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THE CHALLENGING "SCALES OF THE BIRD"
(SHUTTLE TILE STRUCTURAL INTEGRITY)

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INTRODUCTION

The launch and landing of the U.S. Space Shuttle Orbiter has now become almost routine. The development of such a highly successful vehicle involved the resolution of many challenging problems. One problem area where the challenges to creativity, inventive design, and analytical understanding were particularly demanding involved the structural integrity of the thermal protection system (TPS). The problems associated with these tiles were resolved in the unfavorable engineering environments of tight schedule, budget constraints, and high public visibility. The successful resolution of these problems is evident with each landing of the Shuttle (fig. 1).

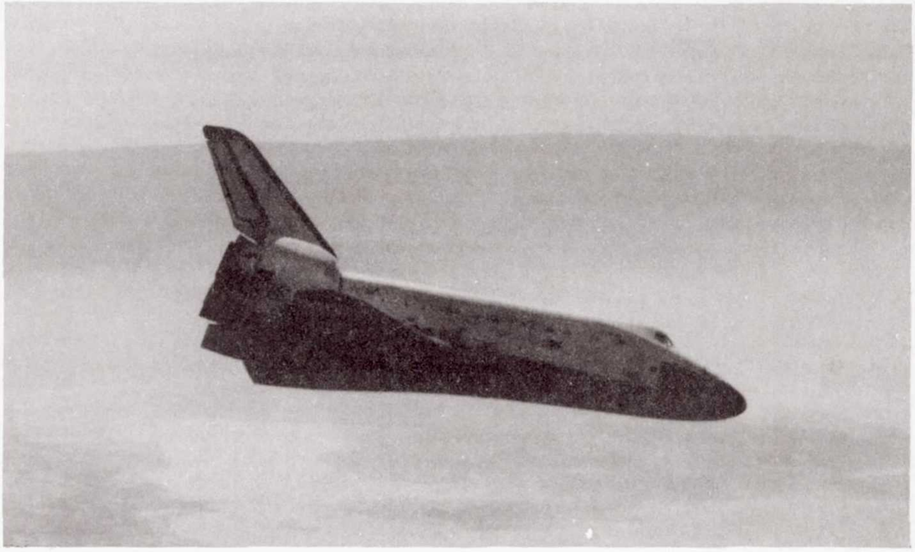

FIGURE 1.- OV102 COMES HOME.

The Orbiter is essentially a conventional skin stringer aluminum structure with some limited usage of graphite epoxy for the cargo bay doors and orbital maneuvering system (OMS) pods. The properties for these materials dictate a maximum structural temperature of 350° F. The reusability goal of 100 missions necessitates a lightweight nonablative TPS that protects the structure and withstands the thermal and environmental loads of space flight. The TPS material selected (LI900) was developed by Lockheed Missiles and Space Company and is an exceptional thermal insulator. This ceramic material is highly brittle and has a low coefficient of thermal expansion. Therefore, any contraction of the aluminum skin to which the tiles are directly bonded would cause the reusable surface insulation (RSI) to fracture. To minimize in-plane incompatibility, a felt strain/isolator pad (SIP) was bonded between the tiles and the structure (fig. 2).

In addition, the plan form dimensions for most lower surface tiles were on the order of 6 inches or less. The 6-inch dimension was computed so as to meet the requirement that the tile gaps should be no less than 0.010 inch. This occurs during entry (when the structure is still cold from deep-space radiation) as the tiles become hot. The stiffness and dimensions of the SIP were designed to minimize the stresses induced into the brittle tile material from deformations predicted for the aluminum structure. Initially, the stresses expected in the TPS were well within the strength of the RSI, but as the design of the Orbiter progressed, mission requirements became firmer, and load predictions became refined, it became clear that the TPS would have to withstand loads higher than originally anticipated. Additionally, stress concentrating stiff spots were found to exist in the SIP (fig. 3). These stiff spots (caused by needling) decreased the allowable system strength to 6 psi in-

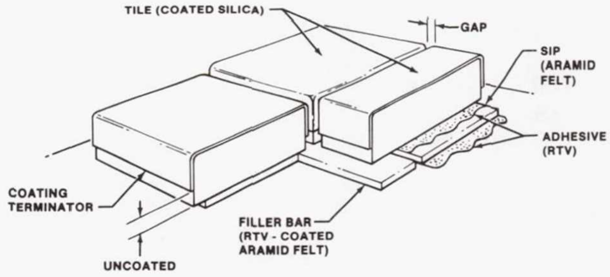

FIGURE 2.- SYSTEM DESCRIPTION.

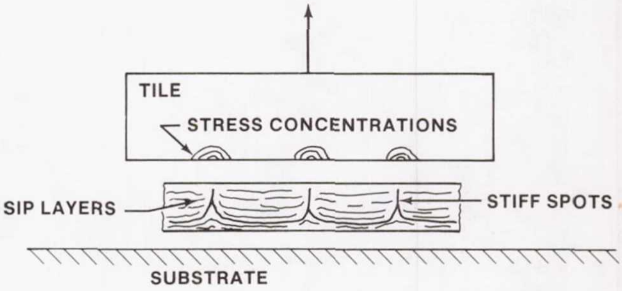

FIGURE 3.- STIFF SPOTS EFFECT ON LOCAL TILE STRESS.

stead of the 13 psi originally used for the tile strength. This caused negative structural margins of safety to exist over large areas of the structure and, in certain areas, the TPS was computed to be inadequate to survive even a single mission.

This paper will cover the principal design issues, tests, and analyses required to solve the tile structural integrity problem and performance based on the recent flight test program.

PROOF TESTING INSTALLED TILES

Because of the cost and schedule limitations imposed on the Orbiter project, it was necessary to begin fabrication and installation of the tiles long before the final loads and stress analysis had been completed. When large numbers of tiles were found to have inadequate structure margins, the Orbiter had just been delivered to Kennedy Space Center (KSC) with all but 6000 of the 33 000 tiles already installed. It seemed that there was no alternative but to remove every tile and start over (seriously impacting schedule and cost) with some new (as yet undeveloped) stronger tile system. The challenge was clear: to salvage the majority of the installed tiles while ensuring sufficient structural margin for a safe flight. The approach devised to overcome this almost insurmountable challenge was the so-called Tile Proof Test. The proof test involved the application of a load to the installed tile so as to induce a stress over the entire footprint equal to 25 percent above the maximum flight stress experienced at the most critical point on the tile footprint.

To fully appreciate the value of this proof test, it is necessary to understand the stress-inducing environments taken into consideration when computing structural margins. In addition to the local flight-induced loads (caused by aerodynamics, vibrations, and acoustic noise) and local substrate displacements (structural response to pressure differential and acoustic noise), a value of 0.019 inch (maximum allowed by installation specification) of tile/structural mismatch is assumed to exist at the point of maximum stress (fig. 4). Also, since this brittle TPS material has a large scatter in the strength data, the low 99-percent value was used in computing margins of safety.

Because most of the installed tiles would be stronger than the statistically derived low strength value, and since most of the tiles would realistically not have the maximum mismatch, it became clear that if the tiles were proof tested, most of them would successfully pass. Therefore, this approach could potentially salvage thousands of installed tiles and only a small percentage would fail and have to be replaced. The tiles that would fail would be replaced with tiles that had been densified on the inner moldline surface. The device used for this proof test (fig. 5) employs a vacuum chuck to attach to the tile, a pneumatic cylinder to apply the load, and six pads attached to surrounding tiles to react the load.

Since any appreciable tile load may cause some internal fibers to break, it was essential to develop a means of evaluating the residual strength of a tile after the proof test had been performed. During the actual proof testing, acoustic sensors (fig. 5) placed in contact with the tiles were used to monitor the acoustic emissions from any internal fiber breakage. A large-scale laboratory program was initiated to arrive at a failure criteria. The program consisted of acoustically monitoring many tiles during the proof loading and subsequently inducing cyclic loads (simulating flight values) until failure occurred or an equivalent of 100 missions was reached. A pass/fail criterion was established from the acoustic signatures of the tiles both failing and passing the laboratory tests. The proof testing of installed tiles was incorporated and not only salvaged tens of thousands of installed tiles but also revealed those tiles (13 percent failing proof test) with inadequate flight strengths.

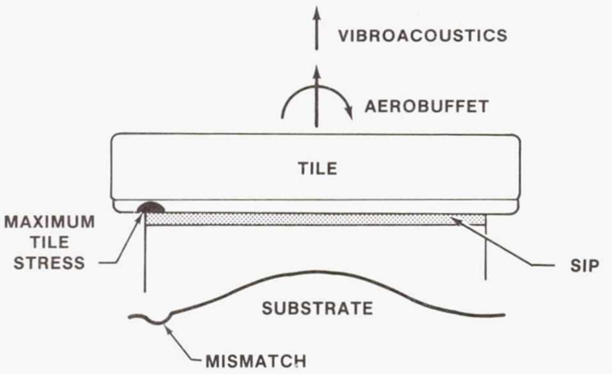

FIGURE 4.- TILE LOAD SOURCES.

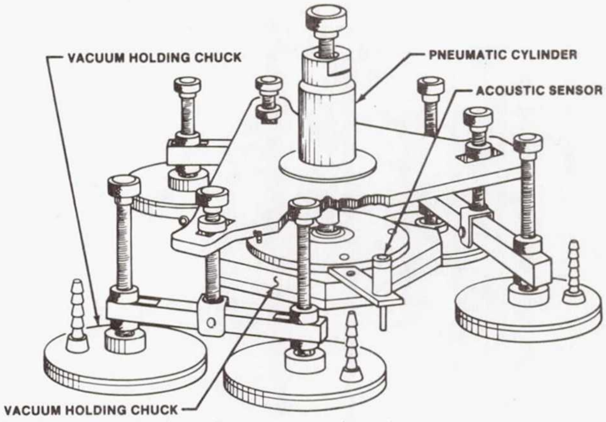

FIGURE 5.- PROOF TESTING DEVICE.

LOAD/DEFLECTION ALLOWABLE

If a tile were to fail during the proof test, it would be removed, the bottom of the tile would be densified (with a coat of colloidal silica particles), and the newly densified tiles reinstalled on the Orbiter. This densified layer, serving the function of a stiff plate on the tile bottom, eliminates the effect of local stiff spots in the SIP and thus increases the tile/SIP system strength from 6 to 13 psi (fig. 6).

However, there existed a large number of tiles where the combined loads were so high that even this doubled system strength was theoretically not adequate. The clear challenge was to exploit any additional densified tile strength not accounted for in the analysis. This challenge was successfully met by the incorporation of the so-called Stress versus Delta (displacement) allowable curves. This idea was conceived by realizing that the combined stresses could be classified into those induced by external loads (aerodynamics, vibrations, acoustics) and those induced by displacement (mismatch, structural out-of-plane displacement existing under the tile). It is the displacement-induced stresses that could possibly be reduced because the densified layer, being stiff, would resist bending and thus not transmit the total displacement stress to the virgin RSI material. This hypothesis was supported by extensive finite element analysis (fig. 7). The solid element models used in this analysis indicated a significant reduction of peak stresses in the virgin RSI material just above the densified layer.

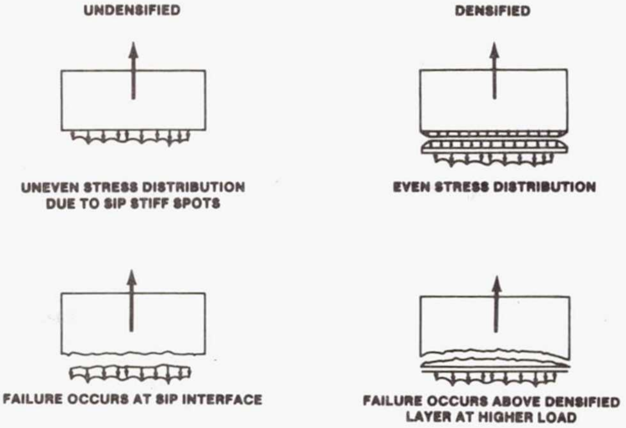

FIGURE 6.- EFFECT OF TILE DENSIFICATION.

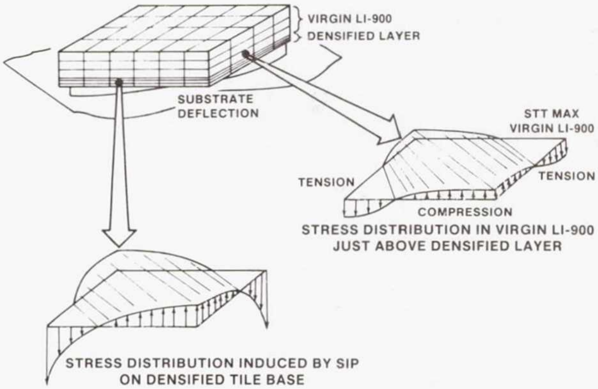

FIGURE 7.- TYPICAL ANALYSIS SHOWING HOW DENSIFIED LAYER REDUCES STRESS INDUCED INTO RSI.

With this information in hand, a test program was initiated to test numerous densified tiles to failure for various combinations of structural displacement and external loads. The test arrangement is shown in figures 8 and 9.

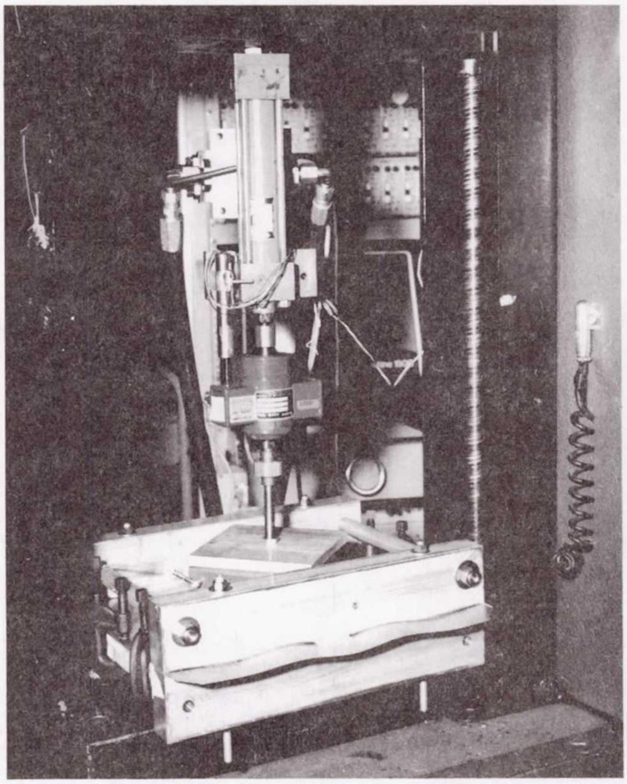

FIGURE 8.- TEST SETUP FOR LOAD/DISPLACEMENT ALLOWABLES.

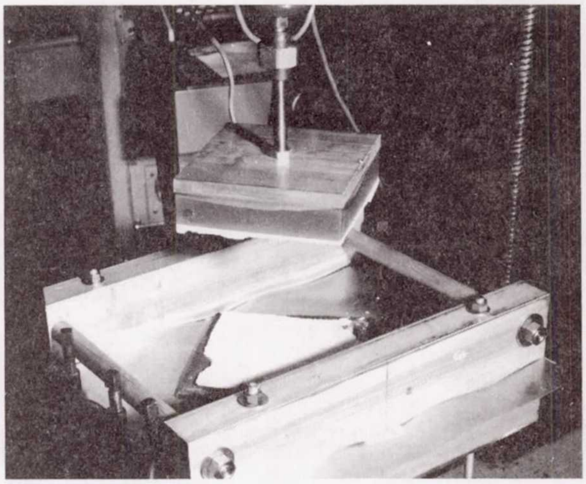

FIGURE 9.- TILE SHOWING FAILURE SURFACE DURING LOAD/DISPLACEMENT TESTING.

The average external stress level (P/A) at which each densified specimen failed was then plotted against the displacement (Delta) imposed under the tile. A bounding curve for densified tiles was then drawn on the Stress versus Delta plot. The results are shown in figure 10 together with similar data for undensified tiles.

The results obtained provided a method by which externally applied stresses and displacement-induced stresses could be realistically combined. The conservatism of simple addition of all stresses was eliminated and the full capability of densified tiles could be used to replace thousands of highly stressed undensified tiles.

AIRFLOW TEST OF SPECIAL TILES

During both ascent and entry, the TPS is subjected to numerous loadings from a severe aerodynamic environment including shocks and pressure gradients. Through development testing of RSI material, a basic load diagram was constructed for each of these conditions (fig. 11). These free-body diagrams make the analysis of square or rectangular (acreage) tiles relatively straightforward. However, most of the tiles adjacent to tile boundaries (such as the wing leading edge, windshield, landing gear doors, etc.) do not have such simple geometry. These special tiles are often located in a very complex flow field and because of their unique geometry create various intricate venting paths that can not be easily analyzed. Therefore, the challenge presented was to ensure the structural integrity of these special tiles and to gain a better understanding of the local flow conditions around such tiles. To meet this challenge, a combination of flight and wind tunnel testing was initiated. Locations (fig. 12) from several of the most complex flow fields and tile geometries were chosen to be tested.

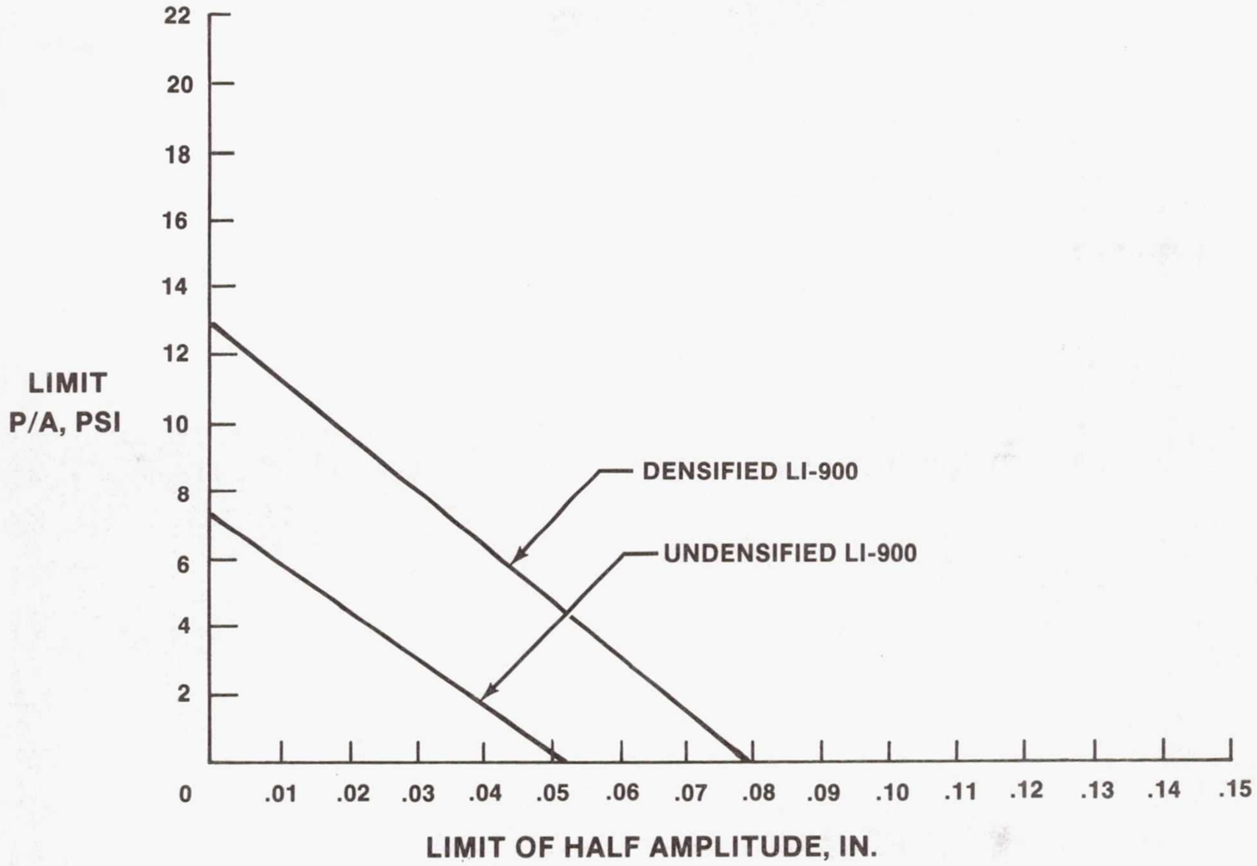

FIGURE 10.- ALLOWABLE FWT IN PRESENCE OF SUBSTRATE DEFLECTION.

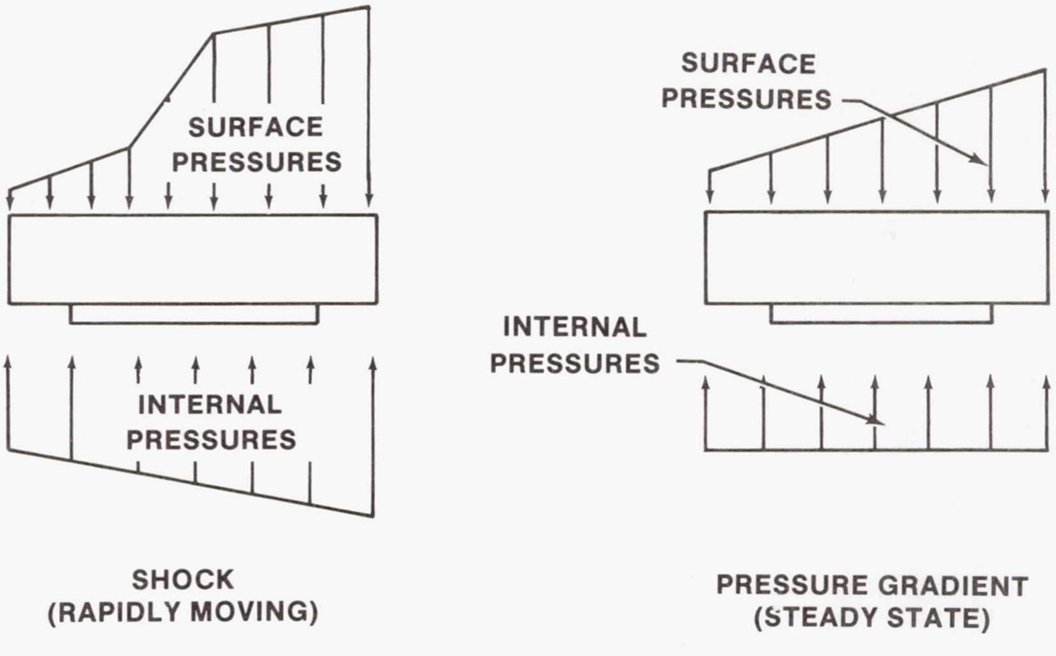

FIGURE 11.- BASIC LOAD DIAGRAM.

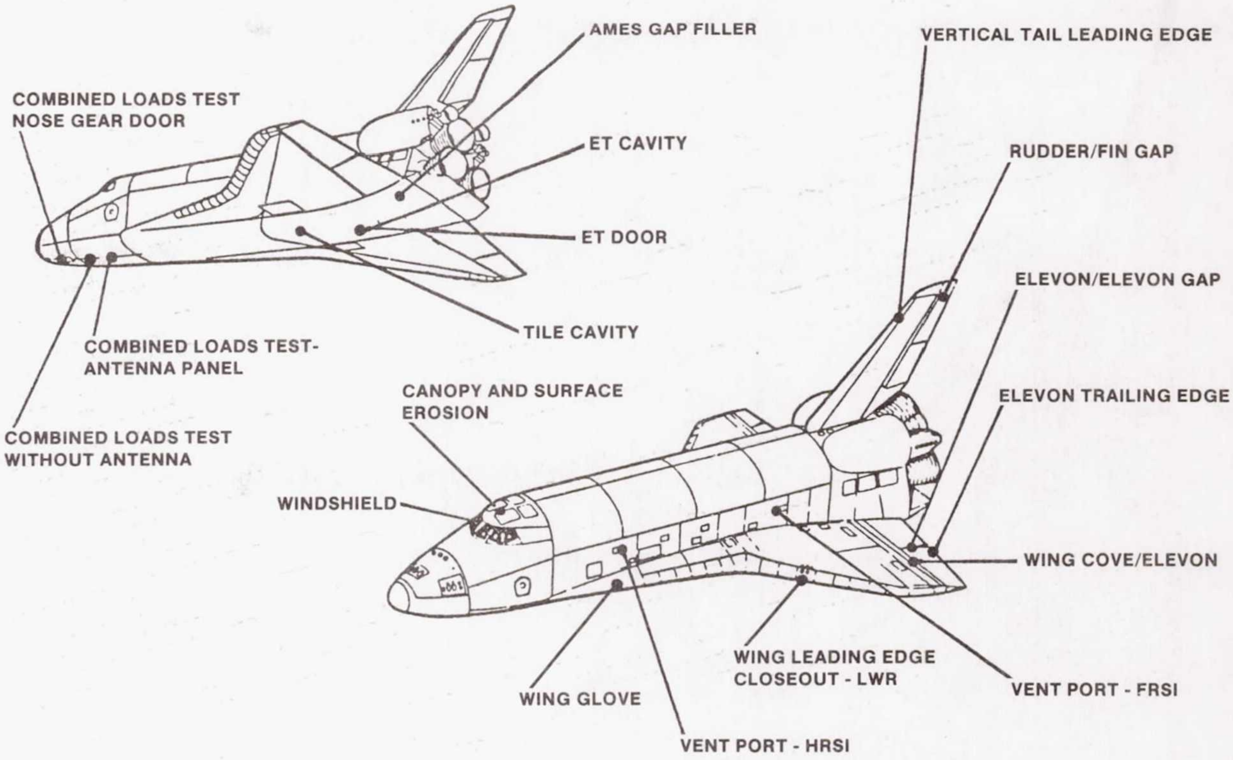

FIGURE 12.- TPS FLOW PROGRAM TEST ARTICLE LOCATIONS.

In each case, the local aerodynamic environment of the Shuttle (obtained from wind tunnel testing of scale models) was correlated to a similar flow field existing at some point on the surface of a high-performance aircraft or in a wind tunnel cross-section. All test articles were constructed to simulate the local Orbiter geometry. The tiles were heavily instrumented to ensure that test conditions achieved were within the predicted aerodynamic regimes (fig. 13).

A partial summary of these test conditions and results is shown in table 1. The tests not only demonstrated the structural integrity of each tile tested but increased the knowledge of flow around, under, and through the TPS. A more detailed treatment of tile flow tests may be found in reference 1.

This test program provided a unique solution to the challenge of aerodynamic loads on special tiles. The program increased confidence in TPS design by identifying design deficiencies which were corrected and retested to ensure their reliability during future flights.

SPECIAL PROBLEM TILES

Late in the certification program, it became apparent through analysis and tests that a few unique tiles had high stress levels that could result in low margins of safety and/or failure. Each of these tiles represented a special challenge since most were already installed on the Orbiter and their removal or redesign could severely impact a tight launch schedule. Development of timely resolutions to these special tile problems presented an immense challenge.

Several examples of the challenges met and the techniques used are described in the following sections.

WINDSHIELD TILES

During ascent, the tiles bordering the Orbiter windshields are subjected to high stagnation pressures (fig. 14) which tend to lift the tiles. Analysis indicated that these pressures could drive

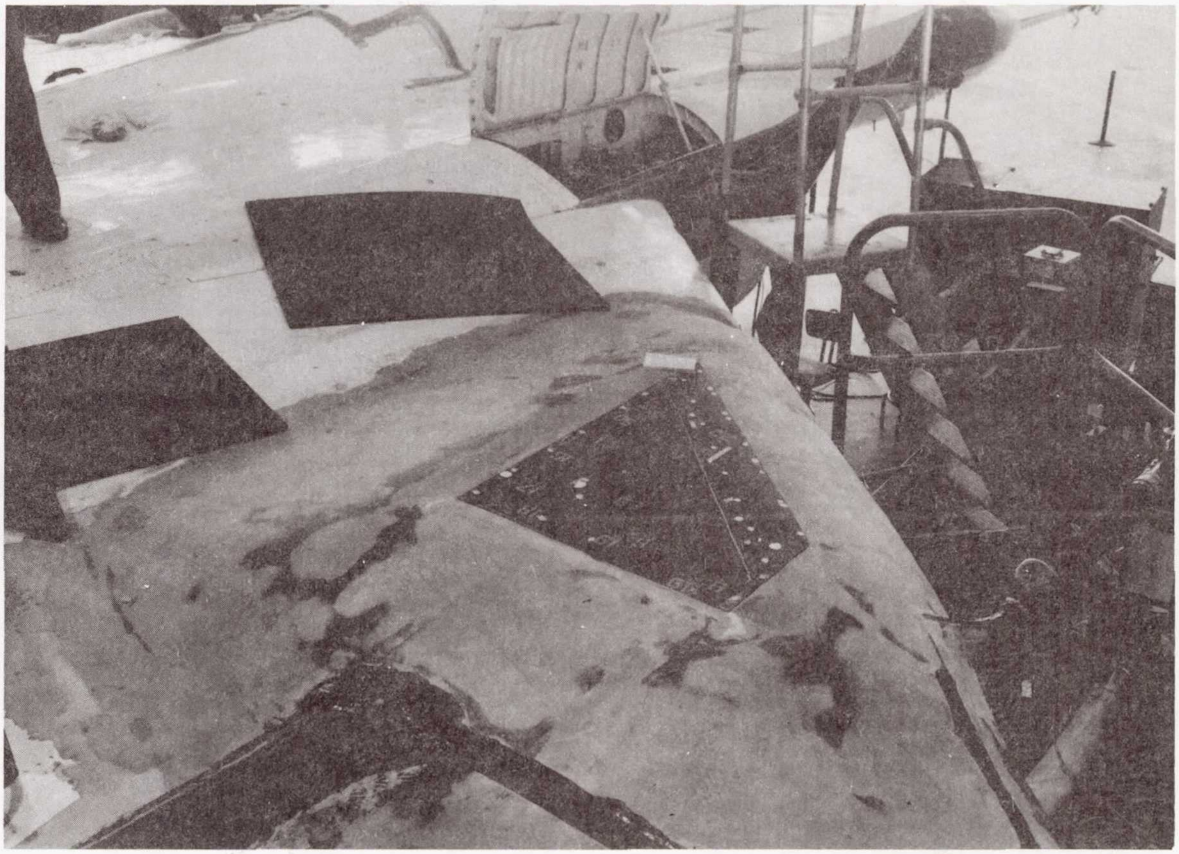

FIGURE 13.- TYPICAL AIRFLOW TEST PANEL ON F-15 AIRCRAFT.

the SIP bondline stresses above the RSI material allowables. This predicament presented a clear challenge; to increase the strength capability of these tiles while maintaining the substructure at an acceptable temperature.

The windshield tiles (like all Orbiter tiles) are machined from blocks of RSI material such that the layers of silica material run in a direction generally parallel to the Shuttle skin. This parallel grain orientation is a thermal requirement to minimize the conduction of heat from the outer moldline (OML) to the inner moldline (IML). However, this grain orientation causes a reduction of strength (through the thickness) because of the relatively low number of vertically running fibers between the silica layers. It is these vertical fibers that transfer loads to the structure. A possible solution was envisioned where the tiles directly around the windshield could be machined with their grain running perpendicular to the Orbiter skin. This would provide twice the strength but would create the possibility of overheating the structure. Accordingly, a thermal analysis was performed with tiles whose grain was oriented in a direction perpendicular to the Shuttle skin. In this configuration, more heat reached the aluminum skin as expected, but the heavy framing around the windows acted as a large heat sink that prevented unacceptable temperatures.

As a result of this analysis, the tiles around the windows were remachined so that the grain ran perpendicular to the Shuttle skin. While this significantly increased the strength of the tiles, an adequate margin of safety was not quite achieved. A further improvement was obtained by bonding the RSI material that overhung the window glass to the glass itself (fig. 14). This extra area, in combination with the grain orientation, provided acceptable margins of safety for flight.

INSTALLED TILE DICING

The curved forward section of the orbital maneuvering system (OMS) pod is covered with thin 8- by 8-inch tiles (fig. 15). Shortly before the first flight of Columbia, it was discovered that the

TABLE 1.- SUMMARY OF AIRFLOW TESTS

Description	Test facility	Test conditions	Results
Elevon trailing edge	F-104	Max Q = 455 psf	No anomalies.
ET umbilical cavity	AEDC[a] 16 ft	Max Q = 900 psf	Thermal barrier frayed, tiles under crossbeam loosened, and baggie retainer cord damaged tile outer moldline (OML). Redesigned hardware tested with no anomalies.
Canopy diced tile	Ames 11 ft	Max Q = 750 psf	Three tiles came off and several loosened. Pretest OML damage did not propagate. Re-test with mini tile edges bonded to filler bar was successful.
Wing leading edge closeout	F-15	Max Q = 1140 psf	Gap filler (horsecollar) migrated beyond OML and tiles showed excessive deflection. Redesigned horsecollar and tile support successfully tested.
Wing glove	F-15	Max Q = 1140 psf	No gap filler migration and tile step and gap change less than predicted. Test successful.
ET umbilical door	AEDC 16 ft	Max Q = 800 psf	Flow restrictors failed in initial test. Redesign successful.
Vent port - FRSI	Ames 11 ft	Max Q = 970 psf	No anomalies.
Vent port - HRSI	Ames 11 ft	Max Q = 970 psf	Limit and ultimate load portion complete. After ultimate condition was reached, portion of aft tile came loose. Life testing to continue.
Windshield closeout tiles	F-15	Max Q = 1140 psf	Initial tests indicated high net airloads. Redesign tested. No anomalies.
Wing cove/elevon	F-104	Max Q = 1125 psf	No anomalies.
Shaved tile/ mini gap fillers	Ames 11 ft	Max Q = 650 psf	No anomalies.
Vertical tail leading edge	F-15	Max Q = 1140 psf	No anomalies.
CLOT - forward fuselage acreage-calibration panel	LaRC[b] 8 ft	Over 90 min of shock from bipod	No anomalies.

[a] Arnold Engineering Development Center.
[b] Langley Research Center.

revised combined loads on the OMS pod structure would produce considerably higher deflections than previously anticipated. Since thin tiles are relatively weak under a bending load, the increase in predicted deflections could cause these fragile tiles to fracture and possibly separate from the OMS pod. The challenge then became how to reduce the effect of these increased deflections on tiles already installed without requiring their removal. The approach pursued was to develop a vehicle dicing procedure (fig. 16) whereby the larger 8- by 8-inch tiles were cut into smaller pieces which could more easily accommodate the high structure deflections.

Dicing had previously been used to reduce deformation-induced stress and to aid in the installation of thin tiles but the tiles were always diced before installation. To perform the operation on the Orbiter, special tools were developed and the cutting carefully monitored to ensure the desired cuts were made without damage to tile or substrate. This procedure was successfully performed on the OMS pod and later in other areas of the vehicle thus providing a timely solution to a challenging problem and salvaging hundreds of tiles.

AUGER

During the calculation of flight stresses for the body flap tiles, it was determined that the trailing edge corner tiles did not have adequate margins of safety for the predicted vibration and acoustic loads during lift-off (fig. 17). This was later confirmed during the acoustic testing of the body flap when both corner tiles (weighing approximately 6 pounds) failed within seconds of start-up. These LI2200 corner tiles are overhung in two directions, thus creating a large overturning moment on a small SIP area and correspondingly high tension stress. But even more significant than the stress levels was the inability of the SIP to withstand this high cyclic loading. The challenge therefore became twofold: (1) how to prevent failure caused by high RSI tensile stress, and (2) how to prevent the SIP from failing because of the high values of cyclic loading experienced on the body

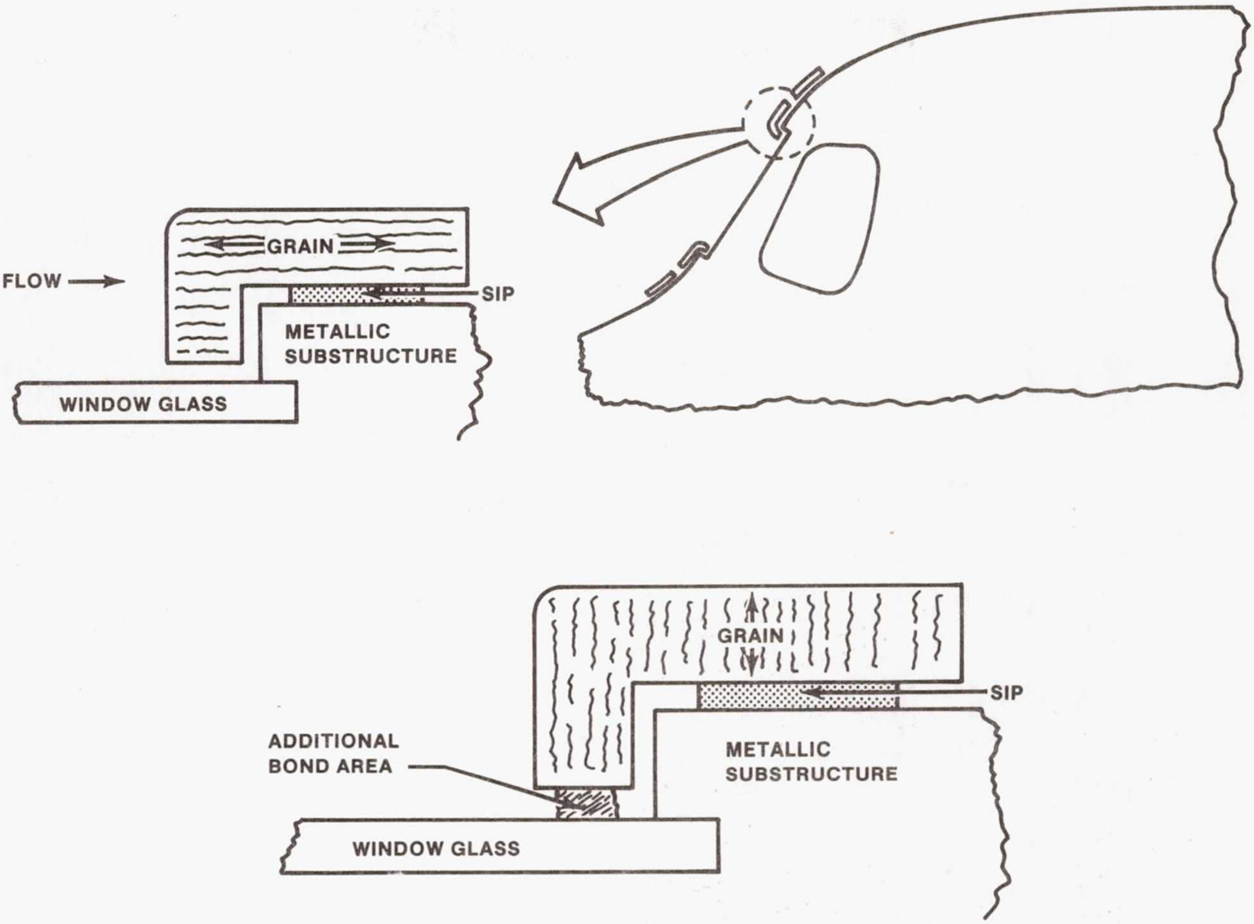

FIGURE 14.- WINDSHIELD TILES.

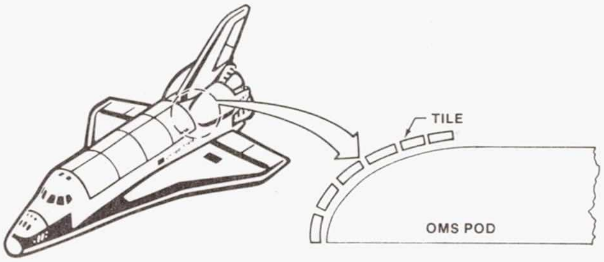

FIGURE 15.- OMS POD TILES.

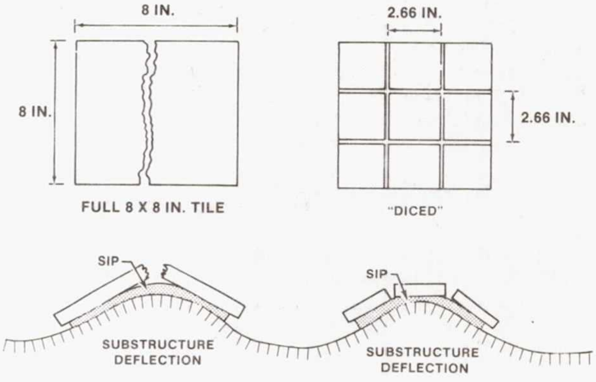

FIGURE 16.- EFFECTS OF DICING.

flap. To increase the capability of the corner tile for high oscillatory load, a mechanical attachment developed earlier called the Auger was considered. The auger system (fig. 18) is twisted into a tile and then attached to the substructure by bolts.

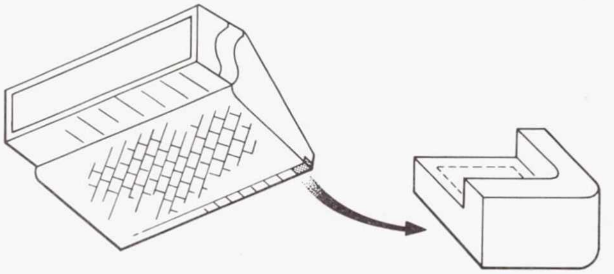

FIGURE 17.- BODY FLAP CORNER TILE.

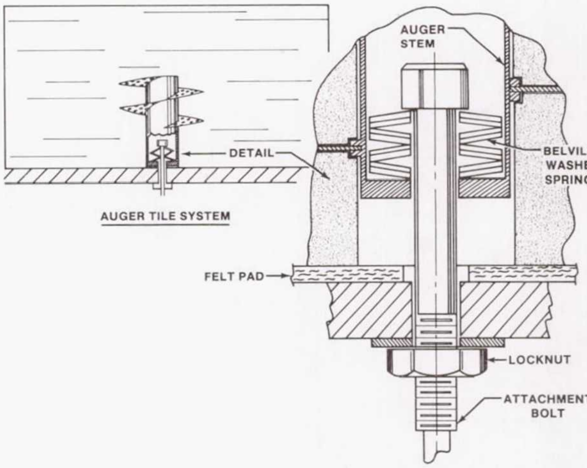

FIGURE 18.- AUGER TILE ATTACHMENT.

The key component of this system is the use of Belville washers to preload the auger itself with a tension load while at the same time inducing a compression stress in the SIP. The preloaded washers (acting as a soft spring) and the compressed SIP (acting as a stiff spring) then worked together as a parallel spring system. The stiff SIP, since it is greatly compressed, takes most of the external cyclic loading, while the Belville washers help prevent significant cyclic loads from being induced by the auger into the intolerant RSI material. The auger system is preloaded to a high enough level that the SIP remains in compression throughout the flight environment, and the tension sensitive bondline is prevented from experiencing a high tensile loading (see load diagrams in figures 19 and 20). The auger system has been fully certified by test for 100 missions and has flown successfully on both OV102 and OV099.

GAP FILLERS AND FILLER BAR BONDS

Two other on-the-Orbiter techniques were developed to meet the challenge of salvaging tiles with high shock-induced stresses in a timely manner. One of these "fixes" involved thick tiles (usually on the lower surface) with a relatively small footprint. As shocks sweep over these tiles, they would tend to rotate inducing high stresses at the SIP/tile bondline (fig. 21). To reduce this shock-induced overturning moment, gap fillers were installed. Once contacted by the rotating tile, a gap filler will create a horizontal reaction that acts against the overturning moment and reduces bondline stresses.

However, for thin tiles (usually found on the upper surface) a gap filler "fix" would not efficiently reduce a shock-induced stress to acceptable levels. Therefore, a second on-the-vehicle technique was developed in which the filler bar surrounding the SIP was bonded to the tile. This was done by inserting a crooked needle into the tile-to-tile gap and depositing RTV on top of the filler bar where the additional bond area is desired (fig. 21). This extra bond area significantly increases the total bonded footprint and decreases the effects of a shock-imposed overturning moment.

Both of these techniques have been selectively implemented where analysis indicated shock-induced stresses were exceeding allowables and needed to be reduced significantly.

The special tiles examples presented in these sections affected very few tiles but their resolution contributed greatly to the highly successful Shuttle flights.

CONCLUDING REMARKS

A wise man once stated, "It is better to attempt a gigantic endeavor but fall slightly short than to attempt very little and be highly successful." The Space Shuttle and indeed the development of the TPS tiles was such a gigantic endeavor but it was almost flawlessly achieved. In this paper, the focus was on the challenges and technical resolution of the tile structural integrity; however, it should be emphasized that the challenges were resolved in an environment of tight cost, tight schedule, and high public visibility. This environment necessitated the practical resolution

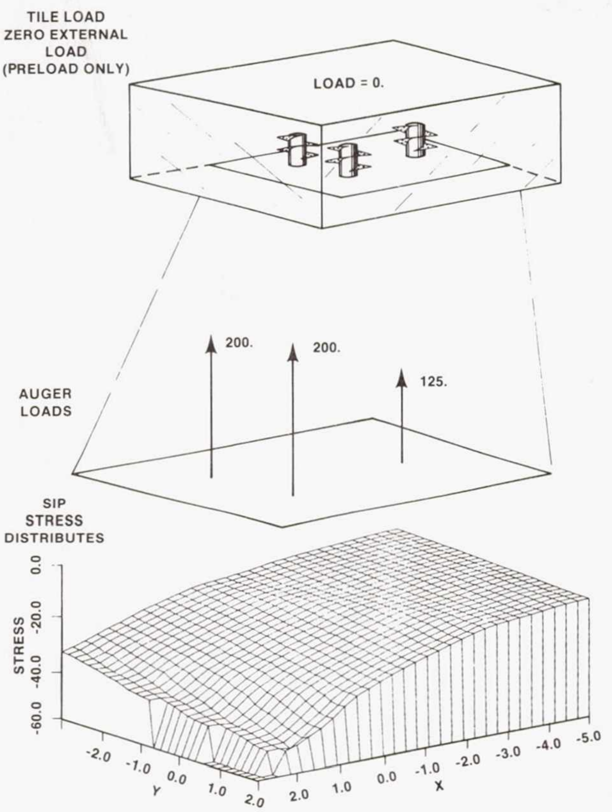

FIGURE 19.- FREE-BODY DIAGRAM OF HIGHLY LOADED AUGER TILE.

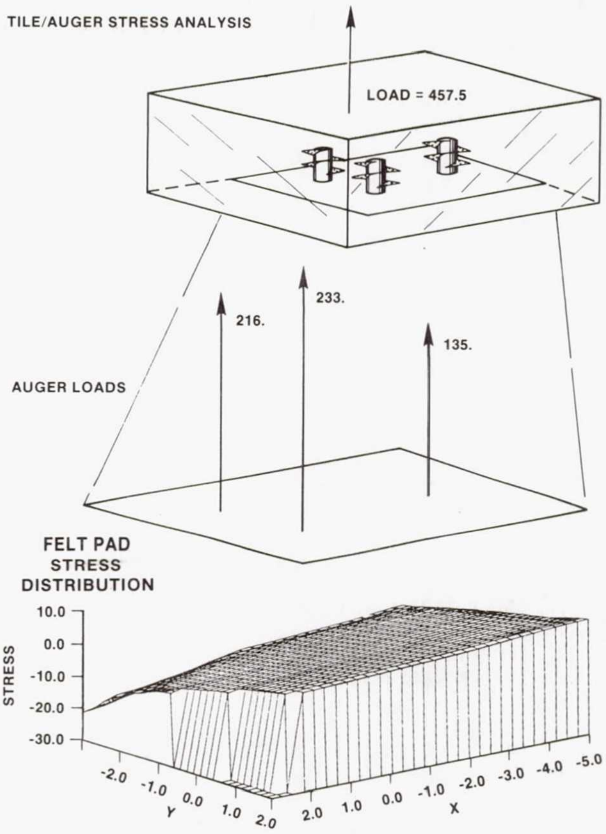

FIGURE 20.- FREE-BODY DIAGRAM OF HIGHLY LOADED AUGER TILES.

afforded first by the Proof Test (affecting tens of thousands of tiles), later by the Load versus Delta curves (affecting thousands of tiles), and the Airflow Tests (affecting hundreds of tiles), and finally by the Special Tile Fixes (affecting small numbers of tiles). It is in this emphasis on the most timely resolution of the tile structural challenges that the program should feel much pride.

REFERENCE

1. Barneburg, Jack: Inflight Aerodynamic Load Testing of the Shuttle Thermal Protection System. AIAA 81-2468.

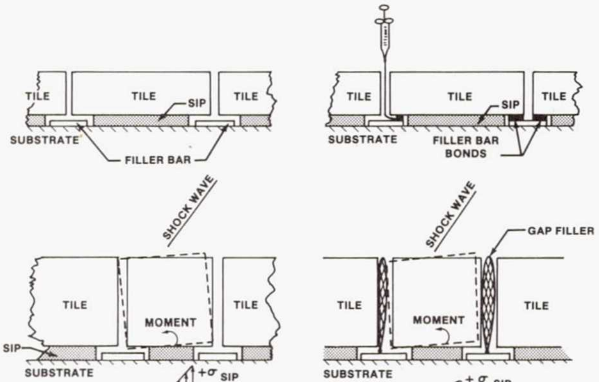

FIGURE 21.- SCHEMATIC OF A TILE AND GAP FILLER INSTALLATION.