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LIFE CONSIDERATIONS OF THE SHUTTLE ORBITER DENSIFIED-TILE THERMAL PROTECTION SYSTEM

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SUMMARY

The Shuttle orbiter thermal protection system (TPS) incorporates ceramic eusable surface insulation tiles bonded to the orbiter substructure through a train isolation pad. Densification of the bonding surface of the tiles increases he static strength of the tiles. The densification process does not, however, ecessarily lead to an equivalent increase in fatigue strength. Investigation of he expected lifetime of densified-tile TPS under both sinusoidal loading and random oading simulating flight conditions indicates that the strain isolation pads are the eakest components of the TPS under fatigue loading. The felt pads loosen under epetitive loading and, in highly loaded regions, could possibly cause excessive step eights between tiles causing burning of the protective insulation between tiles. A ethod of improving the operational lifetime of the TPS by using a strain isolation ad with increased stiffness is presented as is the consequence of the effect of ncreased stiffness on the tile inplane strains and transverse stresses.

INTRODUCTION

The thermal protection system (TPS) on the windward surface of the orbiter onsists of ceramic tiles bonded to strain isolator pads (SIP), which are in turn onded to the orbiter aluminum substructure as shown in the schematic of Figure 1. o prevent premature failure of the TPS at the interface of the SIP and the tile ue to stress concentrations caused by the localized transfer of load through the IP, the faying surface of the tiles was strengthened by a surface densification rocess. The greater static strength achieved by the surface densification does not ully translate into an equivalent increase in fatigue strength (ref. 1 and 2). atigue failure of the densified TPS takes the form of excessive elongation through he thickness of the SIP. On the other hand, fatigue failure of TPS with undensified iles involves complete separation at the SIP/tile interface (see ref. 3). Fatigue ailure of densified TPS is relatively benign when compared with fatigue failure of ndensified TPS since a tile beginning to loosen can be identified and replaced uring postflight maintenance.

lthough the fatigue failure mode of densified tiles is relatively forgiving, tiles hich loosen can cause problems in three ways. First, hot gas may be allowed to enetrate between tiles to the filler bar protecting the substructure. Second, hipping of the protective coating of neighboring tiles may occur. Third, disruption f the airflow could prematurely trip the boundary layer causing turbulent flow which ould lead to an increase in downstream heating. This paper reviews results of tests o evaluate the fatigue characteristics of densified TPS and introduces a possible ethod of increasing the operational lifetime of the TPS if required.

DESCRIPTION OF TPS

A schematic of a typical tile/SIP assembly is shown in Figure 1. The tile is composed of compacted 1.5-micron-diameter silica fibers bonded together by colloidal silica fused during a high-temperature sintering process. Two types of tiles are used on the windward surface of the orbiter, a 9 lb/ft^3 tile designated LI-900 and a higher strength 22 lb/ft^3 tile designated LI-2200. The tiles are coated on five sides with reaction-cured glass (RCG) consisting of silica, boron oxide, and silicon tetraboride to provide an abrasion-resistant watertight surface. The remaining uncoated side of the tile is densified by the application of a ceramic slurry at the surface which fills the voids between fibers and provides a strengthened bonding surface for the SIP. A photomicrograph of the densified region is given in Figure 2 and shows the colloidal silica particles situated between the silica fibers. Most densification material remains within 0.10 in. of the bonding surface as shown in the second photomicrograph of Figure 2 with the larger particles occurring at the surface and with the particle size and number of particles decreasing gradually toward the interior of the tile.

The SIP is bonded to the tile and the aluminum substructure of the orbiter using an elastomeric room temperature vulcanizing (RTV) silicone adhesive. The SIP is a felt pad of nylon fibers compacted by passing a barbed needle normal to the pad surface in a sewing machine like process. The compacting process provides tensile strength and extensional stiffness in the pad thickness direction and provides a load transfer path between the substructure and the tile. A photomicrograph of the SIP is given in Figure 3 and shows a region of transverse fibers produced by the needling process. The RTV adhesive transfer coat is also shown in Figure 3. This coat is bonded to the densified surface of the tile. A filler bar is bonded to the aluminum substructure between tiles to provide thermal protection for the substructure. A

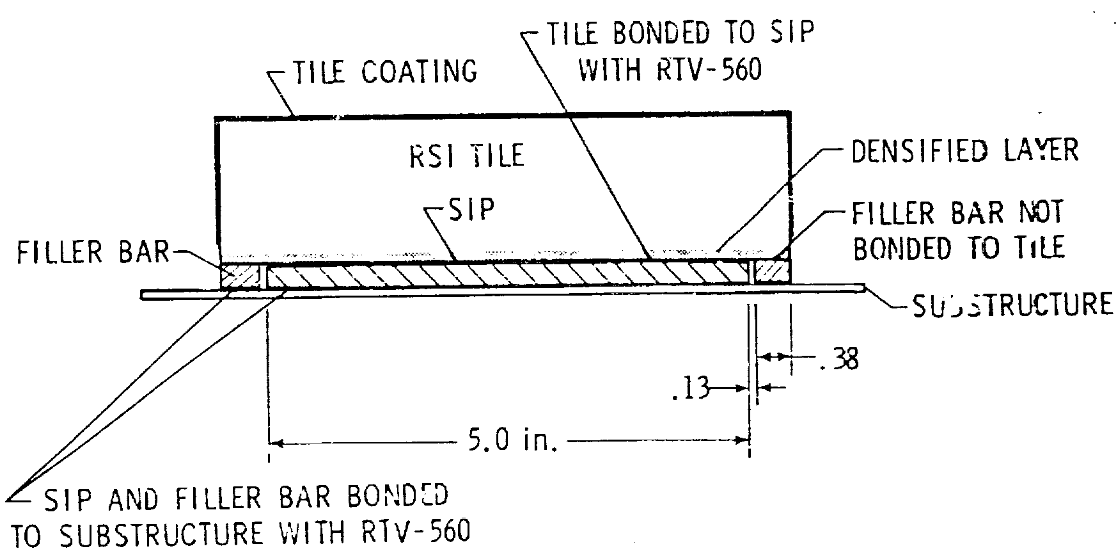

Figure 1.- Schematic of ceramic TPS.

more complete description of the TPS is provided in references 1 and 2. Two types of SIP are used most often on the orbiter and are identified by their thickness in inches, 0.160 SIP and 0.090 SIP. The 0.090 SIP is formed by the same procedure as the 0.160 SIP but is more highly compacted by an increased amount of needling which results in a higher strength and stiffness.

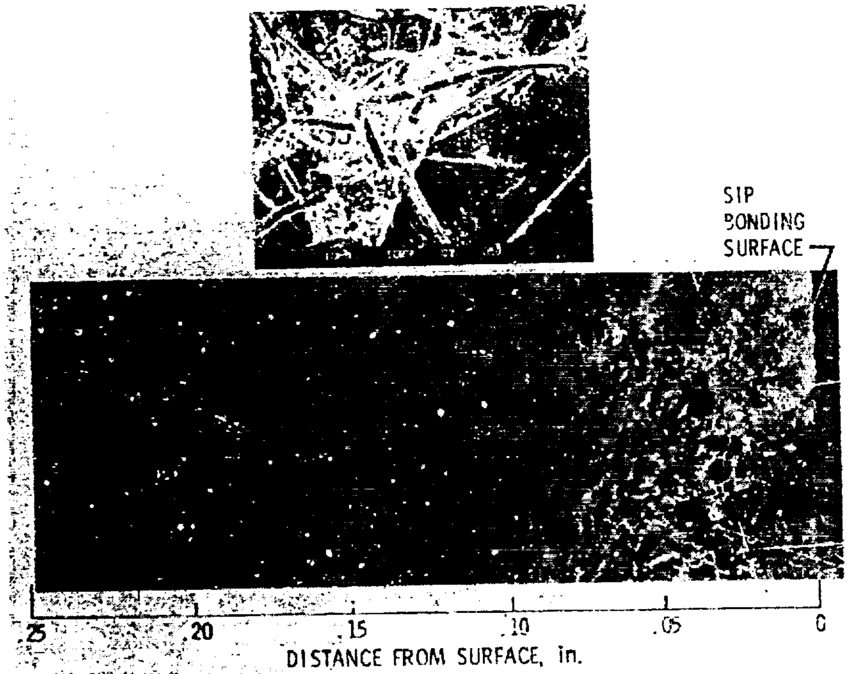

Figure 2.- Photomicrograph of densified region of tile.

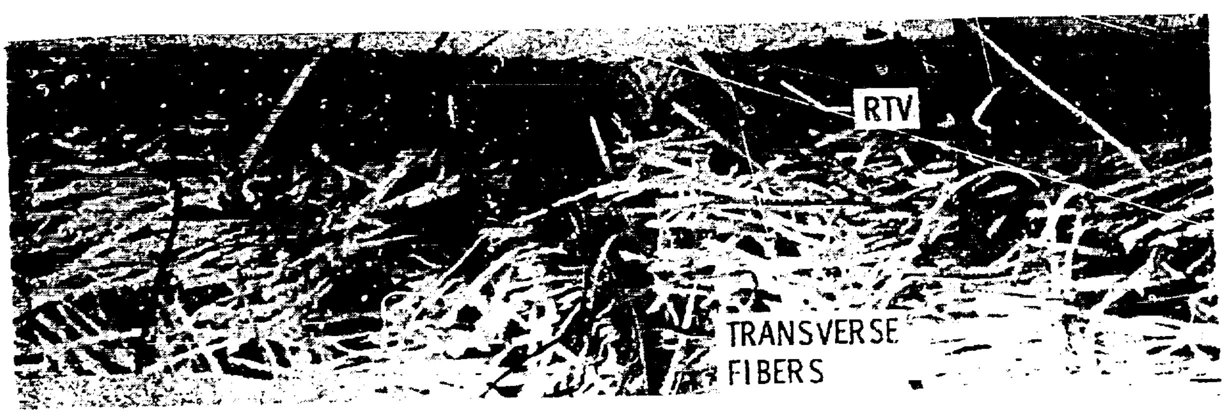

Figure 3.- Photomicrograph of strain isolation pad cross section.

A series of fatigue characterization tests of densified LI-900 tile/0.160 SIP and densified LI-2200 tile/0.090 SIP specimens were performed with results reported in reference 3. The 2.25-in.-diameter specimens were tested under repeated fully reversed sinusoidal loads applied at 1 Hz with results as shown in Figure 4. The lower strength LI-900 tile/0.160 SIP failed under cyclic loads by SIP extension when a total travel of 0.25 in. was arbitrarily selected as a failure condition. A total travel of this amount would constitute excessive looseness on the orbiter. The higher strength LI-2200 tile/0.090 SIP specimens failed by complete separation of the SIP before a total SIP extension of 0.25 in. was reached. For a given stress level, the stronger TPS had several orders-of-magnitude increase in lifetime over the weaker TPS. A comparison of the growth of the SIP during the fatigue tests under a fully reversed sinusoidal applied stress of 12 psi for the two types of TPS is shown in Figure 5. The stress displacement curves shown in the figure indicate that the 0.160 SIP loosens much more rapidly than the 0.090 SIP.

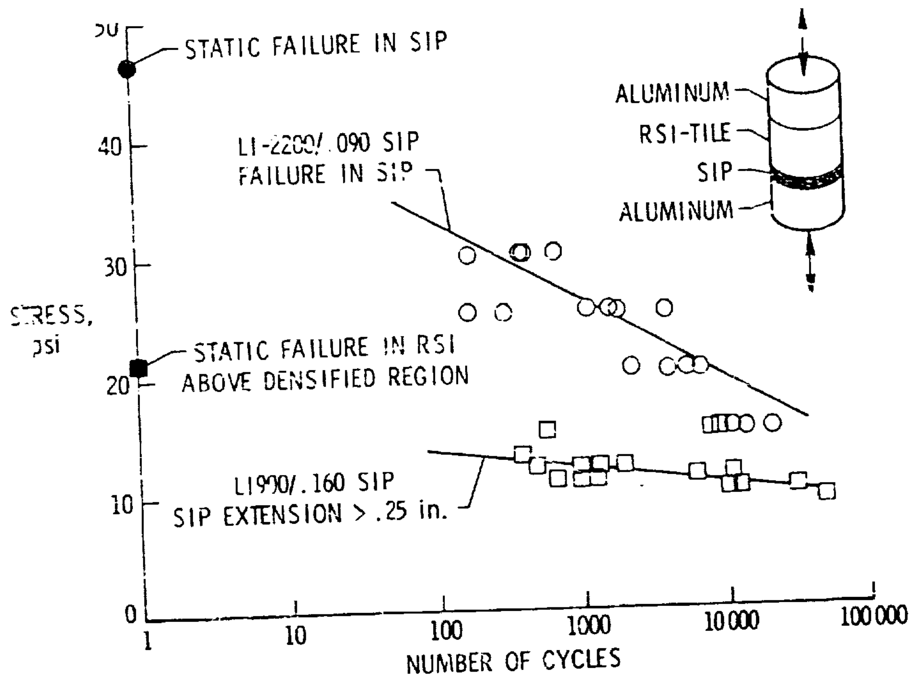

Figure 4.- Fatigue of densified TPS subject to fully reversed sinusoidal loads (R = -1).

Figure 6 shows the measured growth of the 0.160 SIP during the fatigue test for various applied stress levels and indicates the number of cycles at which total displacement is equal to the assumed failure criteria of 0.25 in. As the number of cycles increases, the SIP transverse fibers continue to stretch and unravel resulting in an increase in total specimen travel and a continual loosening of the tile. The growth rate increases nearly exponentially as the growth increases.

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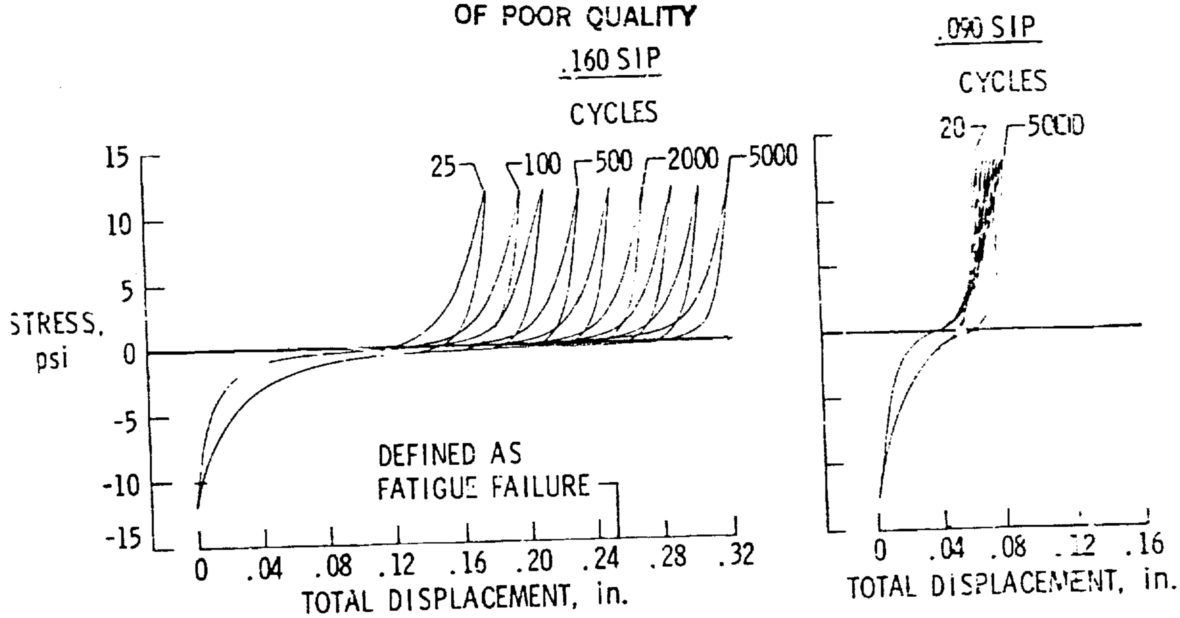

Figure 5.- SIP extension under fatigue loading.

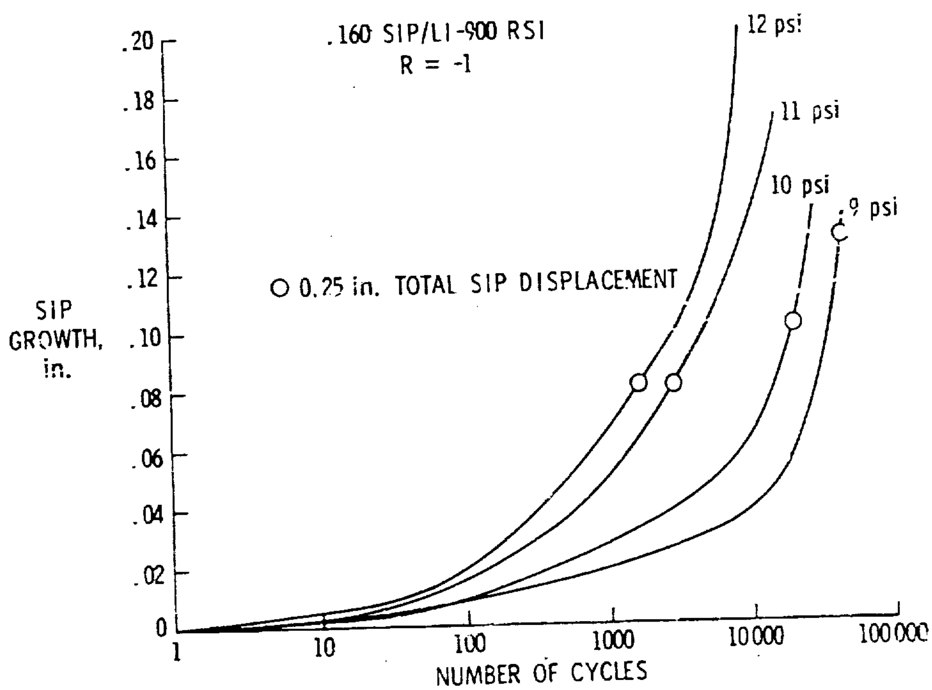

Figure 6.- Measured growth of SIP displacement under sinusoidal fatigue loading.

RANDOM DYNAMIC LOAD FATIGUE TEST

A sinusoidal load condition, while helpful in providing insight into the expected fatigue behavior of the TPS, is a severe load condition not expected under actual flight conditions. The tiles experience a variety of random vibrational loads during ascent. These include: main engine and solid rocket motor ignition overpressures during liftoff, substructure motions due to engine vibrations and aerodynamic loadings, direct acoustic pressure loads caused by boundary layer noise, differential pressures due to shock passages, aerodynamic gradients and gust loads, and tile buffeting due to vortex shedding from a connecting structure. The critical load conditions on the TPS during ascent are expected to occur between the time the orbiter reaches transonic speeds (approximately 40 seconds after liftoff) and the time the orbiter experiences maximum dynamic pressure (approximately 65 seconds after liftoff). During this critical time, the TPS on the lower wing and midfuselage surfaces experiences loads caused by substructure deformation, shock passage aerodynamic gradients, which can cause a net tensile force and moment on the tiles, and random acoustic loads transmitted to the tiles from the orbiter base structure (ref. 4). Prior to the first flight, a series of random dynamic load tests were performed on undensified tiles to obtain a more realistic evaluation of the expected behavior of the TPS under simulated flight load conditions in the windward surface wing and midfuselage region. Results of those tests are reported in reference 5. After completion of those tests and before the initial flight, a densified tile was tested using the same test procedure and fixtures but under slighcly higher load conditions since many densified tiles were expected to be subjected to load levels higher than those experienced by undensified tiles.

Test Setup

A schematic of the load application fixture is shown in Figure 7. The fixture consists of a thin aluminum plate riveted to five thick-walled aluminum tubes. The fixture was designed so that after the tile/SIP test specimen is bonded to the plate, the plate can be deformed to a shape typical of the substructure deformations expected in the orbiter skin in either the wing or midfuselage region. The plate is deformed by bolting the tubes to a rigid base plate with shims under alternate tubes as required for the region of interest. The shims cause the thin plate to deform to an approximate sine wave with the peak-to-peak amplitude given by the shim thickness and the half wavelength governed by the tube spacing.

The fixture surface on which the specimen is bonded is first chemically etched, sprayed with a protective primer, and vacuum baked to remove all volatiles. The specimen is bonded to the test fixture with the tile diagonals parallel to the edge of the test fixture as shown in Figure 7. The tile is located on the test fixture so that one corner of the SIP is over the centerline of one of the tubes. A circular aluminum thin disk is bonded to the top of the tile using epoxy adhesive to provide a load attachment point for application of a steady tensile load and moment which simulate the effect of a steady aerodynamic gradient. The attachment point at the center of the disk is located 0.5 in. from the center of the tile measured along a tile diagonal perpendicular to the tube axes. To apply a random dynamic load to the specimen, the fixture, with the specimen in place and shims installed to simulate substructure deformations at a wing location, is bolted to the drive head of a 30,000 lb electromagnetic shaker. A schematic of the test setup is shown in Figure 8.

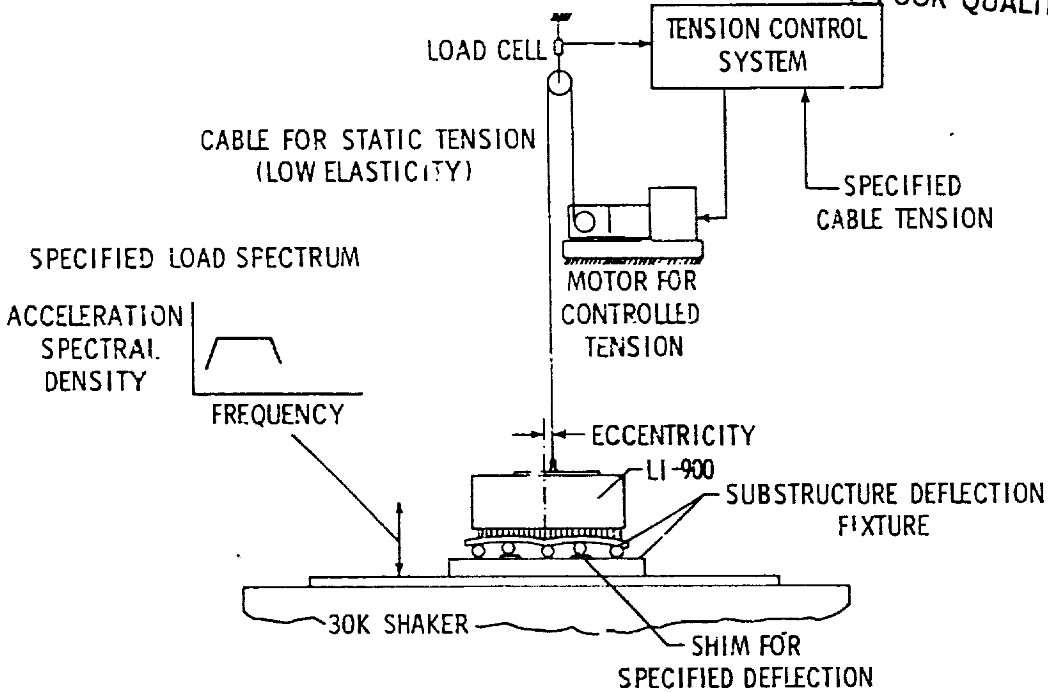

Figure 7.- Random dynamic fatigue test fixture.

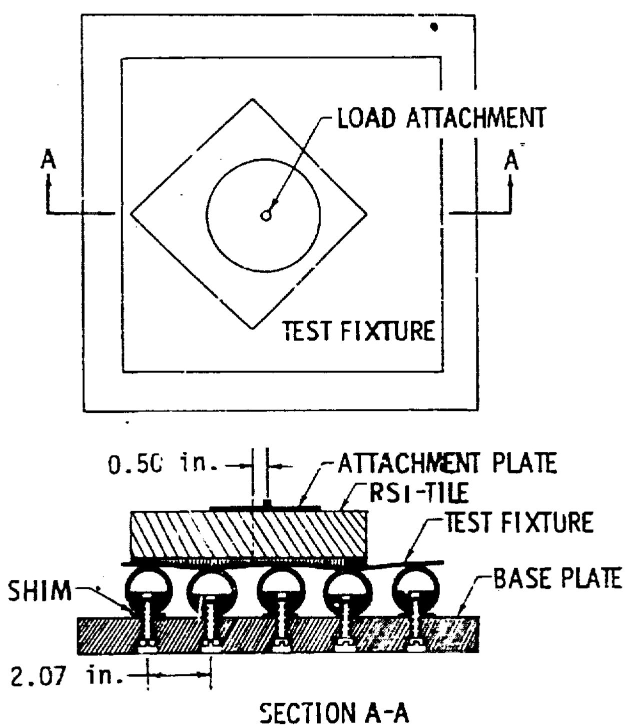

Figure 8.- Schematic of random dynamic load test setup.

Test Program

A series of tests were performed on a 2-in. thick by 6-in. square densified-LI-900 tile bonded to a 5-in. square 0.160 SIP. The specimen, installed on the thin plate with filler bars in place, was first given a bond verification test similar to that given actual densified tiles on the orbiter. The test consisted of a steady load applied to the top of the tile which introduced a uniform tensile stress of 10 psi on the SIP followed by a compressive load of the same stress level to bring the tile back to its equilibrium position. The specimen was then given a 5-psi uniform tension stress followed by a 5-psi compression test with displacement response recorded to establish the stress displacement characteristics which existed before the random dynamic load test was performed. The specimen was then installed on the base plate using shims to provide a static substructure deflection amplitude of 0.015 in. with a half wavelength along the tile diagonal of 2.07 in. A tensile force of 50 lb displaced 1/2 in. from the tile center along the diagonal in the direction which causes the most severe SIP stress was applied and held constant for the duration of the dynamic test. The specimen was given a random base drive of 30 grms with the driving frequencies occurring mainly between 60 Hz and 250 Hz using the power spectral density distribution shown in Figure 9. The dynamic test was conducted for a total of 2.5 hours with measurements of SIP growth at the most highly stressed corner taken every 1/2 hour with all loads removed. With one ascent mission assumed equal to 25 seconds of test time, the total test time simulated 360 ascent missions (100-mission lifetime with a scatter factor of 3.6). Figure 10 contains a photograph of the actual test setup, and Figure 11 provides a closeup view of the test specimen showing the installed instrumentation used to obtain dynamic response information. On completion of the dynamic test, the specimen was again given a 5-psi static tension and compression test with load displacement measurements taken. Finally, the specimen was given a tensile test-to-failure to determine its residual strength.

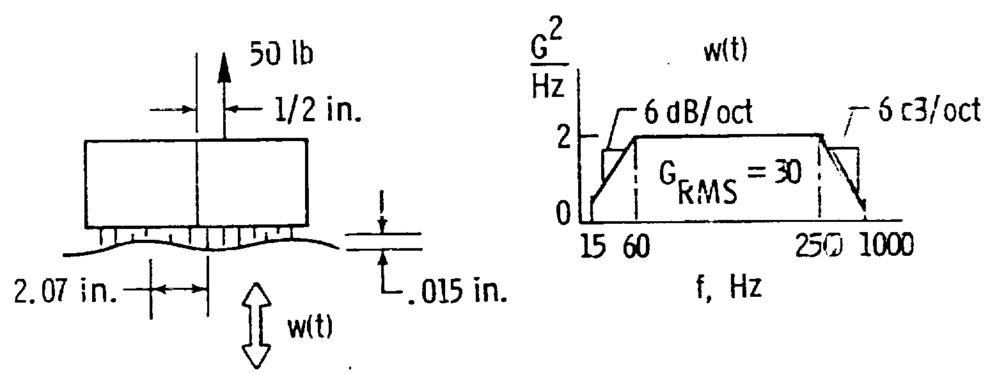

Figure 9.- Test loads applied on densified TPS.

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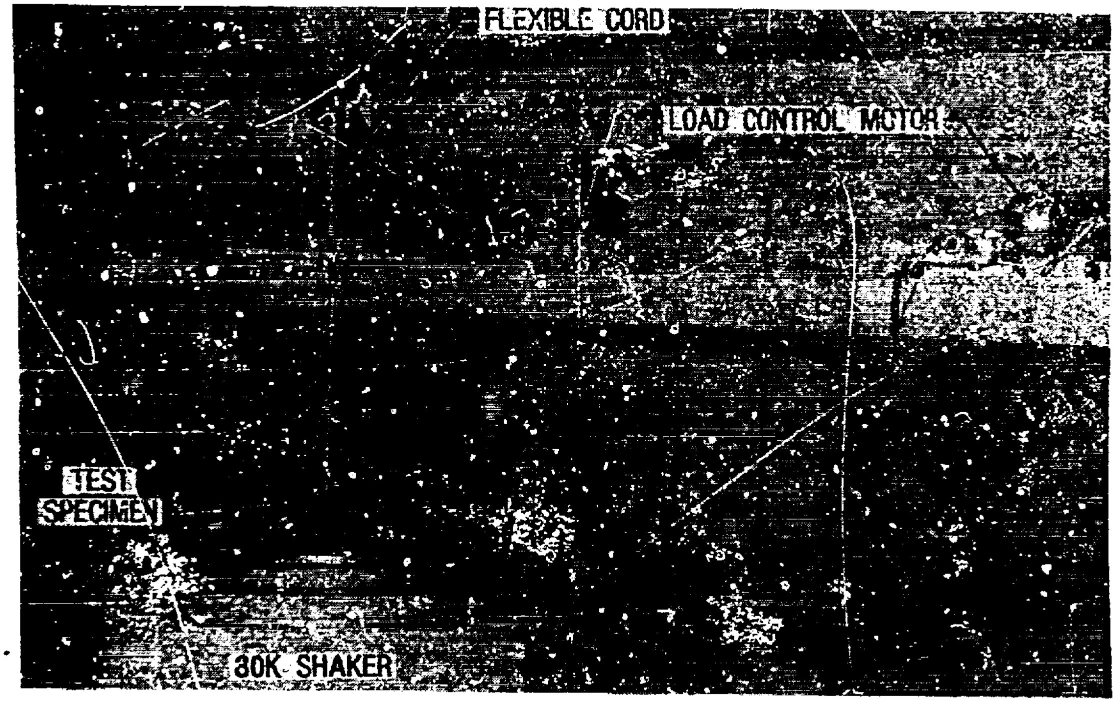


Figure 10.- Photograph of laboratory test setup for dynamic testing of densified TPS.

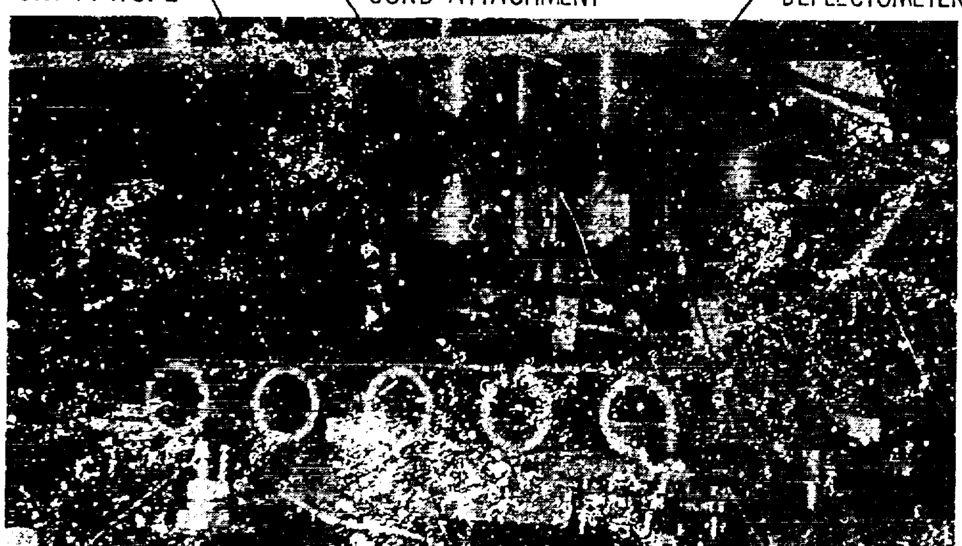


Figure 11.- Photograph of test specimen and fixture.

Figure 12 contains a picture of the tile after completion of the dynamic load test and before the final test-to-failure. The top plate shown in the figure replaces the load attachment disk used during the dynamic test so that the larger tensile loads required to fail the system can be applied. The figure also contains a plot of the development of permanent growth of the SIP at the highest stressed corner as the dynamic test progressed. By the conclusion of the test, the SIP had a permanent extension at this corner equal to the initial thickness of the SIP (i.e., 100-percent increase in thickness). Figure 13 presents a comparison of the applied stress vs. displacement measured during the ±5-psi static uniform load tests

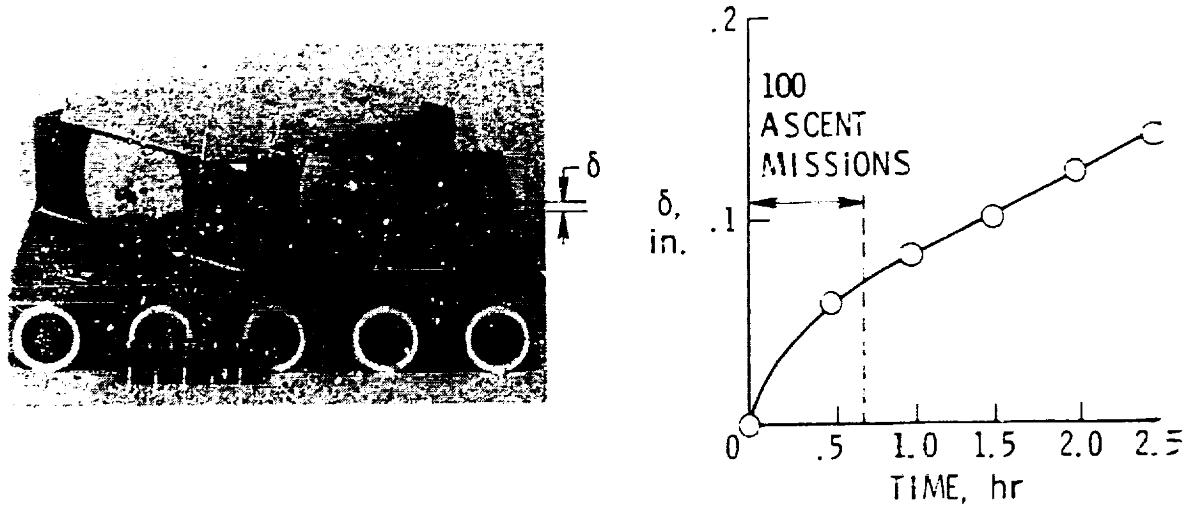


Figure 12.- Permanent growth of SIP subjected to random dynamic loads.

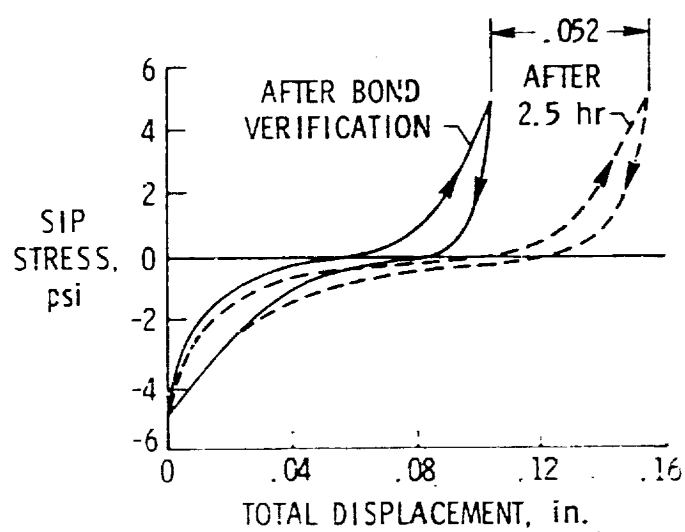


Figure 13.- Loosening of TPS due to multimission random dynamic loading.

performed before and after the dynamic test. The peak-to-peak measurement of 0.052 in. is an indication of the degree to which the SIP has loosened. The tile failed during the final test-to-failure in the parent undensified region at an ultimate static load of 422 lb. This failure load was 70 percent greater than the original bond verification load.

If the load spectrum does represent actual flight conditions, the test data indicate that excessive SIP growth may occur within the operational lifetime of the orbiter. This mode of failure under random loading is benign if corrective action is taken during ground maintenance between flights; however, if loose tiles are not eventually replaced, several unacceptable consequences as discussed in the introduction might result. One of these consequences, that of filler bar burning, has been analyzed, and a maximum growth criterion for prevention of this condition is discussed in the next section.

FILLER BAR BURNING

Table 1 gives a history of tile removal for various causes after each of the first four flights. Tile loosening does not seem to be a developing problem this early in the orbiter lifetime; however, there does seem to be a persistence of incidents of filler bar burning from flight to flight. An indication of the effect of the tile gap and step on filler bar burning is provided in reference 6. The reference contains the results of a study to investigate the cause of the excessive

TABLE 1.- TILE REMOVAL HISTORY FOR OV-102 AFTER FOUR FLIGHTS

	STS-1	STS-2	STS-3	STS-4
TOTAL NO. OF TILES REMOVED	1547	471	1047	271
REMOVED FOR DENSIFICATION (NO STRUCTURAL ISSUE)	526	202	783*	0
REMOVED FOR LOOSENESS	170	18	15	3
REMOVED FOR EXCESSIVELY BURNT FILLER BAR	246	47	39	36
OCCURENCES OF BURNT FILLER BAR NOT SEVERE ENOUGH TO REMOVE	614	360	219	502+

*PRIMARILY WHITE TILES (NONCRITICAL) IN FORWARD FUSELAGE REGION

+PROBABLY DUE TO HIGHER HEATING RATE DURING ENTRY heating observed in the tile-to-tile gaps of the orbiter. A flow model was developed in the referenced study to determine the pressure loading and flow rates in the gap during entry. A thermal model of adjacent tiles, the tile-to-tile gap and step, filler bar, and SIP was used to predict temperature distributions throughout the system. Tests have shown that temperatures greater than 1375°F will cause charring of the RTV and filler bar to a degree which requires replacement of the filler bar. The computed temperature distributions at a wing location where a 0.06 in. step is assumed are shown for various locations in a gap in Figure 14. The peak filler bar temperature calculated for the assumed step is 1750°F. A similar study for a 0.03-in. step yields a maximum filler bar temperature of 1290°F. Thus, from a linear interpolation between these two conditions, the critical temperature for filler bar burning is reached under the flow conditions of the study when a step between tiles of 0.034 in. exists.

Results of the random dynamic load test shown in Figure 12 indicate that a permanent SIP extension of 0.034 in. would occur under the simulated loads well before the 100-mission flight desired lifetime has been completed. One could conservatively estimate that this extension coupled with the increased loosening of the SIP shown in Figure 13 would cause a step of the order of 0.04 in. assuming the neighboring tile was under compression or at least remained unextended. Thus, if the assumed load simulation used in the random dynamic load tests is realistic and the thermal predictions of reference 6 are an accurate evaluation of actual conditions, increased incidence of burned filler bar can be expected during the lifetime of the orbiter.

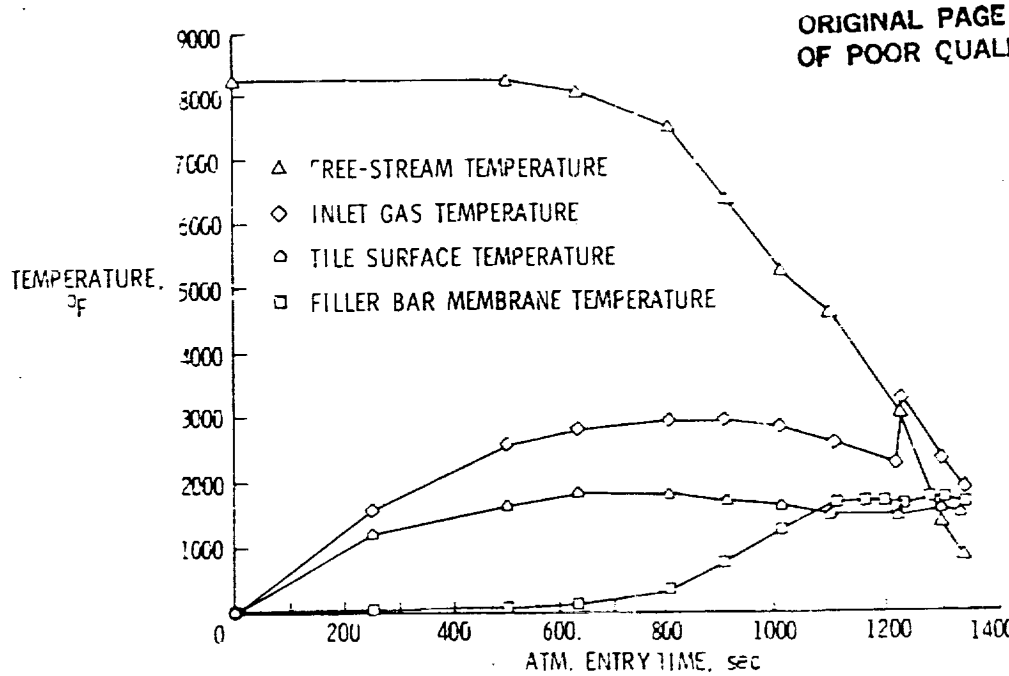


Figure 14.- Calculated temperature of tile and filler bar at wing location during reentry, Step = 0.06 in., ref. 6.

METHOD FOR EXTENDING SIP LIFETIME

Several possible methods can be used to reduce the incidence of filler bar burning and loosening of tiles. Currently, gap fillers are placed in the gaps between tiles where filler bar burning occurs. The gap fillers prevent hot gas influx between tiles and reduce the dynamic response of the tiles to external stimulations. Another possible method is to bond the tiles to the filler bar, thus reducing the nominal stress in the SIP by providing an increased support area for the applied loads. A third method, which will be discussed here, is the replacement of the 0.160 SIP with a SIP of the same thickness but with stiffness and strength properties equal to those of the 0.090 SIP. Replacement with a stiffer SIP is suggested since, as shown in Figures 4 and 5, the 0.090 SIP has at least an order-of-magnitude greater lifetime than the 0.160 SIP for a given stress level. A SIP of this type could be fabricated by starting with a pad thicker than the pad used to form the 0.160 SIP and reducing it to the desired 0.160 thickness when it is needled to the same degree as the 0.090 SIP. Replacement of the standard SIP over the entire windward surface of the orbiter with a stiffer SIP of this type would cause an increase in orbiter dry weight of approximately 300 lb. There is a limitation to the allowable increase in stiffening of the SIP beyond which it begins to fail in its function as an effective strain isolator for densified tiles. An analysis and test program was performed to determine this limitation.

Limitation of SIP Stiffness for Inplane Strains

An analysis was developed and reported in reference 7 to evaluate the inplane strains transmitted through the SIP to the densified region and the top coating of a tile caused by the combined effect of substructure inplane and normal deformations. The problem was treated as a deep stiff beam (including the effects of transverse shear) on a soft elastic nonlinear foundation which resists both transverse extension and shearing. The analysis requires a knowledge of the extensional modulus of the densified region of the tile. To find the modulus, a series of four-point beam bending tests were performed using small beam specimens fabricated from tile material and densified on the loading surfaces. The beams were treated as sandwich structures with an assumed densified region thickness of 0.10 in. Results from these tests, including an evaluation of the inplane failure strain of the densified region, are presented in reference 8.

Using the analysis and the experimentally determined modulus of the densified region, a study was made of the maximum inplane strains in densified tiles of various thicknesses ranging from 0.25 in. to 2.0 in. The tiles were subjected to an inplane substructure strain equal to the yield strain of the aluminum plus the unconstrained thermal strain caused by a rise in substructure temperature of 280°F. In addition, the tiles were subjected to a tensile load of 250 lb offset from the tile center by 0.5 in. This combined load condition is greater than any actual condition expected on the orbiter tiles. Results of the study for a standard 0.160 SIP and a SIP with ten times the stiffness of the standard SIP are shown in Figure 15. Only for the thinnest tiles does the maximum strain in the densified region and the top coating approach the inplane failure strain. Thus, a considerable increase in SIP stiffness can be tolerated without compromising the inplane integrity of the tiles. A 0.090 SIP has approximately three times the stiffness of 0.160 SIP. This is well within the acceptable stiffness range to function properly as an isolator of inplane strains.

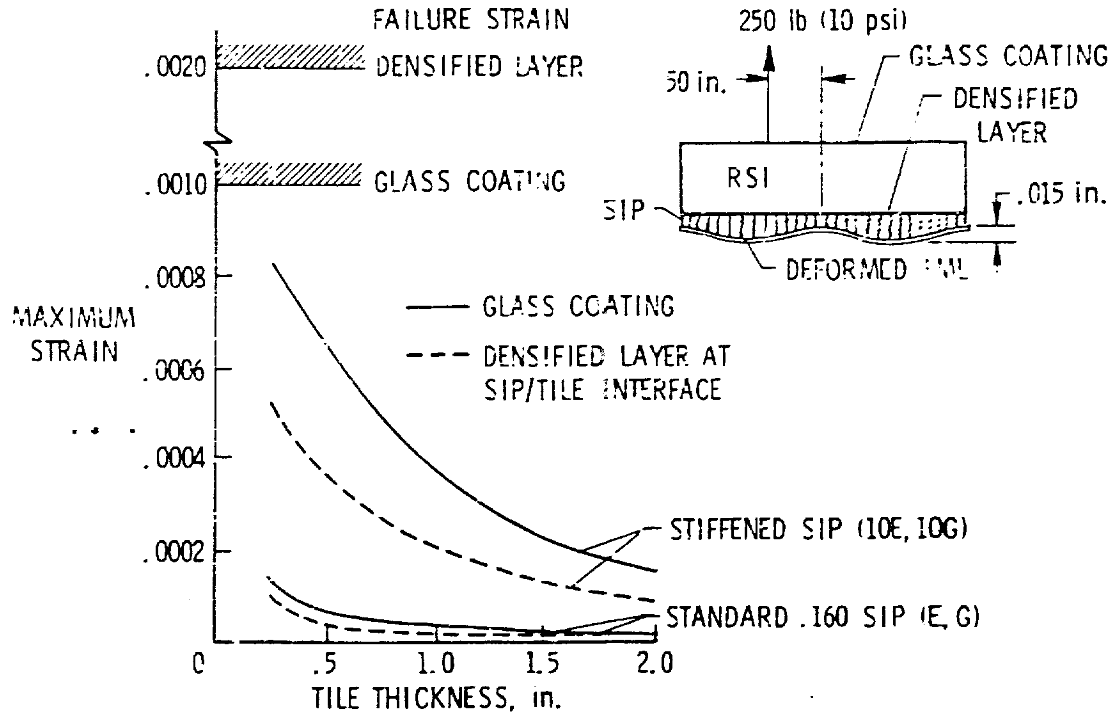
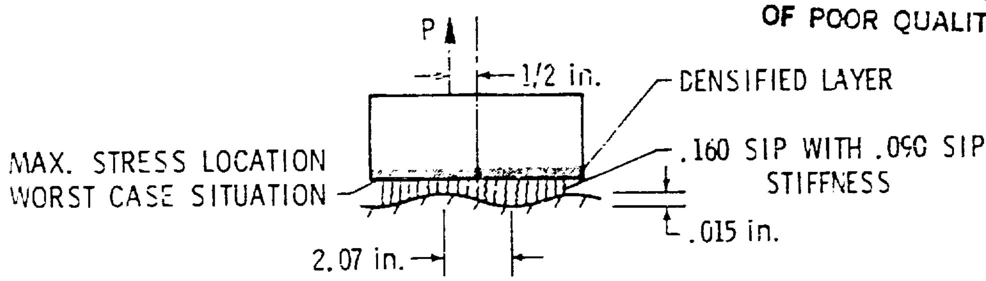


Figure 15.- Effect of SIP stiffness on tile inplane strains for a range of tile thicknesses.

Limitation of SIP Stiffness for Transverse Stress

A SIP with a higher stiffness will increase the stress in the direction normal to the plane of the pad (transverse stress) in the region of the SIP/tile interface when substructure deformations are applied. To evaluate the effect of a stiffer SIP on the transverse stress at the SIP/tile interface, the stresses were computed using an analysis described in reference 9 for a standard 0.160 SIP and a 0.160-in. thick SIP with stiffness properties equal to that of a 0.090 SIP. A comparison of results for typical high-load conditions expected on orbiter tiles is shown in Figure 16. Use of the stiffer SIP causes approximately a 50-percent increase in the maximum stress at the SIP/tile interface for the load conditions considered. At the higher applied load levels shown in the figure, the computed stress in the SIP approaches the failure stress of the tile material so that tile strength in regions of high substructure deformations becomes the limiting factor for determining the maximum permissible increase in SIP stiffness. However, the stress computation shown is most likely conservative in that the maximum stress occurs at the boundary of the SIP, and the computations do not account for the relaxation of stress at SIP boundaries observed in laboratory tests.



P, lb	$\sigma_{max\ ttt}$ STANDARD SIP, psi	$\sigma_{max\ ttt}$ STIFF SIP, psi	INCREASE, %
100	10.1	14.9	48
125	11.5	17.2	49
150	13.0	19.3	49

AV $\sigma_{failure}$ IN PARENT MATERIAL ≈ 21 psi

Figure 16.- Comparison of maximum SIP transverse stresses at tile/SIP interface for standard and stiff SIP.

CONCLUDING REMARKS

Sinusoidal fatigue tests of the ceramic TPS on the windward surface of the Shuttle orbiter indicate that the failure mode of the TPS is an excessive extension of the SIP which is a relatively benign failure mode and can be corrected during ground maintenance by replacement of the offending TPS. Random dynamic tests of the TPS simulating expected flight conditions during ascent indicate that the tiles might loosen sufficiently during the operational lifetime of the orbiter to cause burning of the filler bar in highly loaded regions. Sinusoidal tests indicate that a stiffer SIP can have an order-of-magnitude increase in fatigue lifetime. A method of improving the operational lifetime of the TPS by using a SIP with increased stiffness is presented as is the consequence of the effect of increased stiffness on the in-plane strains and transverse stresses. Results indicate that a stiffer SIP can be used to increase the TPS lifetime without compromising the structural integrity of the TPS except in regions with very thin tiles and possibly in regions with very high substructure deformations and applied loads.

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