile system, however, occurs due to complete separation or excessive elongation of the SIP and the fatigue strength is only slightly greater than that for the undensified tile system.

Introduction

The thermal protection system (TPS) used for high heating areas of the space shuttle orbiter is composed of tile arrays of reusable surface insulation (RSI). The arrays are composed of fibrous silica tiles bonded to nomex felt strain isolation pads (SIP) using RTV 560 adhesive. The tile/SIP combination is, in turn, bonded to the external orbiter aluminum skin surface using RTV 560. During ascent and descent of the orbiter, the TPS are subjected to a variety of repetitive loads caused by static and vibratory motion of the aluminum skin substructure, liftoff and aerodynamic boundary layer and transonic shock passage dynamic loadings, aerodynamic pressure gradient, and differential pressures across transonic shocks. The SIP transfers much of the load transverse to the pad along bundles of fibers created during the manufacturing of the pad. Load transfer through the bundles, spaced approximately .25 cm (.1 inch) apart, cause local stress concentrations in the RSI at the RSI/SIP interface surface which reduces the ultimate strength of the TPS below the strength of either the RSI or the SIP alone.

The loads, although possibly not high enough to cause a static failure of the TPS, could, because of the local stress concentrations and repetitive loading, cause cumulative damage resulting in failure of the TPS either from excessive extension of the SIP disrupting the air flow, or from complete separation from the aluminum substructure. Loadings on the TPS during flight are expected to be random and occur at high strain rates, however, to evaluate the degree of susceptibility to fatigue failure of the TPS material system, a series of fatigue tests were performed using sinusoidal fully reversed applied loads.

Tests were conducted and the results reported herein for four tile density configurations and two SIP thicknesses. The possible significance of the test results in the use of these thermal protection systems is discussed.

Specimens and Tests

Specimens

Materials: The materials considered in this investigation include the undensified and densified LI-900 and 2200 RSI tiles, .41 cm (.160 inch) and .23 cm (.090 inch) thick SIP, and RTV-560 adhesive. These materials form the basis of the thermal protection system used for the shuttle orbiter. The LI-900 and 2200 RSI tiles are made from rigidized silica fibers, have a density of about 145 kg/m^3 (9 lb/ft^3), and 354 kg/m^3 (22 lb/ft^3) respectively, and insulate the primary air frame from the entry heat pulse. Some of the LI-900 and 2200 tiles were densified by applying a ceramic slurry to the tile surface next to the SIP/tile interface. The slurry is a mixture of Ludox which is a collodial silica and a silica slip with small particles of silica. A controlled amount of this mixture is brushed on the faying surface of the tile. On drying, this mixture provides a hard, strong, densified layer approximately .25 cm (.1 inch) thick. The SIP is a needled (non-woven) Nomex felt and is used as a strain isolator pad (SIP) between the RSI tiles and the aluminum primary structure of the vehicle. The RTV-560 is a silicone rubber adhesive which cures at room temperature. It is used to bond the RSI tile to the SIP and the SIP to the skin of the vehicle.

The tile and SIP material were obtained from the same supply as that for the shuttle. The tiles with the densified coating were supplied by Rockwell International. Fresh RTV-560 was obtained from the manufacturer to insure that the shelf life had not been exceeded. All specimen support fixtures were made from 2024-T4 aluminum. Aluminum fixture surfaces that were to be bonded to test specimens were chemically etched, sprayed with a protective primer (Koropon), and vacuum baked to remove all volatiles. The bonding procedure used to make the specimens is a very close duplicate of that used on the actual shuttle. The bonding and quality control personnel received special training at JFK Center to insure that the correct procedure was used in making the specimens. Care was taken to insure that the RTV had cured to a Shore hardness of 50 or greater before testing the specimen.

Configurations: Detail dimensions of the poker-chip specimens used in the present investigation are shown in figures 1(a), and 1(b), respectively for the undensified and densified tile systems. The test materials are bonded between two aluminum blanks 5.72 cm (2.25 inches) in diameter with a .8 cm (.3 inch) diameter alignment pin hole through the center. The SIP and tile were bonded together and to the aluminum blanks using a .018 cm (.007 inch) thick layer of RTV-560 adhesive. For the densified tile specimens, the densified surface is bonded to the SIP. An alignment pin is inserted through the center of the aluminum blank and the test material while bonding and during the cure of the adhesive, but is removed before testing the specimen. The tile material was 1.59 cm (.62 inches) thick for the undensified tiles and 2.54 cm (1.00 inches) thick for the densified tiles. SIP materials with thicknesses of .41 cm (.160 inch) and .23 cm (.090 inch) were tested.

Tests

All tests were conducted on a hydraulically actuated test machine that can be operated in either the load or displacement control mode. A 890 newton (200 lb) tension-compression load cell was used to measure the load applied to the specimen and to control the test machine when in the load control mode. Specimen displacement was measured using an LDVT which indicated testing machine head motion. Data were recorded or monitored using a x-y recorder, an oscilloscope, a maximum digital voltmeter, and a mechanical counter.

The test setup is shown by the photograph in figure 2. The procedure followed in setting up a test is to zero the load cell with the upper half of a typical specimen attached to the load cell. The test specimen is then attached to the load cell and alignment checked using a dial indicator as shown in figure 3. The base of the dial indicator is mounted on the hydraulic ram and the ram rotated while noting the indicated runout. If the runout is greater than .025 cm (.010 inches), shims are installed between the load cell and the specimen to reduce the runout to within the indicated limit. After satisfactory alignment, installation of the specimen is completed with the test machine in the displacement control mode. The test machine control mode is then switched to load control which removes any residual setup loads. The x-y recorder and oscilloscope is then calibrated and the counter reset.

All tests were run at one cycle per second with a fully reversed ($R = -1$) sinusoidal load cycle. Startup of the test was begun at a low load level to prevent shock loading the material and then the load rapidly increased to the test level. Test levels were reached less than 25 cycles into the tests. During the tests, the lateral movement of the specimen was monitored using a dial gage as shown in figure 4. Total lateral movement was less than .020 cm (.008 inches) for each test. The load wave form was monitored using the oscilloscope to insure that all specimens received the same loading cycle. A typical load wave form is shown in figure 5 and a typical stress-displacement curve is shown in figure 6. The flat portion of the load curve near zero load (fig. 5) indicates that the test machine is not able to maintain a sinusoidal load curve. The difficulty in providing the desired load wave form is evident in figure 6 where near zero stress levels, large displacements are required to obtain small changes in stress level. Although the test machine is not able to maintain the desired sinusoidal load curve, the smoothness of the load curve (figure 5) indicates that the material was not subjected to shock loadings.

Results and Discussion

A summary of the results of the cyclic load tests are shown as follows: Figure 7 for the .160 SIP/LI-900 tile system, figure 8 for the .090 SIP/LI-2200 tile system, figure 9 for the .160 SIP/LI-900 densified tile system, and figure 10 for the .090 SIP/LI-2200 densified tile system. The stress levels are shown as a function of the number of fully reversed (R = -1) cycles to failure for each SIP/tile system. The dashed line on each figure is a least squares fit of the test results where the intersection at 1 cycle shown as a solid symbol is the mean static failure stress of at least 45 tests performed by Rockwell International, the prime contractor for the shuttle orbiter. The Rockwell static tensile tests were performed on square specimens, where the tile was 15.24 x 15.24 cm (6 x 6 inch) and a SIP planform of 12.70 x 12.70 cm (5 x 5 inch), and where stress in the SIP is reported. A small number of static tests were performed during the current fatigue program and results are plotted at the one cycle location as open symbols. For figures 9 and 10, static failure occurs in the RSI whereas for cyclic loading, failure occurs in the SIP. The static results fell above the Rockwell means results for the .160 SIP/LI-900 RSI tile system and below the Rockwell mean results for the .090 SIP/LI-2200 RSI tile system. In both cases, the results were well within two standard deviations of the Rockwell static results.

The dashed curves are based on only a few test data points and are meant to provide the reader with a general rather than specific indication of the fatigue behavior of the RSI/SIP thermal protection system. Several factors not considered in the test program would tend to lower the expected lifetime below that suggested by the indicated curves for an actual tile on the orbiter. These factors include material process control variations, installation variables, and the effect of cumulative damage which might occur at lower stresses during a given flight mission or as a result of a static proof test before a flight mission. Similarly, several factors not considered in this test program would tend to raise the expected lifetime as determined from the indicated curves. These factors include higher testing rates, R values greater than -1, and an increase in specimen cross-section size.

Undensified Tile Results

Cyclic loading results in a relatively large reduction in the stress level that each of the SIP/tile systems can withstand for a small number of cycles. For the .160 SIP/LI-900 undensified tile system (Fig. 7), the strength is reduced from approximately 81 kPa (11.7 psi) average static strength to 62 kPa (9 psi) fatigue strength after a thousand cycles. For the .090 SIP/LI-2200 undensified tile system (Fig. 8), the average static strength is reduced from approximately 198 kPa (28.7 psi) to 117 kPa (17 psi) fatigue strength after a thousand cycles. Failures in both the LI-900 and LI-2200 undensified tile systems occur at the SIP/tile interface. The .090 SIP/LI-2200 RSI tile system shows a considerable improvement in lifetime in comparison to the .160 SIP/LI-900 RSI tile system. For example, at 69 kPa (10 psi) the .160 SIP/LI-900 RSI tile system will fail on the average at about 100 cycles whereas the .090 SIP/LI-2200 RSI tile system will survive on the average for 70,000 cycles.

Densified Tile Results

The flatwise ultimate tensile strengths of the RSI tiles, the SIP, and the total protection system, i.e. RSI tile/RTV/SIP/RTV/aluminum have been determined experimentally by Rockwell International Corporation. It was found that the average ultimate strength of the individual components, the RSI tile, RTV, and SIP considerably exceeded the average ultimate strength of the combined system as shown in Table 1. The SIP is composed of a mat of fibers lying in a plane and held together by discrete bundles of transverse fibers. These transverse fiber bundles are composed of inplane fibers pulled through the mat by barbed needles during manufacture of the pad. The reduced strength of the system is attributed to stress concentrations at the SIP/tile interface caused by discrete load transfer across the SIP occurring mainly at the fiber bundles as shown in reference 1. Densification of the tile surface strengthens the SIP/tile interface sufficiently that failure occurs in the RSI above the densified region for the LI-900 RSI and either the RSI above the densified region or the SIP for the LI-2200 RSI tiles. As shown in Table 1, densification of the .160 SIP/LI-900 tile system increases the average static strength from 81 kPa (11.7 psi) to 154 kPa (22.3 psi) and for the .090 SIP/LI-2200 tile system, from 198 kPa (28.7 psi) to 319 kPa (46.3 psi).

For a densified tile thermal protection system, fatigue failure of the SIP during cyclic loading occurs due to excessive elongation of the SIP material. Figure 11 shows typical load deflection curves for the .160 SIP after various load cycles. Each load cycle results in slightly increased elongation of the SIP during the tension portion of the cycle until complete separation failure occurs. Mission failure due to excessive elongation may occur before complete separation in either the RSI or the SIP takes place. Large elongations of the

SIP can allow a tile to move into the airstream during reentry and disrupt the laminary boundary layer creating premature flow transition which in turn can cause excessive heating downstream. Figure 11 shows that the SIP undergoes a rapid fatigue extension at a low number of cycles. After only 75 cycles at $\pm$69 kPa (10 psi) total tile motion is .41 cm (.16 inches). Of more importance, the major portion of this displacement occurs under very low loads. For example, the tile can undergo a displacement of .25 cm (.10 inches) when subjected to a stress between $\pm$7 kPa ($\pm$1 psi). Practically, this degree of tile looseness would mean that a tile once subjected to a low number of stress reversals could be positioned anywhere within a .25 cm (.10 inch) range.

For the .160 SIP/LI-900 densified tile system shown in figure 9, failure of the SIP was arbitrarily assumed to have occurred when the elongation between the maximum and minimum loads exceeded .64 cm (.25 in.). According to figure 11, the tile is loose enough so that it can be moved .46 cm (.18 inches) with less than $\pm$7 kPa ($\pm$1 psi) applied stress. Once the total elongation reaches .64 cm (.25 inch), the specimen rapidly deteriorates under further load cycling until complete SIP separation failure occurs. The plus symbols in figure 9 indicate complete separation failure for a few typical specimens. The small numbers beside the symbols identify the specimens for which complete failure is given. For the .090 SIP/LI-2200 densified tile system shown in figure 10, the data points represent complete failures of the SIP material. If a more restrictive elongation criteria is chosen as a failure condition for either SIP/tile system, the degradation in system strength due to cyclic loading would be more severe.

The .160 SIP/LI-900 densified tile system at 69 kPa (10 psi) has a mean lifetime of approximately 15,000 cycles whereas the same system undensified has an expected mean lifetime of only 100 cycles at the same stress level. Similarly, the .090 SIP/LI-2200 densified tile system at 138 kPa (20 psi) has a mean lifetime of approximately 8,000 cycles whereas the same system undensified has an expected mean lifetime of only 200 cycles at the same stress level.

Limitation on Repetition of Proof Tests

A large number of tensile tests of the individual material components; the RSI, SIP, and RTV; were performed before full scale production began to obtain allowable strength predictions. When it was discovered that the system had considerably less strength than the weakest of the individual components, these material allowable values could no longer be used in evaluating the margin-of-safety of the tile at various locations. When a reduced allowable, obtained by statistical extrapolation from a small number of complete system tests (RSI/RTV/SIP/RTV), was used, a large number of tiles already installed on the orbiter had a negative margin. Rather than relying on this lower reduced allowable to predict acceptability of a tile installation, a proof tensile load equal to 1.25 times the maximum stress expected during flight (limit stress) was applied to tiles that were installed on the orbiter. Survival of the applied proof load is an indication that the tile system has sufficient static strength to give a positve margin of safety. If a tile fails the proof test as determined by either separation from the substructure or exceedance of measured noise counts in an acoustic emission test taken during the loading process, it is removed and densified. Any tile whose predicted limit stress dictated a proof stress higher than 10 psi was automatically removed, densified, and reinstalled.

After a mission has been completed, the integrity of a tile/SIP TPS might be reaffirmed by performing another "proof" test to 10 psi. If the tile is undensified and mounted on .160 SIP, the results of figure 7 suggest that the average tile/SIP can survive only slightly over 100 such "proof" tests before complete separation occurs. By applying a scatter factor of 4 to the lifetime and considering that the tile/SIP TPS sustained some degree of cumulative fatigue damage during each flight, the projected life will be less than 25 missions if the tile is proof tested between each mission. Obviously, if undensified tiles will be used for more than one flight, they may not be proof tested to 10 psi between flights and another method to insure integrity must be found.

Concluding Remarks

Static and cyclic load tests were conducted to determine the static and fatigue strength of the RSI tile/SIP thermal protection system used on the orbiter of the Space Shuttle. The material systems investigated include the densified and undensified LI-900 tile system on the .40 cm (.160 inch) thick SIP and the densified and undensified LI-2200 tile system on the .23 cm (.090 inch) thick SIP. The tests were conducted at room temperature with a fully reversed uniform cyclic loading at 1 hertz. Curves showing the number of cycles to failure at various stress levels were obtained for each tile/SIP system.

The test results show that cyclic loading causes a relatively large reduction in the stress level that each of the SIP/tile systems can withstand for a small number of cycles. For example, the average static strength of the .40 cm (.160 inch) thick SIP/LI-900 tile system is reduced from 86 kPa (12.5 psi) to 62 kPa (9 psi) for a thousand cycles. Although the .23 cm (.090 inch) thick SIP/LI-2200 tile system has a higher static strength, similar reductions in the fatigue strength are noted. Densifying the faying surface of the RSI tiles changes the failure mode from the SIP/tile interface to the parent RSI or the SIP. Densification thus greatly increases the static strength of the system but only slightly increases the fatigue strength. The low fatigue life for the densified tile system is due to complete separation or excessive elongation of the SIP. Thus, further improvements in the RSI tile strength will not result in any improvements in the total system fatigue strength.

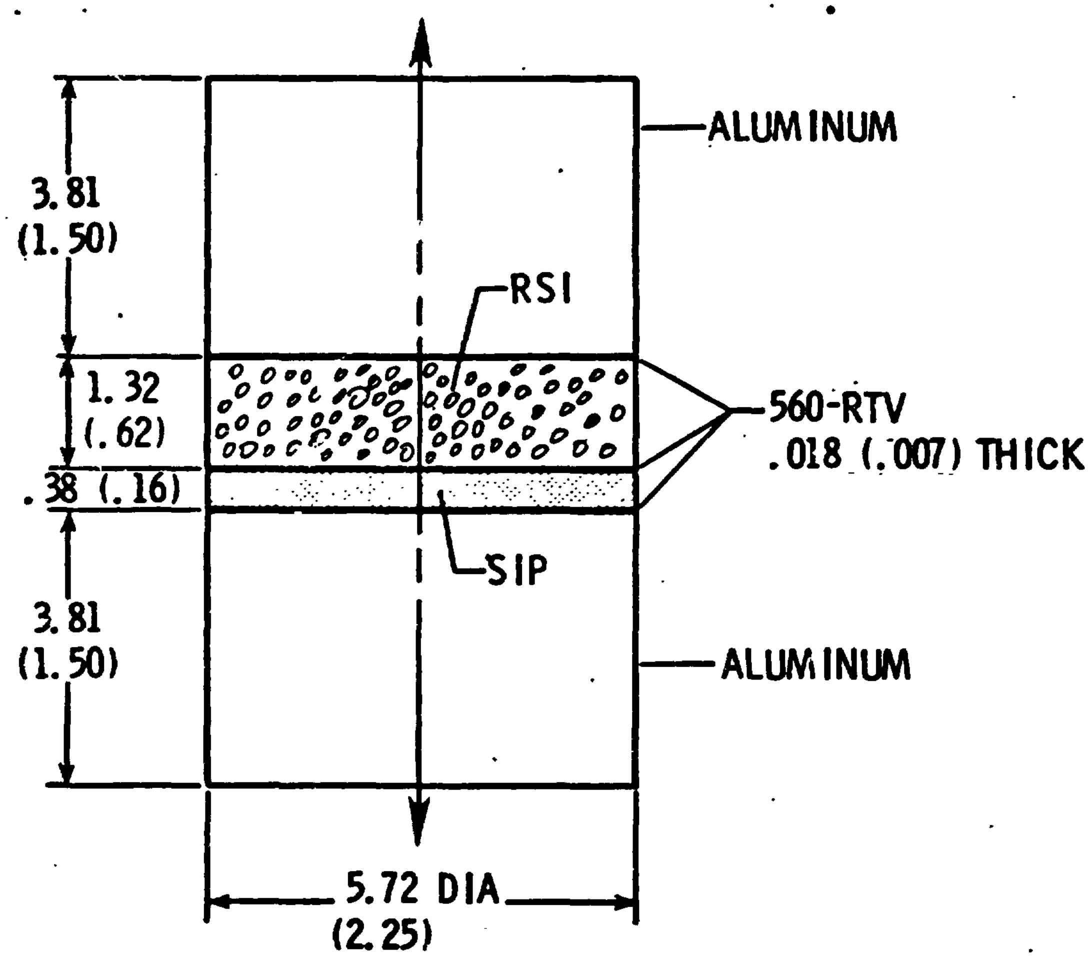
References

1. Prabhakaran, R. and Cooper, Paul A.: "Photoelastic Tests on Models of Thermal Protection System for Space Shuttle Orbiter," NASA Technical Memorandum 81866, August 1980.

TABLE 1 - AVERAGE ULTIMATE TENSILE STRENGTH OF TPS COMPONENTS AND FULL SYSTEM LOADED IN THE DIRECTION NORMAL TO THE BONDED SURFACES

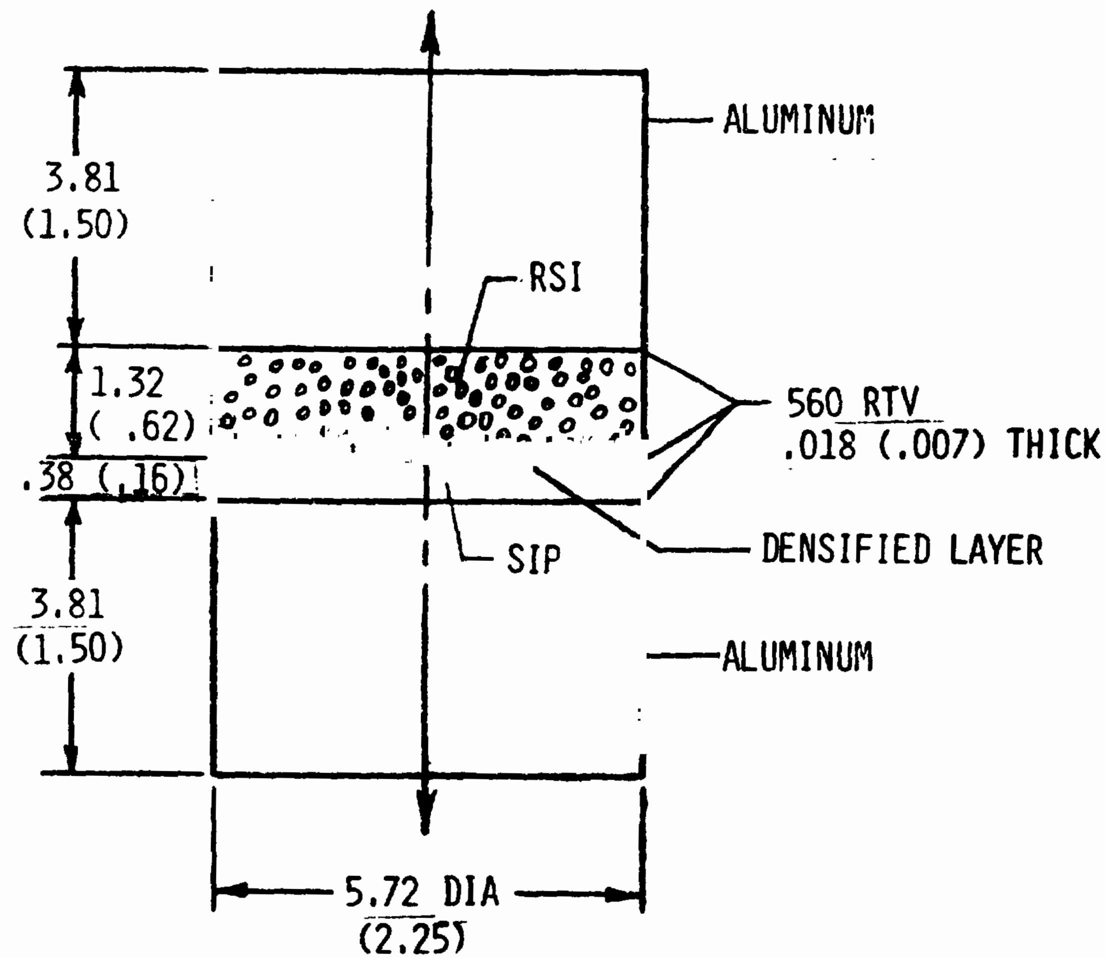
	kPA	PSI
LI 900 RSI	165.5	24*
.160 SIP	288.2	41.8
RTV 560 ADHESIVE	3309.0	480
.160 SIP/LI-900 TILE SYSTEM	80.7	11.7
.160 SIP/LI-900 DENSIFIED TILE SYSTEM	153.7	22.3
LI 2200 RSI	413.6	60
.090 SIP	468.8	68
RTV 560 ADHESIVE	3309.0	480
.090 SIP/LI-2200 TILE SYSTEM	197.9	28.7
.090 SIP/LI-2200 DEN[illegible] TILE SYSTEM	319.2	46.3

* VALUES OBTAINED FROM INTERNAL ROCKWELL INTERNATIONAL CORPORATION DOCUMENTATION.



(a) SIP/Tile system

Figure 1 - Test specimen for SIP/RSI tile system. Dimensions are given in cm (inches).



(b) SIP/Densified tile system

Figure 1 - Concluded

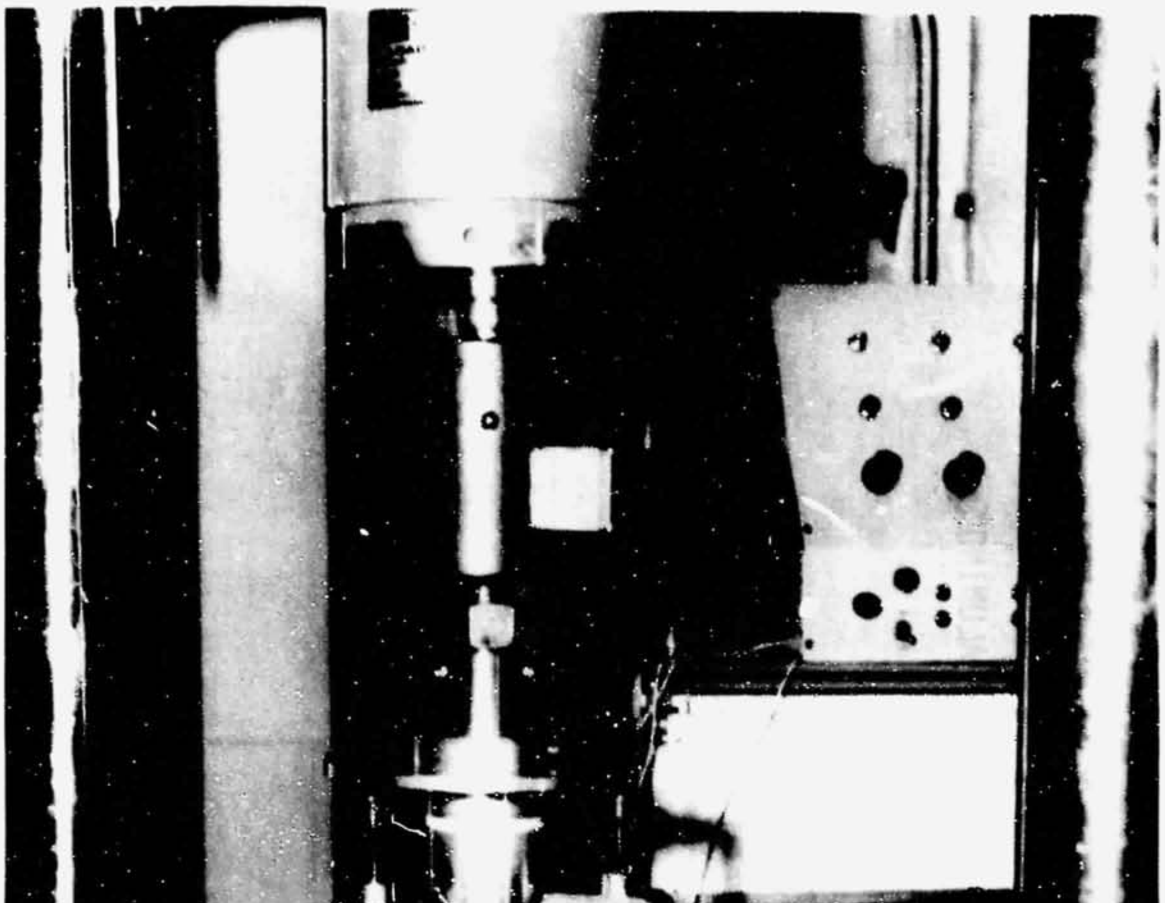


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Figure 2 - Photograph of test setup.

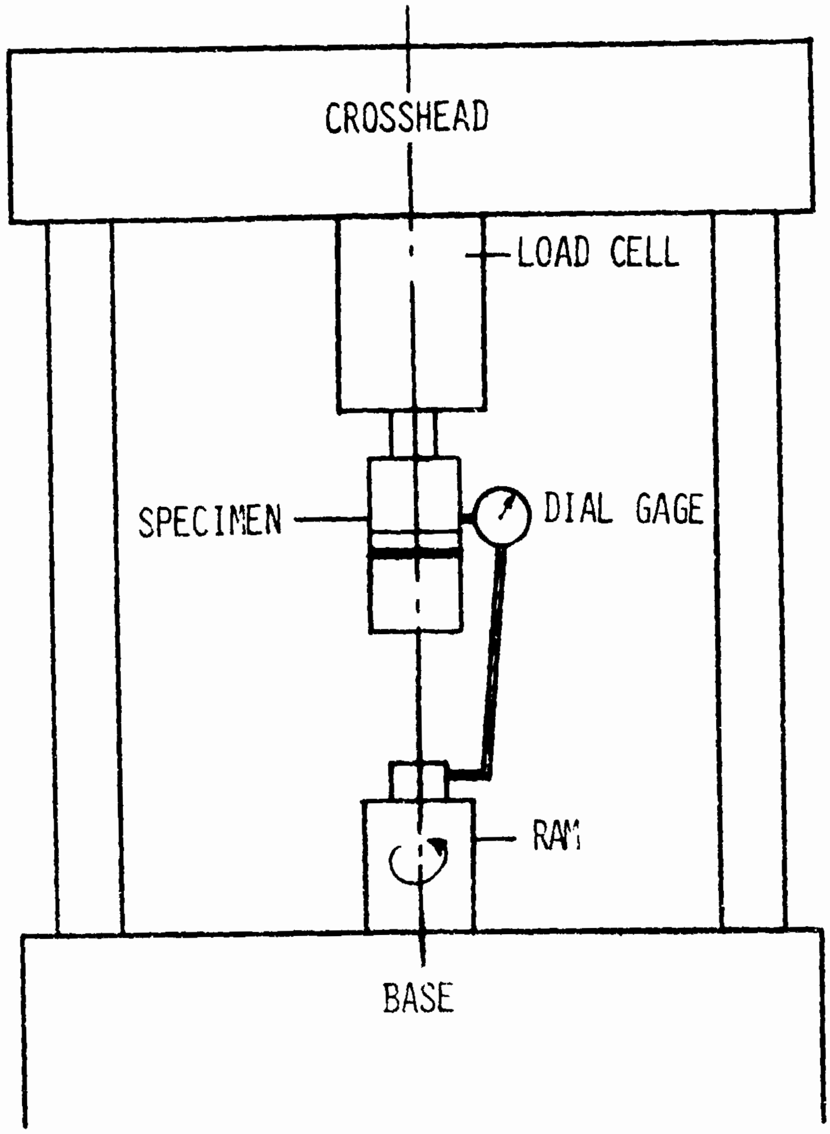

Figure 3 - Alignment check of test setup.

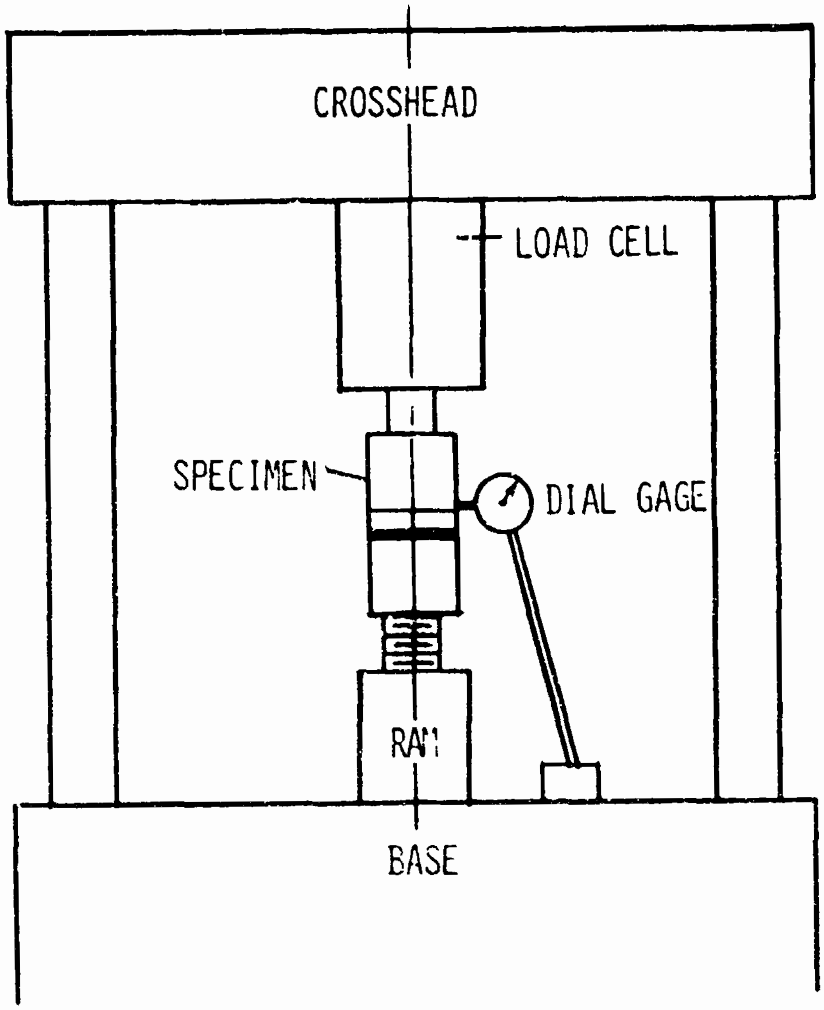

Figure 4 - Measurement of lateral movement of test specimen.

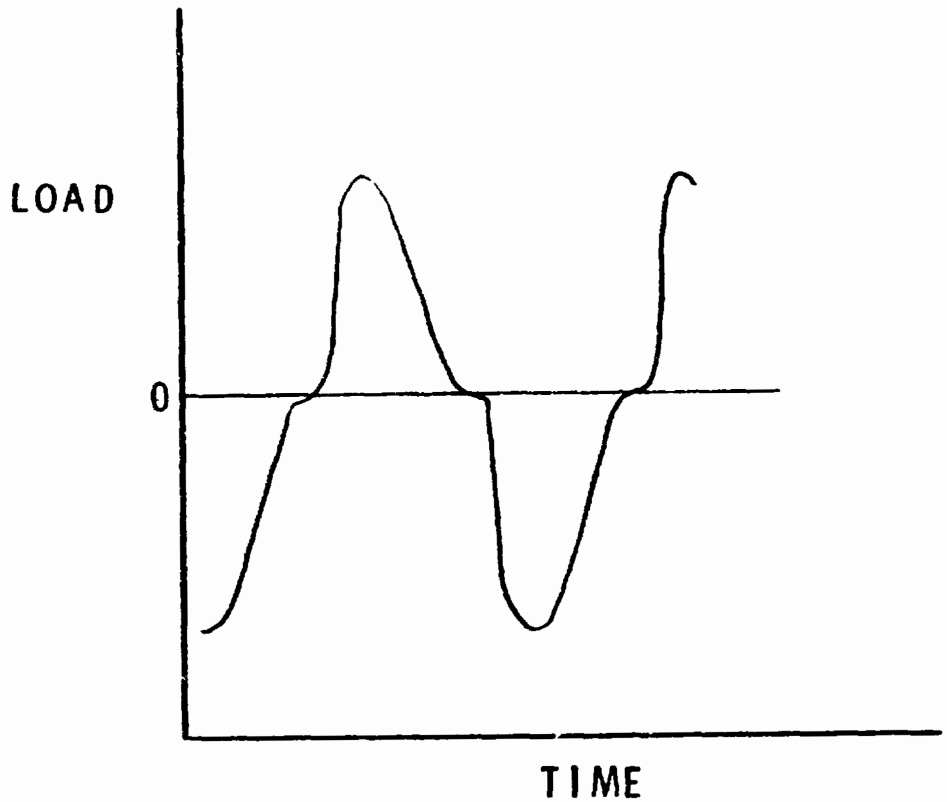

Figure 5 - Typical loading cycle for SIP/RSI specimen.

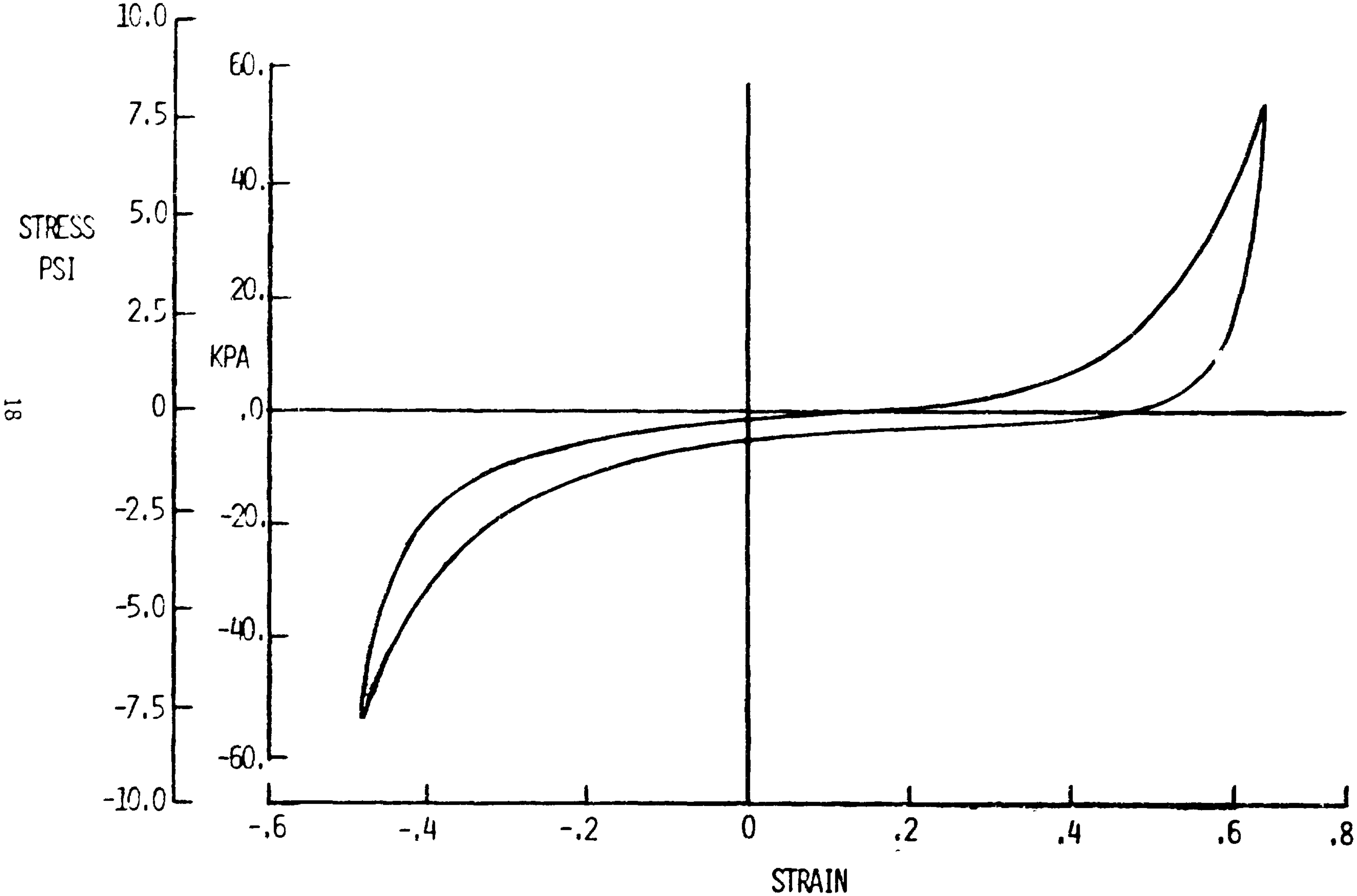

Figure 6 - Typical stress-strain curve for SIP/RSI specimen.

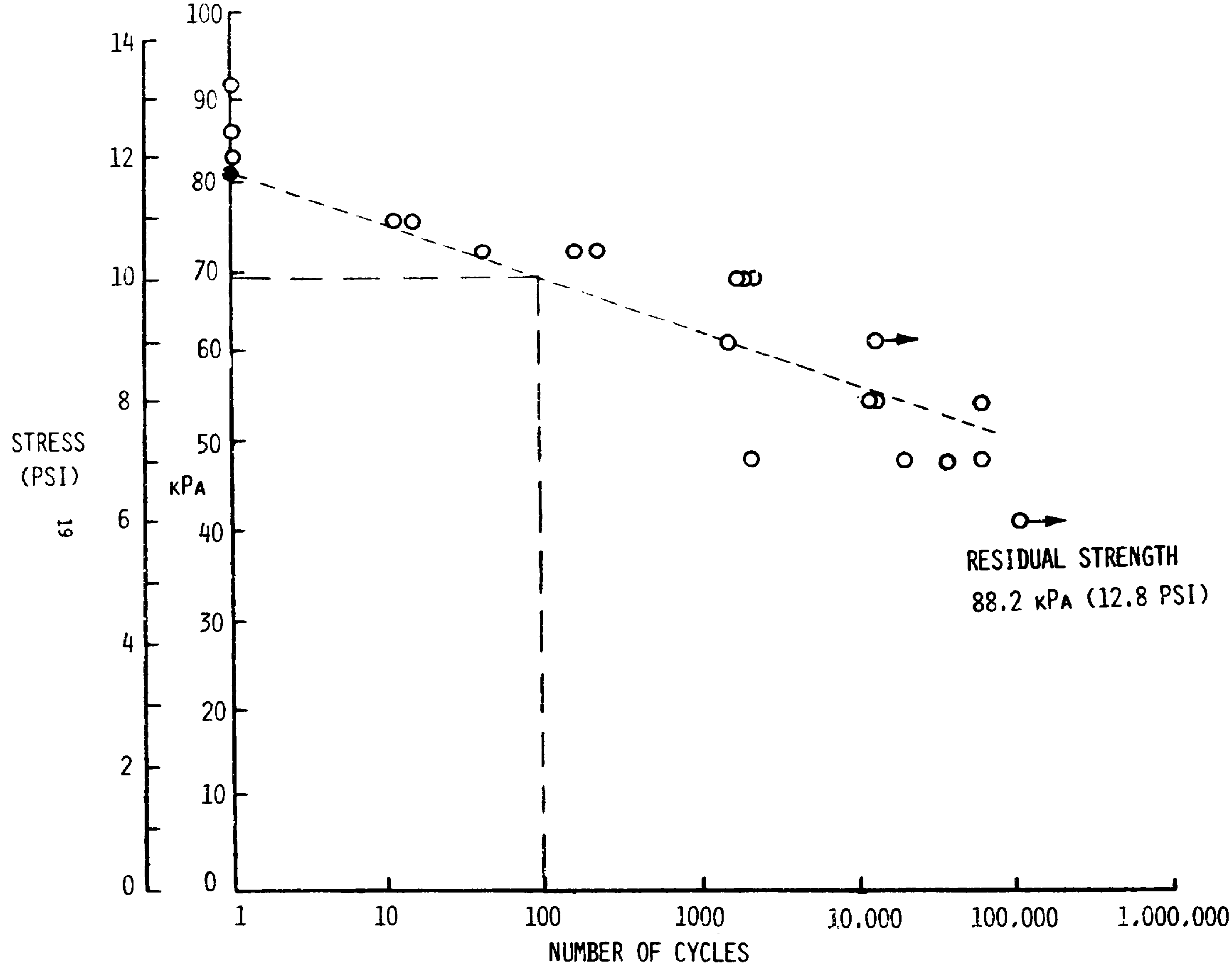

Figure 7 - Cyclic load tests of .41 cm (.160 inch) thick SIP/LI-900 tile system. R = -1. Failure occurred at SIP/RSI interface.

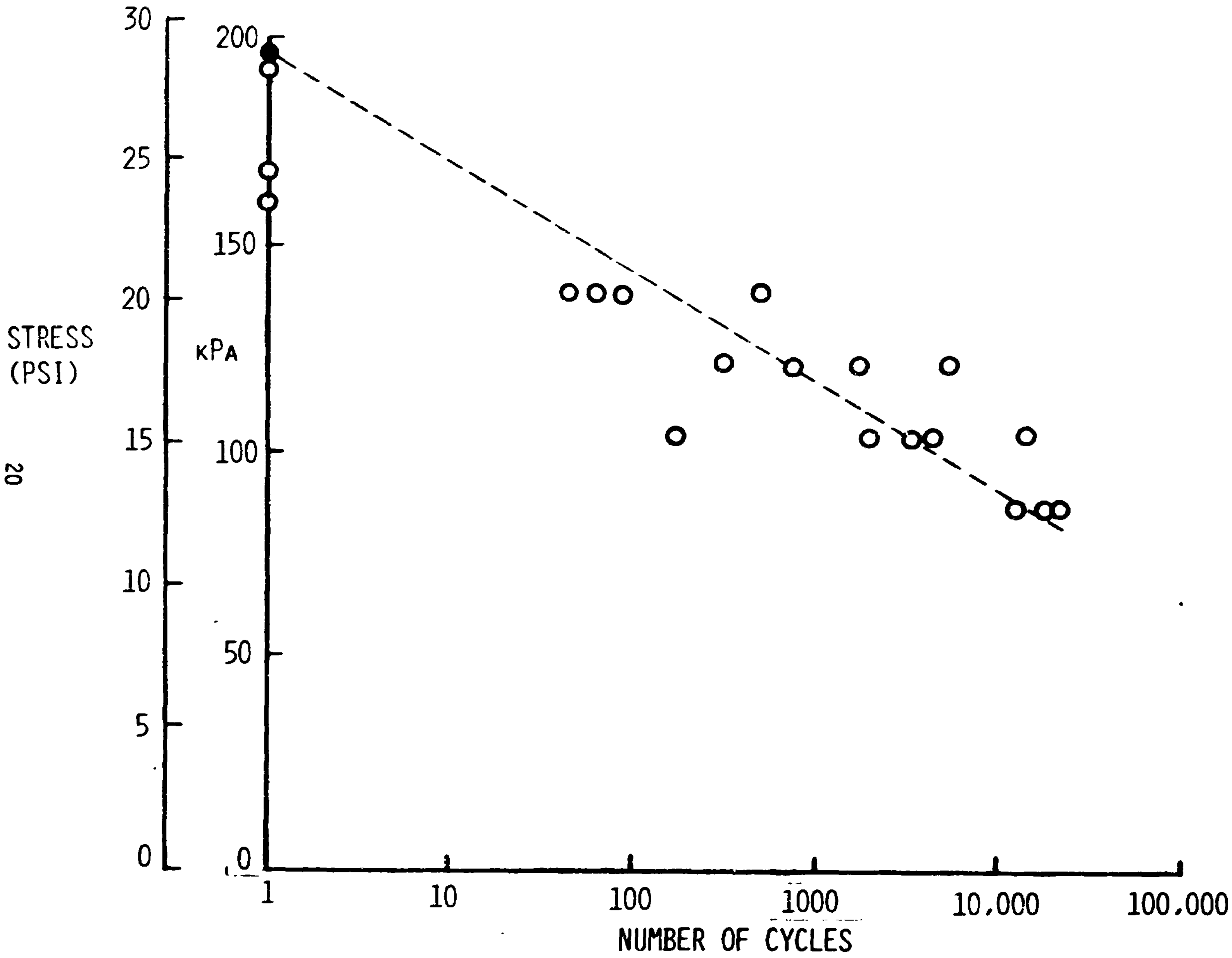

Figure 8 - Cyclic load tests of .23 cm (.090 inch) thick SIP/LI-2200 tile system. R = -1. Failure occurred at SIP/RSI interface.

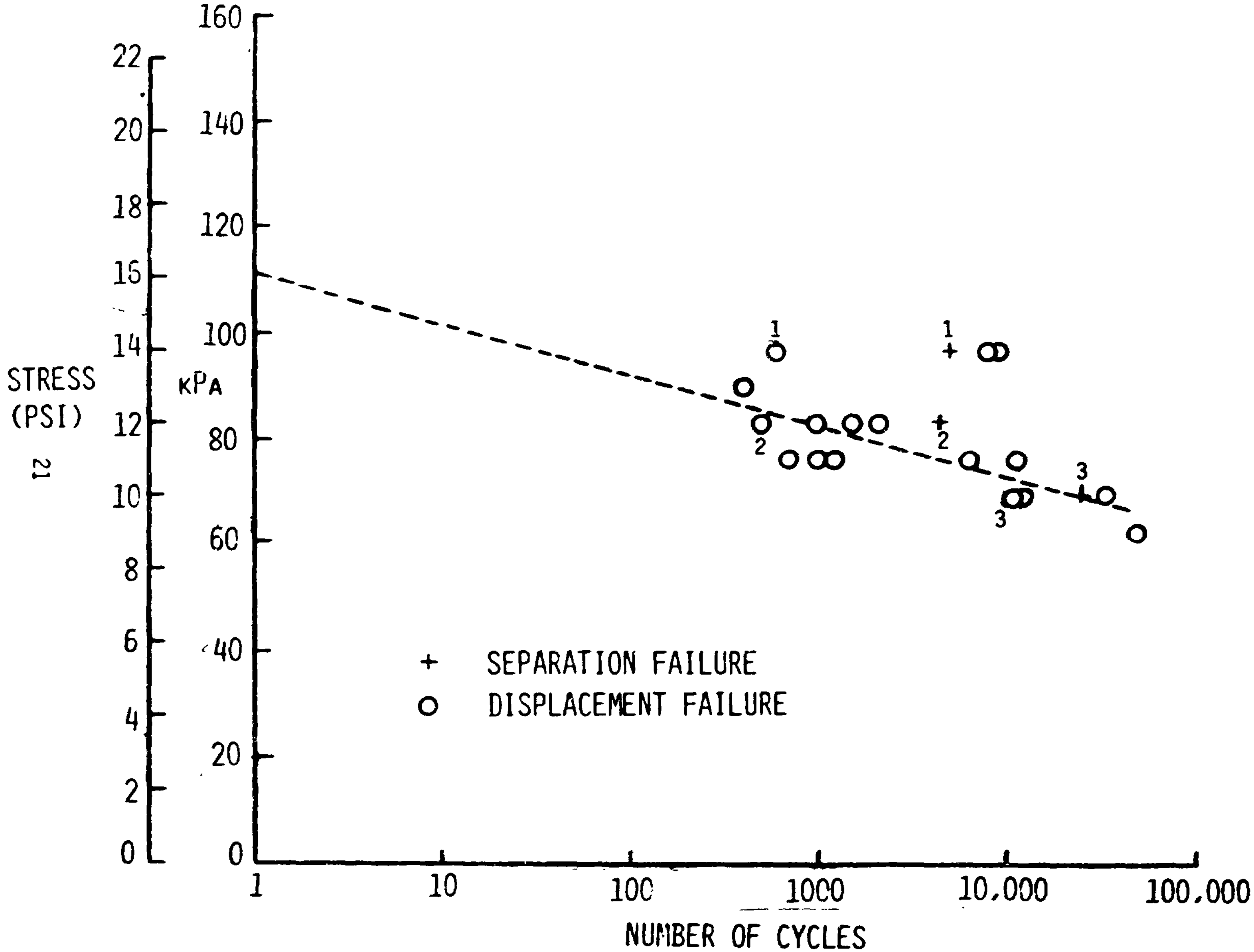

Figure 9 - Cyclic load tests of .41 cm (.160 inch) thick SIP/LI-900 densified tile system. R = -1. Failure occurred due to excessive displacement (Greater than .64 cm (.25 inches)).

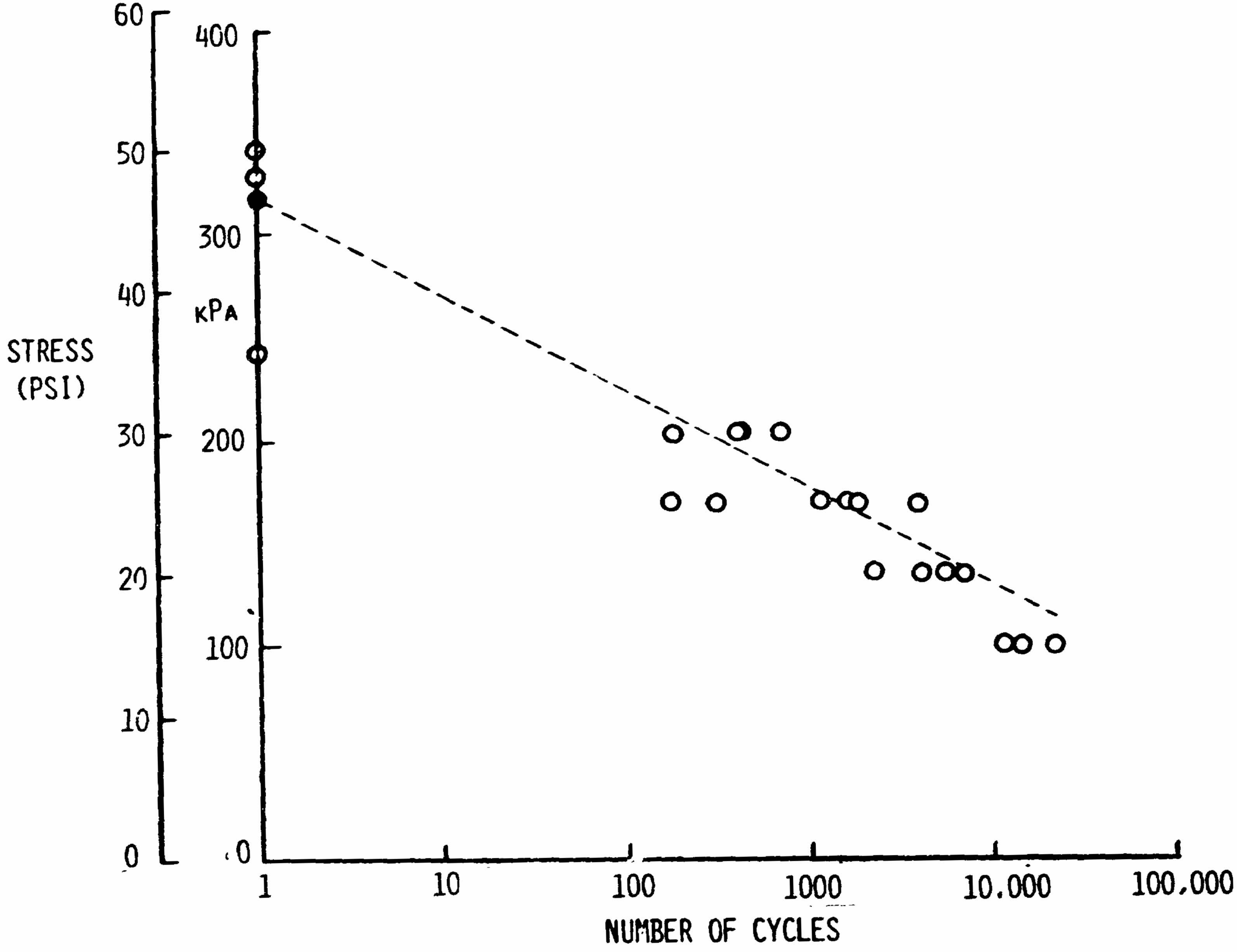

Figure 10 - Cyclic load tests of .23 cm (.090 inch) thick SIP/LI-2200 densified tile system. R = -1. Failure occurred in SIP.

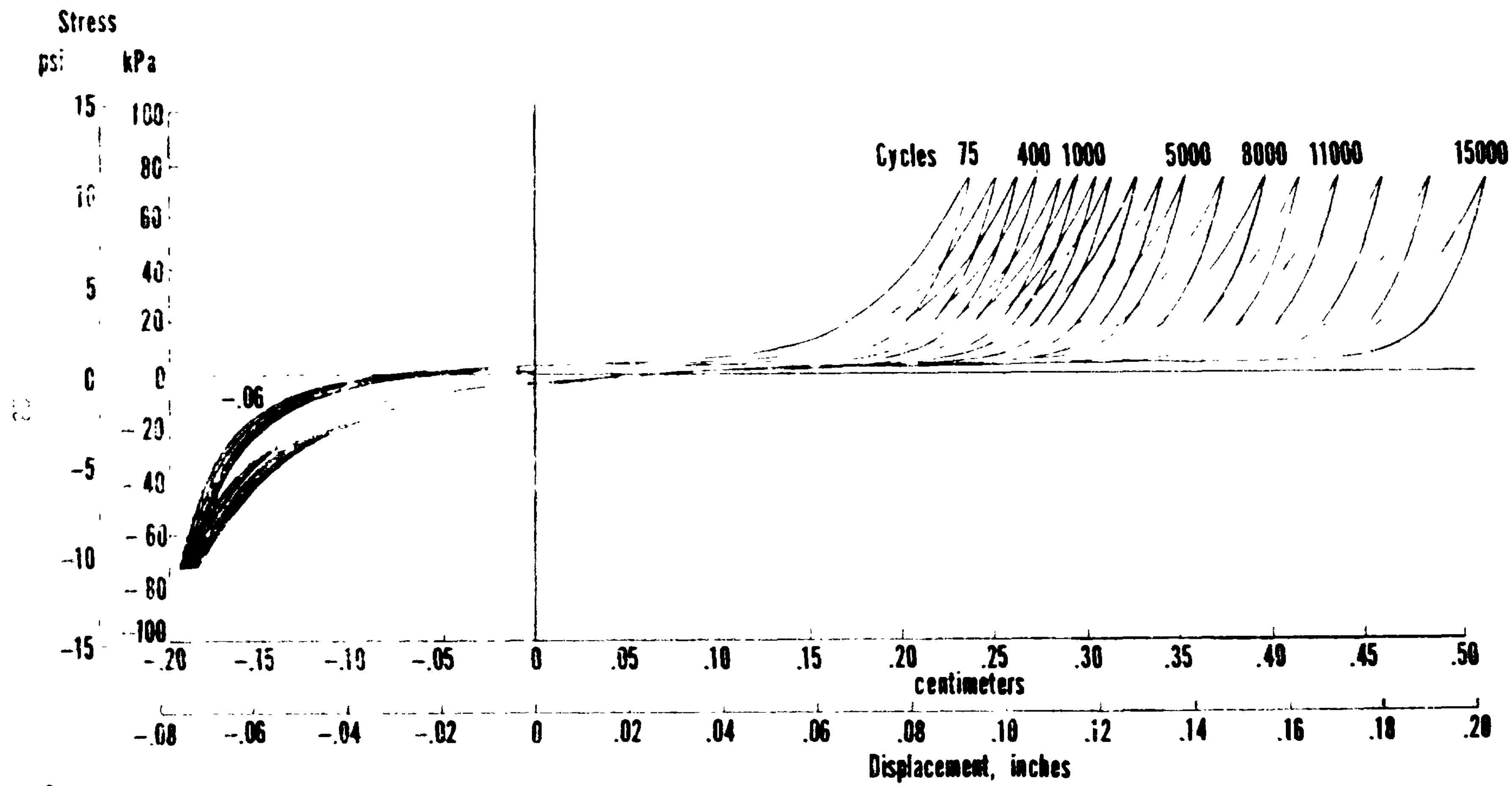

Figure 11 Effect of cyclic loading on displacement of .41 cm (.160 inch) thick SIP/ LI-900 densified tile system. R = -1.