

**RELIABILITY ENGINEERING OF THE  
SPACE SHUTTLE: LESSONS LEARNED**

Thomas L. Moser

NASA Lyndon B. Johnson Space Center, Houston, TX 77058

**ABSTRACT**

The Space Shuttle demands very high structural reliability because this space transportation system represents a major national commitment by the United States, human lives are directly involved in the operations, and scientists and engineers from all sectors rely on it. This paper addresses how the strength integrity challenges were met and resulting precedents, which emerged during the development of both the structure and thermal protection system (TPS), are reviewed. Innovations in criteria, design solution, and certification are highlighted, and brief comments on the lessons learned are included.

**KEYWORDS**

Structural Reliability; Space Shuttle; Strength Integrity;  
Thermal Protection System

**1. INTRODUCTION**

The National Space Transportation System (NSTS, or STS, or "Shuttle", as it is commonly known) has been a major challenge for structural engineers because (1) this vehicle operates in extreme environments, both natural and self-induced; (2) during the development, many of the loads and environments could not be simulated on earth; (3) the TPS tiles were great in number, each critical for safety or operations, low in strength, and difficult to attach; (4) classical methods of analyses and certification could not be employed; and (5) a reusable manned spacecraft with high mission flexibility had never been developed. Highly reliable single-use boosters and spacecraft had been previously developed and early studies did not identify significant technology issues with structural reliability. As engineering concepts emerged, design loads and environments defined, and program constraints became reality, it became obvious innovative structural engineering approaches were required and new precedents would be set.

## 2. DESIGN LOADS AND ENVIRONMENTS

The operational concept of the Shuttle was to employ a reusable spacecraft (Orbiter) thrust vertically into low earth orbit using three stages of powered flight, orbital operations, and return to earth using atmosphere braking and unpowered flight to a classical aircraft horizontal landing. Figure 1 delineates a typical mission.

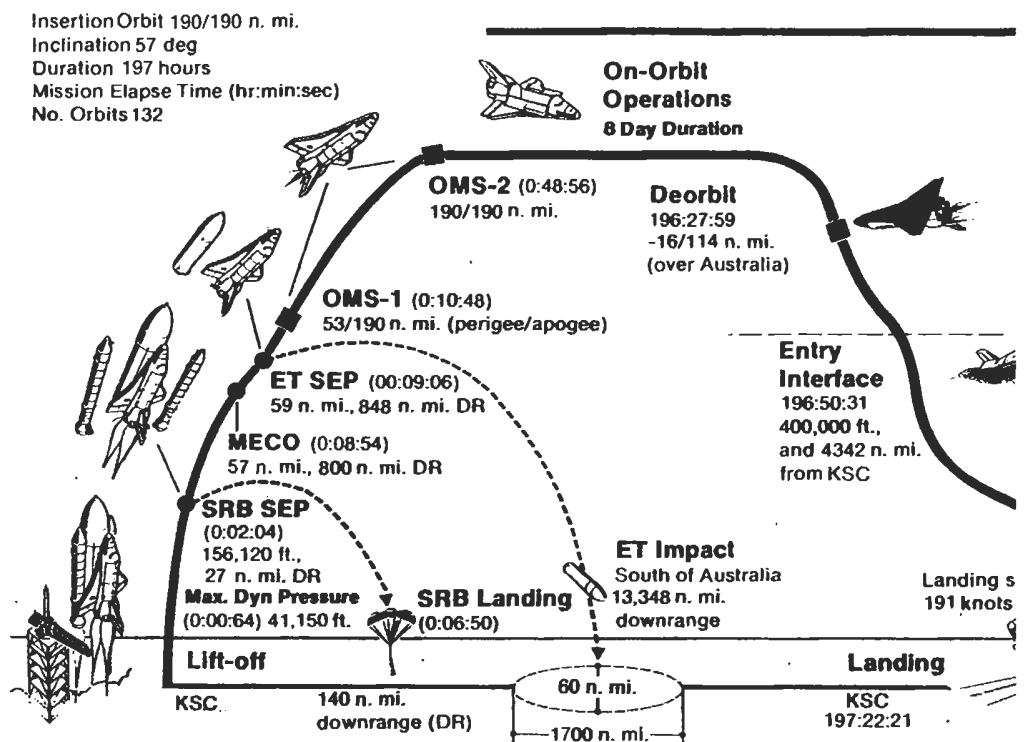


Figure 1.- Space shuttle nominal mission.

Results of early Shuttle studies had shown a clear performance benefit with increasing dynamic pressure ( $q$ ) and minimum rocket engine throttling. A conscious design decision was made to limit the maximum dynamic pressure to 650 PSF nominal and the maximum longitudinal accelerations to 3g axial. A desired effort was to limit the  $q$ -sensitive parameters such as peak differential pressure, buffet intensity, aerodynamic noise, aerodynamic loading, control authority, and flutter requirements within manageable bounds. The liftoff and maximum dynamic pressure were conditions in which the statistics of the winds and the variations in the engine operations, Solid Rocket Booster (SRB) and the Space Shuttle Main Engines (SSME), were significant contributors to the structural loading. Table 1 depicts the major effects which contribute to the dynamic response and liftoff loads. Figure 2 shows the sequencing of the winds and thrust, and the resultant moments and crew cabin accelerations.

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#### Effects Considered for Design Loads

- o Ground Wind and Gusts
- o Vortex Shedding
- o Proximity and Shapes of Nearby Structures
- o Pressurization
- o CYRO Shrinkage of Structure
- o Rocket Engine
  - Start Sequencing & Deviations
  - Thrust Vector Misalignments
  - Ignition Overpressure

Table 1. Liftoff Loads

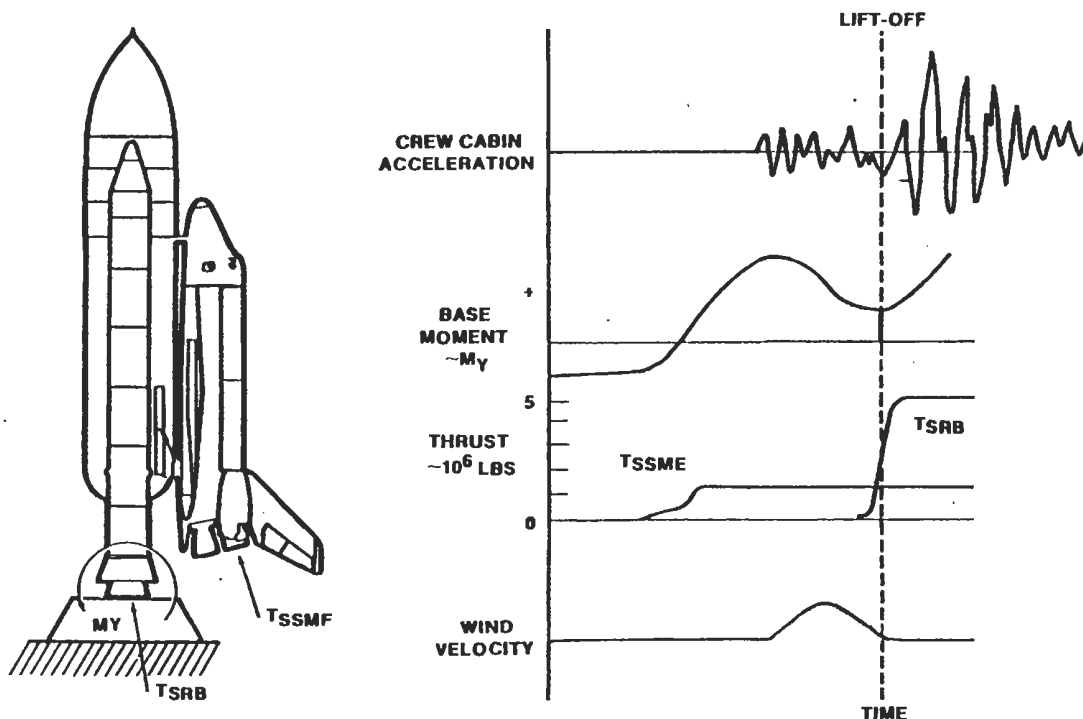


Figure 2.- Liftoff loads.

As the critical loads analysis studies progressed, it became obvious that trajectory simulations of high-q ascent were sufficiently cumbersome to prevent surveying the entire flight envelope for hardware design cases. For ascent, an entirely new precedent emerged. Analogous to an airplane V-n (velocity versus normal load factor) diagram, the squatcheloid was derived for ascent loads conditions as a function of dynamic pressure (q), angle of attack ( $\alpha$ ), angle of side slip ( $\beta$ ), and mach number ( $M_\infty$ ).

Further explanation of this process is as follows. Synthetic wind profiles were developed using NASA TMX 53872, Terrestrial Environment (Climatic) Criteria Guidelines for Use in Space Vehicle Development. The wind profiles used the 95 percent

9m/sec quasi square wave gust was superimposed. When combining shear buildup and gust an 85% factor was applied to the gust.

Angle of attack and sideslip excursions were defined by analytically flying the vehicle (with control system) through the wind profiles defined above. System dispersions such as SRB thrust mismatch, aerodynamics, thrust variations and flight control system variations were statistically defined at the +3σ-level. These dispersions to angle of attack and sideslip were then added to those caused by the wind profiles. Loads for structural design could then be generated at any point around the squatcheloid envelope of angle of attack and sideslip. Squatcheloids with critical load cases are shown in Figure 3.

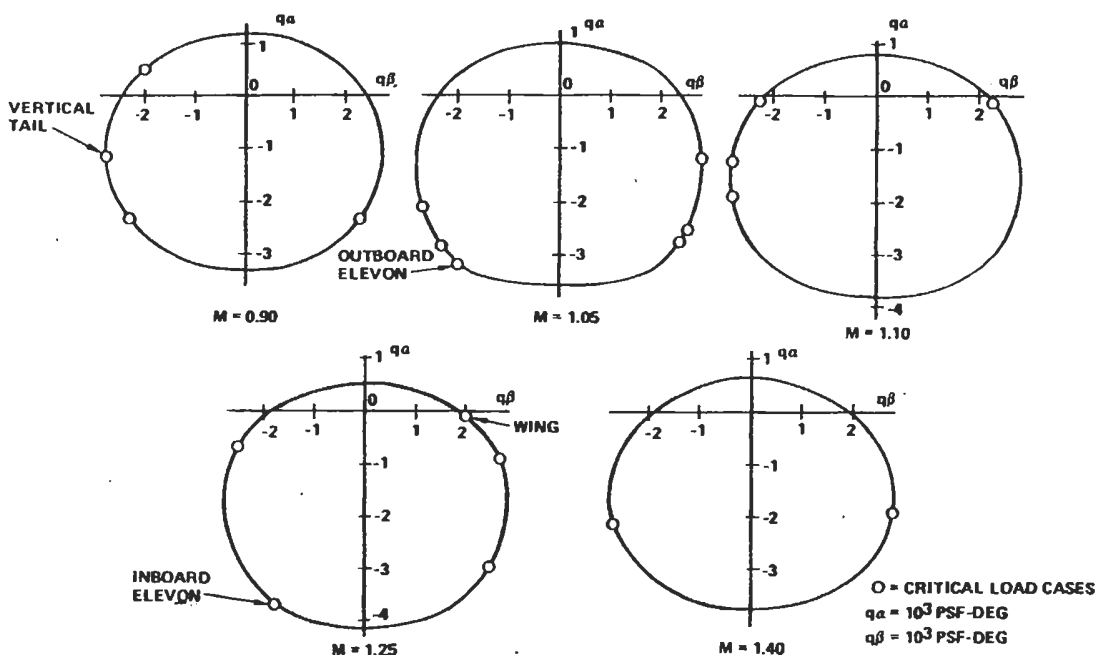


Figure 3.- Squatcheloids with critical load cases.

This innovative concept preceded the development of the ascent control system as well as the multi-mission and real-wind trajectory simulations. The Shuttle loads analysis was capable of surveying hundreds of potential design conditions within the flight envelope. Load surveys and structural indicators were evaluated even though the trajectory surveys had not been performed. The Orbiter SSME thrust structure could be designed for compatible engine positions, consistent with the control system and engine mixing logic rather than with a worst case geometric mix. This allowed the performance, flight control, and structure disciplines to work in parallel rather than in the serial manner required with load trajectory simulations. Using the squatcheloids, a survey of approximately 65,000 load cases was made. Fifty of which were finally used for final detailed structural analyses.

Descent maneuver loads were derived in a similar manner using V-n diagrams for various mach numbers. This approach was judged prudent and

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proved to be correct even though early entry trajectories did not require significant maneuvers.

3. STRUCTURAL DESIGN CRITERIA

The methods described above enabled an early set of design loads and conditions to be defined which had a low probability of not being exceeded but at the same time were not so conservative that structural weight penalties would result. The strength integrity criteria selected was somewhat less conservative for ultimate and yield factors of safety than those used in conventional aircraft design, both military and commercial. The significance of the analyses would be paramount because, as will be discussed later, the strength integrity of the Orbiter was certified by analyses. The design criteria for major elements of the Shuttle (Orbiter, SRB, and External Tank (ET)) varied somewhat but, for discussion, that of the Orbiter was:

1. Ultimate factor of safety  $\geq 1.4$  for limit loads.
2. Yield factor of safety not specified; however, detrimental deformations were not allowed at limit load.
3. Thermal and mechanical stresses were added except when thermal stresses were relieving.
4. Structural life (100 missions) had a scatter factor of 4 applied and all parts were considered for fracture mechanics.
5. An ultimate factor of safety  $\geq 1.25$  was required at the end of 100 missions when considering only the degradation of material allowables as a result of time at temperature.
6. Material allowables were based on
  - o 95 percentile and 95 percent confidence for single load paths
  - o 90 percentile and 95 percent confidence for redundant load paths

The initial design philosophy used for all elements was for a safe-life structure and current (1972) technology. The philosophy held throughout the development, by in large, with the exception of specific areas in the Orbiter. In order to increase the reliability of closing the large payload bay doors onorbit (when considering thermally induced and zero-g structural distortions) the doors were designed to react only pressure differential and fuselage torsion loads. This enabled the doors to be flexible and zipped closed with a series of latches. Graphite epoxy structure was used in the doors to reduce thermal expansion. The only other exceptions to the highly reliable conventional metal structures were the graphite-epoxy Orbital Maneuvering System (OMS) skins, boron epoxy overlay on the SSME thrust structure (designed to be fail-safe), and small boron aluminum thrust tubes in the Orbiter mid fuselage frames. Figure 5 shows the structural arrangement of the Orbiter.

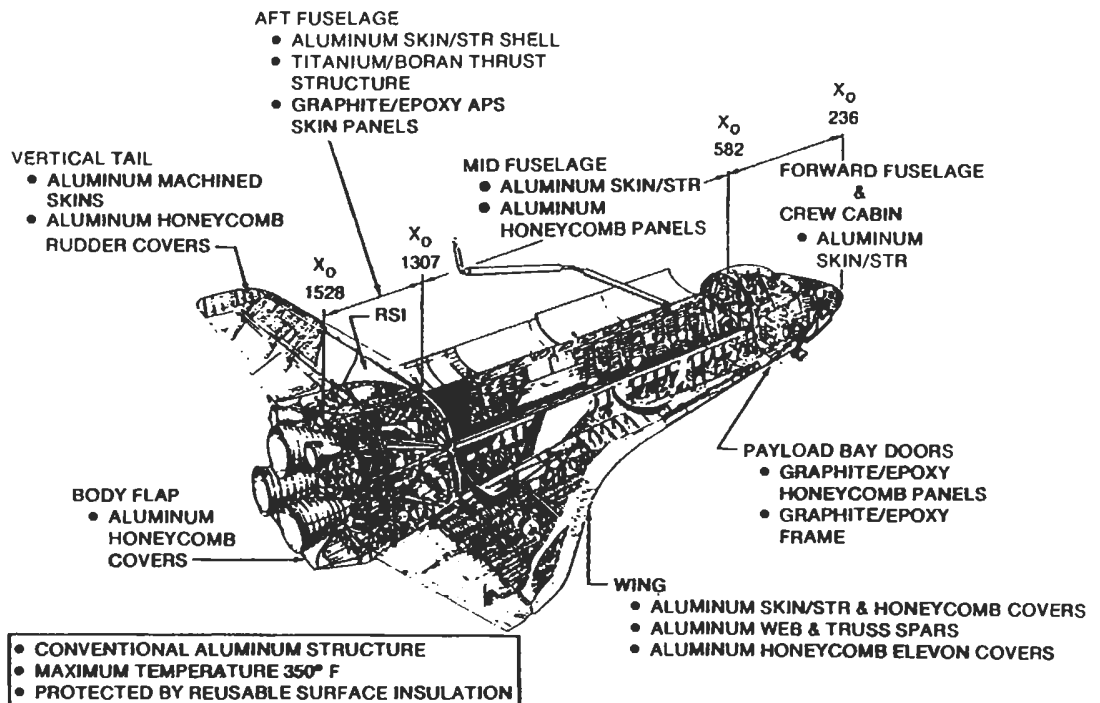


Figure 5.- Orbiter structure.

#### 4. STRENGTH INTEGRITY ANALYSES

Conventional finite element structural analyses were used for analyzing the structures. Idealized structural models were analyzed separately for critical external loads, thermal loads, mechanical loads, and internal compartment pressures. The final internal loads were obtained from combining these solutions using a series of computer programs called the post-processor. The post-processed data were searched and the most critical conditions identified on an element by element basis. These elemental data were used to perform a detailed stress analysis and compute a margin of safety.

Thermal stress played a significant role in the design and analysis of the Orbiter primary structure. As expected, the most significant thermal stresses occur during the atmosphere entry phase of the mission. The most critical times during entry are maneuver and landing since the thermal stresses have to be combined with the associated mechanical stresses. For many areas of the Orbiter structure the magnitude of the thermal stress is substantial and drives the design. For example, the thermal stress for the lower surface of the midfuselage is approximately 60 to 70 percent of the total stress. Similarly, the wing and aft fuselage have areas where the thermal stress is over 50% of the total stress.

Although the thermal protection system (TPS) maintains the structure temperatures below 350°F, temperature gradients still exist between various structural elements resulting in substantial thermal stresses. The structural areas influence by temperature gradients include:

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- o gradients between skin-stringer panels and frames or ribs
- o gradients between upper and lower wing covers
- o circumferential gradients around frames
- o gradients between lower surface and side skin panels
- o overall gradients between the wing and midfuselage; vertical tail and aft fuselage
- o local gradients on skin-stringer panels

Results of early studies had not revealed the complexity of defining design-case thermal stresses. Attempts were made to desensitize the minimum weight concepts for thermal stresses but they were not practical. Also, conservative thermal gradients were inconsistent with the three-dimensional finite-element loads combination approach. As a result deterministic temperatures were established for eight initial temperature conditions on the Orbiter at time of entry and at several times during the entry. A typical thermal model of which 120 represented selected regions of the Orbiter is shown in Figure 6. The temperatures were extrapolated and interpolated to about 100 times the thermal models and distributed to the structural model nodes. This experience demonstrated the technology weakness of determining the design-case transient thermal stress for large three-dimensional structures. It remains for the operational planners to ensure that the operational envelope stays within the budget.

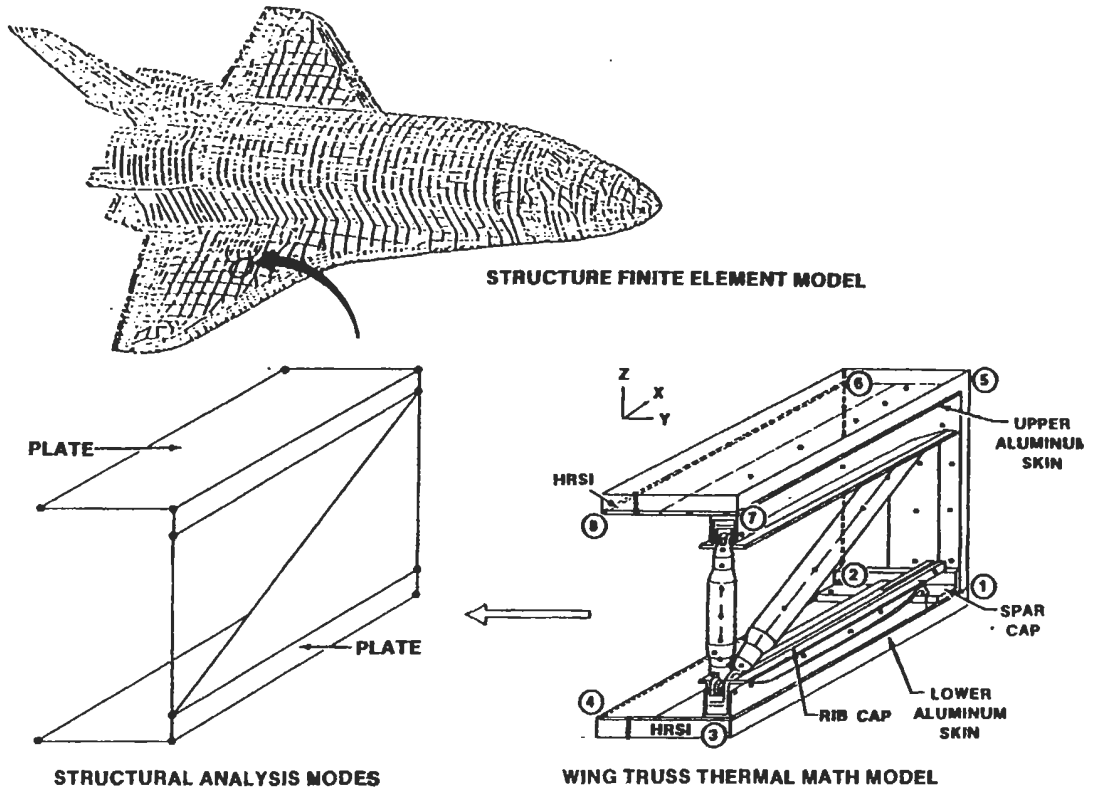


Figure 6.- Orbiter thermal stress analysis modeling.

5. STRUCTURAL FLIGHT CERTIFICATION

The structural reliability of most aircraft designs is certified by test

demonstration. In the case of the Orbiter this was not possible because the critical stresses could not be induced by ground tests. These limitations enabled the emergence of an innovative certification approach which has set a precedent for structural certification.

The Orbiter structure had evolved under such weight-saving pressure that virtually all the primary structure had a significant thermal stress component. Attempts to factor mechanical loading into equivalent thermal loadings resulted in inconsistent stress distributions which were not meaningful simulations. Thus, it became clear that the classical demonstration of design ultimate strength was not feasible without a thermal simulation. Such a simulation was not practical and probably not possible for the transient cases of interest. The objective of the test then had to emphasize the correlation of the stress analysis with the measured strain data. It also became evident that a test of ultimate load (1.4 times limit) would not achieve design ultimate stresses but would probably result in deformations and strains to render the airframe unusable for flight. From this situation emerged a precedent-setting proposal: (1) test to 1.2 times the final design loads, (2) require detailed stress analysis of each test condition, (3) include unit load test evaluations where required, (4) perform a combined thermal and mechanical test of the forward fuselage, (5) instrument sufficiently to compare the analysis and identify peak critical stresses, (6) perform additional component test investigations for ultimate strength and fatigue of identified critical interface hardware, (7) perform and document a critical post-test inspection, and finally, (8) refurbish the airframe structure for use as a flight vehicle. Daring as this proposal initially sounded, the technical detail and innovative imagination was sustained through complete management review as well as special technical review teams.

The results of the testing were quite impressive. The stress distributions in the critical test regions compared within 10 percent of the analysis with few exceptions. The thermal test measured stresses compared well (10 percent) with those measured on the frames and internal structure. The skin stresses in the circumferential directions were considerably less (30 percent) than predicted analytically and in good agreement longitudinally.

The proof test concept used on the Challenger vehicle continues to achieve significant cost savings as it has been applied to several Space Transportation System (STS) payloads. This concept is a recognized verification concept for payloads. It is emphasized that use of this approach requires detailed engineering with attention to the structural details, sufficient instrumentation, and rigorous post-test inspection.

## 6. THERMAL PROTECTION SYSTEM

The Thermal Protection System (TPS) of the Space Shuttle Orbiter is a unique, specially developed system for thermally protecting the conventional aluminum structure from the intense heat encountered during reentry to the earth's atmosphere. Three material systems comprise the total TPS, but the one of pure-silica fiber tiles, covering most of the vehicle, is particularly interesting to those concerned with structural reliability. The tiles, which are extremely light-weight, brittle, and low-strength must maintain their structural integrity through the grueling acoustic and aerodynamic load environments of Shuttle launch, the thermal extremes of space operation, and the high temperatures of reentry. To assure that each



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of the more than 30,000 individual tiles had adequate strength, it was necessary to define and verify the macroscopic vehicle loads and environments and then the microscopic tile loads and environments; to stress analyze each tile for its unique configuration and environment; to demonstrate the integrity of selected tiles by acoustic, aerodynamic, thermal, vibration, static load, and combined environment tests; and then to proof load the tiles after installation on the Orbiter. It was necessary to develop, late in the program, processes for doubling the strength capability of the bonded interface of the tiles, pulling on the fragile tiles bonded to the Orbiter and yet making sure that this loading did not result in excessive damage to the tile, and nondestructively determining the strength of the silica material.

The tiles are one of the three major material systems which comprise the total Orbiter TPS and which had to meet the general design requirements:

- o Limit structure temperature to 350° F
- o Useful life of 100 missions
- o Withstand surface temperatures from -250° F to 2500° F  
Heat loads to 60,000 Btu/ft<sup>2</sup>  
Acoustic levels to 166 dB  
Aerodynamic pressure (freestream) to 819 psf
- o Provide the aerodynamic moldline
- o Attach to aluminum structure
- o Economical weight and cost

The Reusable Surface Insulation (RSI) tiles, shown conceptually in Figure 7, are designed to radiate 90% of the reentry heat back to space before it can be conducted to the Orbiter's structure. Since the structure deforms in-plane during a mission, continuous covering for large areas would not work without fracturing the structurally weak silica material - thus, the nominal 6-inch square tile with a 0.05-inch gap between it and its neighbor. To accommodate the flight-induced out-of-plane structural deformation, the individual tiles are mounted on a compliant strain isolation pad (SIP) made of Nomex felt.

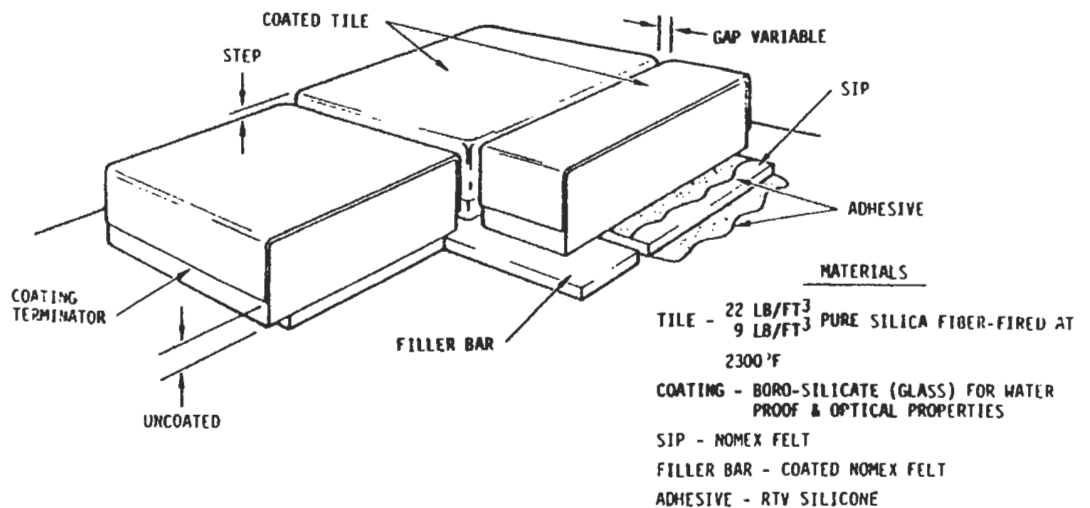


Figure 7.- Tile design.

Establishing the tile concept was just the beginning and was quite simple. The real engineering problems then began. It was necessary to design thousands of unique tiles which had compound curves, which interfaced with thermal barriers and hatches, which had penetrations for instrumentation and structural access, etc. The overriding challenge then was to assure the strength integrity of the tiles with a confidence that there was no greater chance than 1 in 10,000 of losing any one of the more than 10,000 more critical tiles (i.e., a probability of tile failure of no greater than 1 in  $10^8$ ). The statistical treatment of the tile strength integrity is addressed in Reference 1.

To accomplish this magnitude of system reliability and still minimize the weight, it was necessary to define the detail loads and environments on each tile. To appreciate the importance and magnitude of this task, one must first examine the sources which induce stresses in tiles. The sources are:

- o Substrate or structure out-of-plane displacement
- o Aerodynamic loads on the tile
- o Tile accelerations
- o Mismatch between tile and structure at installation
- o Thermal gradients in the tile
- o Residual stress due to tile manufacture
- o Substrate in-plane displacement

The first four are the predominant sources of stress but all must be accounted for, small as they may be, because of the low ultimate allowable tensile stress of 6 psi. Structural deflections as small as 0.020 inch under a tile can result in stresses equivalent to 50% of the allowable.

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The substrate-induced stress results from the structure deflecting under the tile because of pressure differential across the structure, vibration from engines and aerodynamics, in-plane buckling loads, and thermal gradients. The more compliant SIP accommodates this deflection by stretching but, in so doing, loads the interface of the tile.

All significant sources which induce stresses in each tile on the vehicle are considered for each phase of the mission. The matrix of load combinations is shown in Fig. 8.

	PRE LIFT-OFF	LIFT-OFF	ASCENT	ENTRY / LAMB	LANDING
MIS-MATCH/WARPAGE	X	X	X	X	X
IGNITION OVERPRESSURE - SSMF - SRFB	X	X			
AIRLOAD - GRADIENT - SHOCK - VERT LAG - SKIN FRICTION			X	X	X
VIBROACOUSTICS			X	X	X
OUT-OF-PLANE DEFLECTION		X	X	X	X

Figure 8.- Baseline load combination.

Verifying the strength integrity of tiles on a manned spacecraft is not unlike other components whose strength integrity is important and which are exposed to a combination of severe environments. The problem is conducting realistic combined load tests to demonstrate the ultimate strength capability. The prime method of verifying the strength integrity of all tiles was therefore by stress analyses and to test demonstrate where possible. Prior to STS-1, each tile was analyzed for the combination of loads shown in Fig. 8 and resulting factors of safety were compared to the requirements of 1.4 for ascent and 1.0 for the postheating flight regimes. An example of the population distribution of tile strengths is shown in Fig. 9. These results represent linear elastic analyses. To verify that the nonlinear stress-strain properties of the SIP did not result in stresses which violated the strength requirements, separate nonlinear stress analyses were performed on selected tiles which appeared to be the most highly loaded.

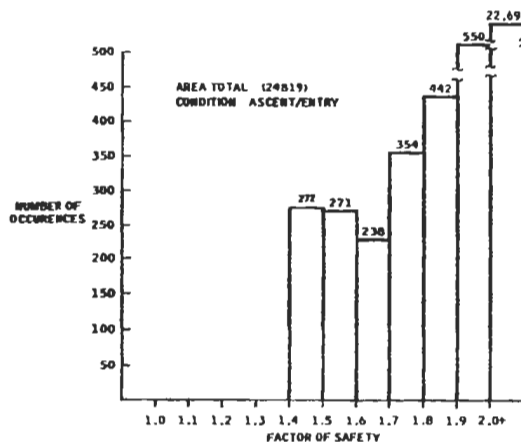


Figure 9.- Factor of safety histogram.

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Even though the stress analyses were performed on all the more than 30,000 tiles to verify the strength integrity, there was a broad spectrum of tests performed on hundreds of tiles to add confidence to the design, to verify the analyses, and to determine the microscopic load conditions on various regions of tiles. The test articles were selected based on the regions where the analytical methods were suspect, where a single environment (like acoustic vibration) was the predominant load source, and where the tiles were most highly stressed and critical for flight safety.

The final step was to verify the strength integrity of the actual tiles bonded on the spacecraft, whereas the tests and analyses were generic tests, which served to verify the design. The tests performed on the Orbiter tiles were:

- o Proof tests to demonstrate a required strength capability
- o Acoustic emission (AE) monitoring to assure that the damage induced by proof tests was not excessive
- o Pulse velocity tests (PVT) to determine the lower bound strength of the densified RSI
- o Bond verification tests to demonstrate the strength of the bonded interface to nominal stress levels

All of these test methods were developed for the tiles in order (1) to utilize the inherent strength capabilities of the as-manufactured and installed tiles as opposed to using a more conservative lower bound material system strength, (2) to demonstrate that thousands of the already installed and undensified tiles with low flight-induced stresses were adequate and did not require densification prior to STS-1, and (3) to save cost and schedule.

At a point when all of these test methods were developed, the Orbiter tiles were partially installed, there were both densified and undensified tiles, there were critical and non-critical tiles (i.e., loss of a single tile would not result in excessive structural temperatures), and there were large thin tiles which failed-safe because the critical flight-induced through the thickness stresses were reduced by the first noncritical failure (breaking into smaller segments). In order to determine what action would be taken to which tile to demonstrate the required strength integrity for the Orbiter Flight Test (OFT) series (STS-1 through STS-4), a rather complex logic path was followed (Fig. 10).

The TPS was a major challenge to the Shuttle program - the material system development was a technology advancement and the strength integrity engineering to assure a high reliability of tens of thousands of individual, low strength flight critical elements subjected to a multitude of loads was awesome.



are structurally acceptable. Structural or aerodynamic modifications may be required to gain the maximum performance from the vehicle and still operate within the original design flight envelope.

## 8. LESSONS LEARNED

### Development Flight

Program plans should accommodate some surprises from the experiences and data obtained during flight tests. The Shuttle Program was very success oriented and fortunately has not encountered any major technical surprises which have caused major impacts.

The overpressure from the SRB ignition was readily contained. The wing pressure distribution during ascent could have caused major redesign of the structure or aerodynamic configuration. These modifications were not necessary because other parameters such as ascent trajectory and engine throttle profiles could be altered to relieve the undesirable loads.

### Design Sensitivities

The reliability of most structures is sensitive to one or more parameters such as, a type of load, temperature, corrosion, etc. The sensitivities should be recognized early in the design and accommodated. The Orbiter was sensitive to many things - weight, high temperatures, corrosion, rapid pressure changes, and many types of flight loads. All of these were adequately considered. The sensitivity of compressive stress in the Orbiter midfuselage skin panels to small thermal gradients was not recognized early enough. The inability to integrate the thermal and structural analysis into a common finite element model precluded an accurate quantification of the stresses.

With today's large computational capabilities, such an integrated thermal/structural, analyses could be performed and the temperatures should be based on a statistical analysis considering a multitude of variables.

### Innovative Engineering

A program such as the Shuttle offers a lot of creative and innovative engineering in the early design and development but programmatic pressures later in the evaluation can also create such opportunities. A budget shortage and the inability to fully test enabled the innovative approach of certifying the Orbiter strength integrity without the benefit of a dedicated structural test article. This has helped establish a precedent in using a protoflight concept for certifying aerospace structures.

Program schedule pressure helped force the innovative approach to doubling the strength of the TPS tiles by a simple process and developing a logic and screening method of proving the adequacy of low strength tiles already installed on the Orbiter.

Program pressures can enable the opportunity for innovative engineering but only motivated engineers can accomplish it.

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