STRUCTURAL LOAD CHALLENGES
DURING SPACE SHUTTLE DEVELOPMENT

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ABSTRACT

The challenges that resulted from the unique configuration of the Space Shuttle and capabilities developed to meet these challenges are described. Discussed are the methods and the organization that were developed to perform dynamic loads analyses on the Space Shuttle configuration and to assess dynamic data developed after design. Examples are presented from the dynamic loads analysis of the lift-off and maximum dynamic pressure portion of ascent. Also shown are Orbital Flight Test results, for which selected predicted responses are compared to measured data for the lift-off and high-dynamic-pressure times of ascent.

INTRODUCTION

The challenge of the Space Shuttle was to develop a system which had optimum structural weight, structural integrity, and the operational flexibility to carry a wide variety of payloads to Earth orbit. The Space Shuttle structural system, which had a unique combination of configuration, environments, and operating procedures, represented the greatest challenge to the dynamic loads analyst in the history of space vehicle design. This configuration had four bodies connected in parallel, whereas all previous space vehicle configurations were axisymmetric (sometimes with strapped-on motors). The Orbiter had wings and a vertical tail, whereas no previous configurations had aerodynamic surfaces. Three of the four bodies had thrust forces in the millions of pounds. The winged Orbiter configuration and the proximity of the external tank (ET) and the solid rocket boosters (SRB's) resulted in complex and difficult to define forces and pressure distributions on all of the bodies, whereas previous space vehicles had the relatively clean aerodynamic configuration of an axisymmetric vehicle. The structure that connected the elements of the Shuttle was very sensitive to the external forces applied to any element. A small change in aerodynamic force or a small change in thrust or thrust direction was magnified into a large percentage of change in the interface struts and backup structure. Therefore, during all ascent loading, balance had to be maintained between the vehicle elements during periods of transient thrust, such as lift-off, and during the period of high aerodynamic loading.

To meet the challenge of developing a structural system that would meet the Space Shuttle program overall goals, new capability had to be established in both the analytical and organizational areas. In the analytical area, the capability to evaluate the variables that would affect the vehicle loading and response was required. Typical of these variables are thrust and thrust transients, winds and gusts, and mass variations. Analytical tools had to be developed to assess each effect that could contribute to the vehicle loading. In addition, lines of communication had to be established between the structural loads analysis community and each group or organization that had the responsibility for definition of all effects that should be considered in the dynamic loads analysis.

The interactions among vehicle systems and environmental effects are shown schematically in figure 1. The flow of design data for vehicle structural design is shown by the arrows. In some cases, the events or effects from the different disciplines can interact and result in changes from the original definition of the effect. The Space Shuttle design conditions included all significant loading events. These were prelaunch, lift-off, maximum dynamic pressure, maximum load factor during SRB boost, SRB staging, and Orbiter/ET ascent with Space Shuttle main engine (SSME) burn.

In this paper, two analysis conditions that presented the greatest challenge to the vehicle loads and dynamic analyst are discussed. The first is the lift-off event, which was chosen because of its extremely transient nature in which engine ignitions, overpressure waves, release of holddown constraints, and winds must all be considered. The second is the high-dynamic-pressure (high q) region of ascent. It is chosen because of the complexity of the aerodynamic environment and the concept developed to define high-q loading conditions for vehicle design. Other conditions, such as staging, that have been so important in transient loads analysis in previous space vehicle designs are quite benign for the Space Shuttle and will not be addressed here.

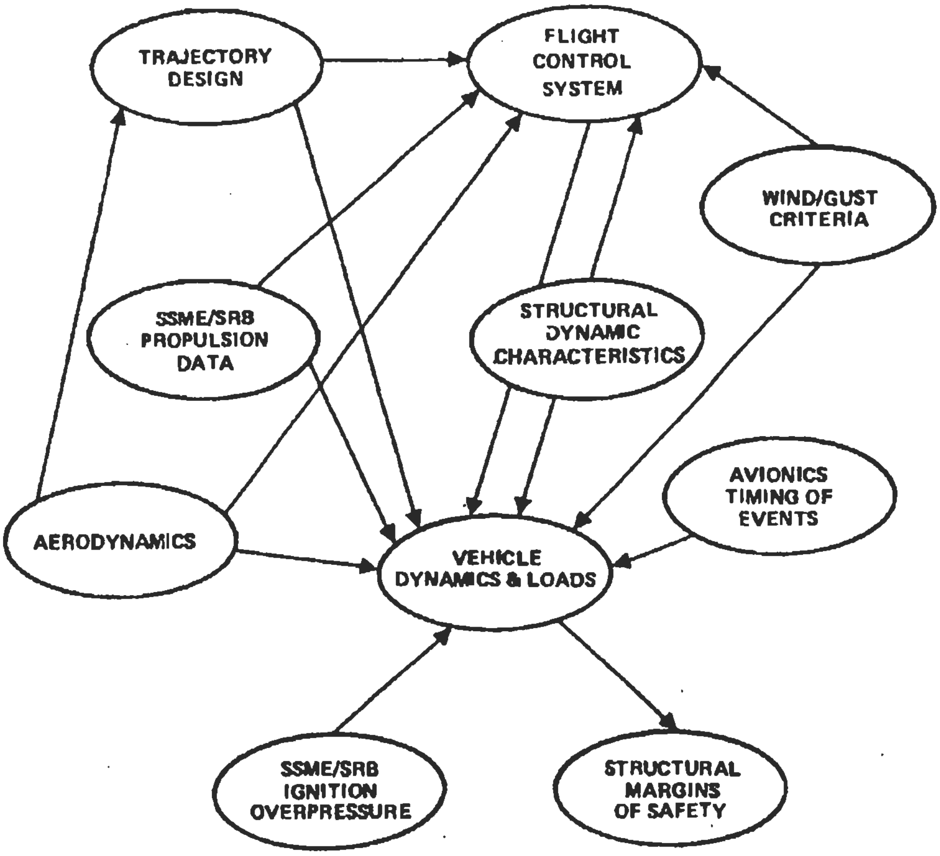

FIGURE 1.- VEHICLE SYSTEMS AND ENVIRONMENT INTERACTIONS.

LIFT-OFF

The lift-off event, because of its extremely transient nature, represented the greatest challenge to the analyst in predicting the overall elastic-body dynamic response of the Space Shuttle. The effects that were of greatest concern were the ability to simulate the SSME and SRB ignition characteristics and the longitudinal expansion of the SRB motor case, accurate inclusion of the SRB ignition overpressure environment, and the physically accurate simulation of the constraint force release between the vehicle and the launch facility.

Developing the capability to make realistic predictions of vehicle lift-off loads and to satisfy all the pre-analysis concerns was the challenge. Three areas of development had to be completed for a prediction of lift-off loads for design or design certification. These were:

1. Development of a structural dynamic mathematical model
2. Development and definition of the variables or the effects significant to the lift-off event
3. Development of the structural design criteria and load analysis procedures

SPACE SHUTTLE STRUCTURAL DYNAMIC MATHEMATICAL MODEL

The Space Shuttle structural dynamic mathematical model development presented several challenges. These were:

1. The coupling of four large bodies and payloads into the math model

2. Accounting for temperature effects on the stiffness characteristics of the solid rocket motor propellant

3. Consideration of pressurized and nonpressurized SRB's

4. Requirement for many degrees of freedom in the model, typically in the range of 1000 (Previous space vehicles had degrees of freedom in the range of 500.)

A comprehensive discussion of math model development is given in reference 1.

EFFECTS SIGNIFICANT TO THE LIFT-OFF EVENT

The number of effects and their variations that were significant contributors to the analysis of lift-off are as follows.

1. Structural dynamic mathematical model
    a. SRB propellant stiffness (hot or cold)
    b. Effects of external tank cryogenic-induced shrinkage (preloads at base)
2. SSME thrust characteristics
    a. Buildup rate (fast or slow)
    b. Thrust misalinement (±pitch, ±roll, ±yaw)
    c. Dispersion on start time (simultaneous or 333-millisecond delay)
    d. Ignition overpressure
    e. Failure case (loss of thrust on one SSME)
3. SRB thrust characteristics
    a. Buildup rate
    b. Thrust level (high or low performance)
    c. Mismatch (symmetric or unsymmetric thrust buildup)
    d. Thrust misalinement (inboard, outboard, ±pitch, ±yaw, ±roll)
    e. Ignition overpressure (magnitude, frequency, and timing)
4. Winds
    a. Direction and speed
    b. Gust wave length and timing
    c. Asymmetric vortex-shedding
5. Timing of events - Nominal timing and dispersions
6. Sudden release of reaction forces at vehicle base

The challenge in properly assessing these effects was getting each effect defined in a manner which was applicable to the structural load analysis and combining the effects to define a structural limit load for the lift-off event.

STRUCTURAL DESIGN CRITERIA AND LOAD ANALYSIS PROCEDURES

The lift-off dynamic loads event that is initiated with the start of the SSME's is shown schematically in figure 2. This event involves the general dynamic response of the Space Shuttle when attached to the mobile launch platform (MLP) and when free from the MLP. The challenge to the structural loads analyst is to evaluate this sequence of events for structural loading. Shown in figure

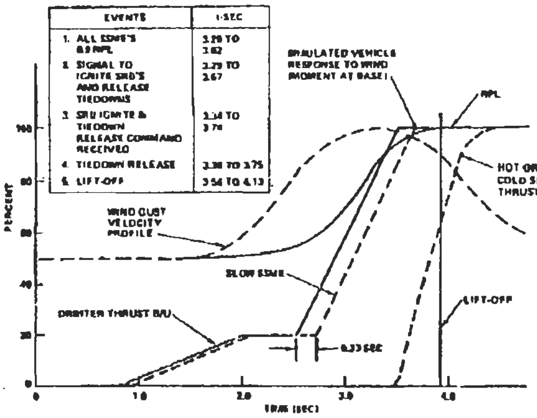

FIGURE 2.- LIFT-OFF SEQUENCE.

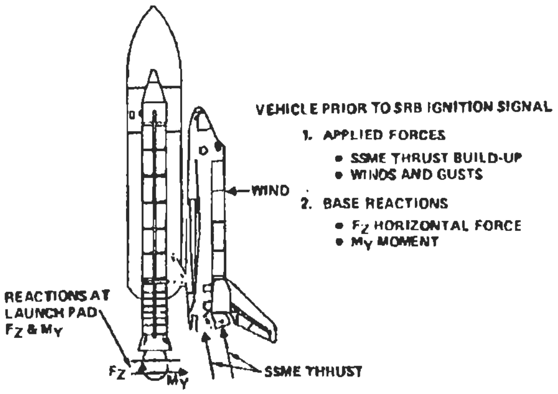

FIGURE 3.- LIFT-OFF CONFIGURATION AND APPLIED FORCES.

3 is the Space Shuttle and the external forces acting on the vehicle just before SRB ignition and holddown release. The effects that are applied in the lift-off simulations are combined to yield an engineering approximation of an overall 3σ event.

The SSME engines are ignited and build up to 100 percent of rated power level. The design-level winds, including gusts, are applied. When all three engines are at 90 percent thrust or greater, a signal is given to ignite the SRB's and release the vehicle. Before release, the horizontal forces and overturning moments are reacted at the base of the vehicle by the launch pad. At the time of release, a significant moment has built up at the base of each SRB to counteract the wind and SSME forces. In figure 4, the left side shows the deflected shape of the SRB's just before release, and the middle shows the deflected shape just after lift-off. The forces at the base of the SRB's decay rapidly to zero at the time of lift-off since there are no reacting forces once the vehicle leaves the pad. This rapid decay of base forces and change in deflected shape represents a shock input to the structure. The shock excites, or "twangs," the vehicle and causes it to vibrate significantly, mainly in its lower frequency structural modes. The right side of figure 4 shows a time history of the base moment.

An update to the lift-off analysis data base was conducted in 1977 in support of the Shuttle critical design review. This analysis resulted in a marked increase in dynamic loads, notably in the region of the Orbiter/ET forward attachment structure. Although the analysis included updates to all areas of the data base, the increase in dynamic loads was primarily attributed to refinements in the stiffness characterization of the SRB's. Changes were made in the treatment of the stiffness properties of the solid propellant and in the stiffening effect of internal pressure. Among the measures considered to alleviate the loads were:

1. Lift-off with a lower thrust level on the SSME's
2. Lift-off with one engine out
3. Tilting the vehicle on the launch pad
4. Devising a controlled release for the base restraints
5. Introducing a time delay for SRB ignition and vehicle release

A study of these options showed that most of them were either ineffective or unfeasible, or introduced undesired risks. Option 5 proved to be both effective and easy to implement.

A time history of the base-bending moment of the vehicle and the time of nominal release are shown in figure 5. It is known that if the magnitude of the base-bending moment at the time of release could be reduced, the subsequent twang loads would also be reduced; thus, it was proposed that the time of the lift-off be delayed past the time of peak moment until the vehicle has rebounded and the bending moment is in the trough. The delay chosen was 2.7 seconds. The effect of this time delay is to reduce the critical twang load in the forward attachment structure by 25 percent. The effect of the SRB ignition delay on payload capability (a loss of 600 pounds) is considered acceptable, and the effect on the acoustic life of the structure is negligible.

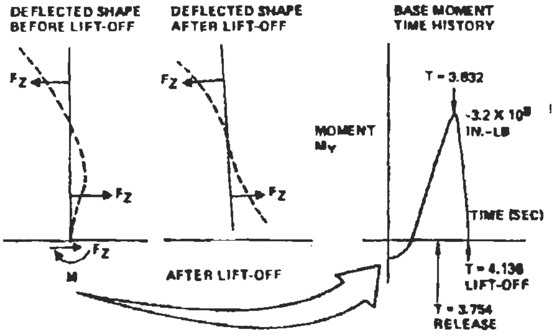

FIGURE 4.- LIFT-OFF TWANG EFFECT.

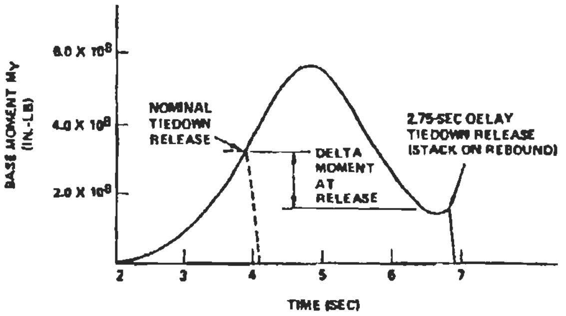

FIGURE 5.- DELAYED SRB IGNITION BASE M_Y VERSUS TIME.

The implementation of the 2.7-second SRB ignition delay required assurance of the ability to accurately predict the cantilevered dynamic characteristics of the vehicle, i.e., the time and extent of the rebound. Full-scale dynamic testing was conducted using SRB's bolted to the launch pad. Final verification was obtained from the flight readiness firing of the Shuttle engines before STS-1. Figure 6 is a time history of the strain in the tiedown bolts between the SRB's and the launch pad. This strain is a measure of base-bending moment. The predicted optimum time for lift-off coincided precisely with the time of minimum strain in the bolts. The 2.7-second SRB ignition delay is now the baseline procedure in the Shuttle lift-off sequence.

HIGH-q BOOST - GENERAL DESCRIPTION

The second ascent event presenting significant challenges in loads analysis is high-q boost. As shown in figure 7, the time of high dynamic pressure (i.e., greater than 400 psf) is approximately 30 seconds to 90 seconds flight time, which corresponds to a Mach number range of 0.6 to 2.7. These values will vary from flight to flight, being dependent on specific trajectory design and dispersions such as winds. Features, some new or unique, of the high-q boost event are as follows:

1. Vertical ascent through wind shears and gusts

2. Throttling of the three main engines to as low as 65 percent of rated power to limit the value of maximum dynamic pressure

3. Movement of the elevons through a predetermined deflection schedule to limit airloads on the elevons

4. An active load-relief control system providing commands for gimbaling the three SSME's and the two SRB's in response to wind shear and gust

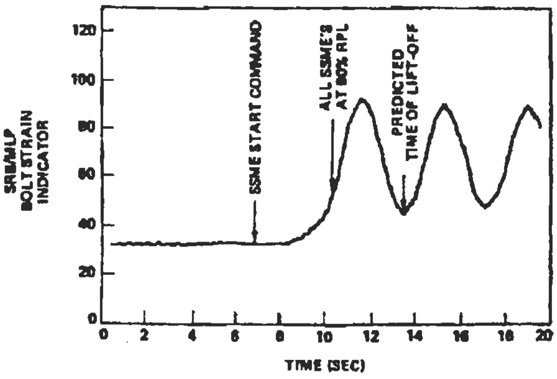

FIGURE 6.- FLIGHT READINESS FIRING TIEDOWN BOLT STRAIN.

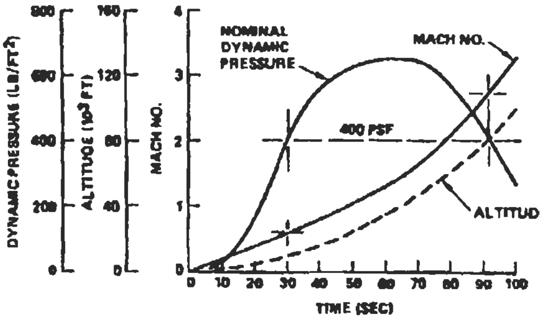

FIGURE 7.- TYPICAL HIGH-q BOOST TRAJECTORY DATA.

HIGH-q BOOST LOADS SURVEY

In early Shuttle load studies, full dynamic simulations were made of the elastic vehicle transient response. Approximately 20 cases were run in a typical loads survey; however, it was apparent that the Shuttle configuration (i.e., winged vehicle with parallel staging) made it more sensitive to wind azimuth and system dispersions than was an axisymmetric vehicle such as Apollo/Saturn. This difference is illustrated in figure 8. The structural loads survey considered dispersions on parameters such as:

1. SSME thrust level and thrust vector alinement
2. SRB thrust level and thrust vector alinement
3. SRB thrust mismatch
4. Trajectory differences for the various design missions
5. Variations in rotational accelerations
6. Tolerances in aerodynamic coefficients
7. Loss of thrust of any one SSME.

A calculation technique was required to provide a more rapid and cost-effective means of surveying all combinations of flight time, wind azimuth, and systems dispersions. Expanded use of full-transient-response simulations would be time-consuming and expensive; thus, a new technique based on the use of weighting factors applied to unit sensitivity load cases (load partials) was devised to identify the critical combinations of dispersions. These selected critical cases were then evaluated to obtain balanced distributed loads.

The focus of the load survey was the q-alpha versus q-beta flight envelopes called "squatcheloids." The squatcheloid provides a means of defining the pertinent flight dynamics parameters such as dynamic pressure (q), angle of attack (alpha), angle of sideslip (beta), and the rotational accelerations ($\dot{p}$, $\dot{q}$, and $\dot{r}$). An example is shown in figure 9. The inner A squatcheloid is based on nominal wind criteria as noted. The B squatcheloid is based on the full design wind criteria; i.e., 99 percentile wind shear and 9 m/sec gust, reduced by a multiplying factor of 0.85 to account for a statistical combination of shears and gusts. The A1 squatcheloid includes the effects of system dispersions such as thrust variations and accelerometer alinements. The load increments between the B and A squatcheloids and between the A1 and A squatcheloids are treated as dispersions and are combined appropriately with other dispersions in the loads calculation process. Such a methodical treatment is necessary because of the sensitivity of the Shuttle configuration to dispersions in vehicle and environmental data.

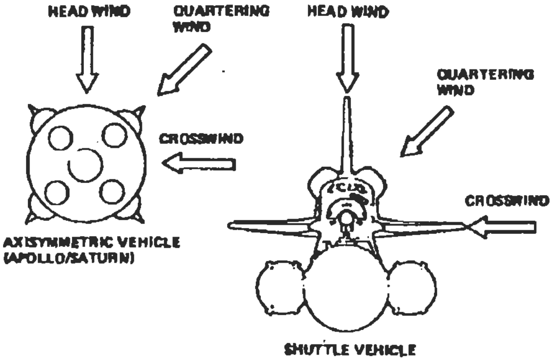

FIGURE 8.- CONFIGURATION DIFFERENCES.

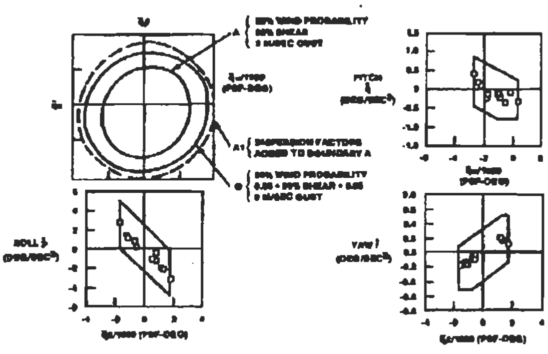

FIGURE 9.- EXAMPLE OF SQUATCHELOID FOR MACH 1.05.

Squatcheloids are developed for each of several Mach numbers of interest in the high-q regime for both no-failure and one-engine-out conditions. The high-q loads analysis then becomes the methodical survey of the squatcheloids, including consideration of all pertinent deterministic and random dispersions in the data base. The method for handling dispersions is as follows.

$$L_{max} = L_A + \Sigma \text{ (deterministic load increments) + RSS (random load increments)}$$

where L_{max} is the maximum load for survey and L_A is the baseline load (Mission 3; A squatcheloid). The load increments are defined as follows.

1. Deterministic load increments
    a. Portion of SRB thrust dispersion
    b. Effect of SSME throttling
    c. Missions other than Mission 3
2. Random load increments
    a. SRB thrust misalinements
    b. SRB thrust mismatch
    c. Rotational acceleration dispersions
    d. Elevon deflection dispersion
    e. Effect of maximum wind shear and gust (squatcheloid B minus squatcheloid A)
    f. Effect of flight control dispersions (squatcheloid A1 minus squatcheloid A)
    g. Aerodynamic tolerances
    h. Portion of SRB thrust dispersion

Using the load partials, the effects of deterministic dispersions are combined directly, whereas the effects of random independent dispersions are combined by root sum square (RSS). The load survey is conducted by calculating loads for approximately 30 places on the vehicle including the wing, the vertical tail, and the interface structures between the Orbiter and the ET, and between the SRB's and the ET. Computer programs have been developed for the rapid and inexpensive survey of load cases using rigid-body calculation techniques. When the critical cases have been identified, balanced distributed load cases are developed including the loads caused by elastic-body response.

At the time of the Shuttle critical design review, the methodology described was used to survey approximately 65 000 load cases in the high-q boost regime. Of these, approximately 50 cases were selected for final distributed loads. Figure 10 illustrates a typical distribution of critical cases on the squatcheloids, wherein each data point represents a maximum load on the wings, the vertical tail, or the interface structure. The squatcheloid survey technique has proved to be an efficient method for the survey of all Shuttle system dispersions.

ORBITAL FLIGHT TEST PROGRAM RESULTS

In this paper, several challenges to the structural load analysis discipline resulting from the unique Shuttle vehicle configuration are discussed. In the case of lift-off, changes to the characterization of the vehicle dynamic properties, SSME and SRB thrust buildup data, and ignition overpressure data all posed threats to the structural design during Shuttle development. Similarly, for high-q boost, updates to aerodynamic characteristics and the advent of higher performance trajectories also had the potential to impact the structural design. After years of analysis and re-analysis, the final verification of structural design load adequacy was to come from data obtained during the Orbital Flight Test (OFT) program. The OFT program consisted of the first four Shuttle flights, STS-1 through STS-4. On these flights, as well as on STS-5, development flight instrumentation collected data for the postflight reconstruction of the loads. In both lift-off and high-q boost, there was general verification of the design data base; however, some surprises also occurred.

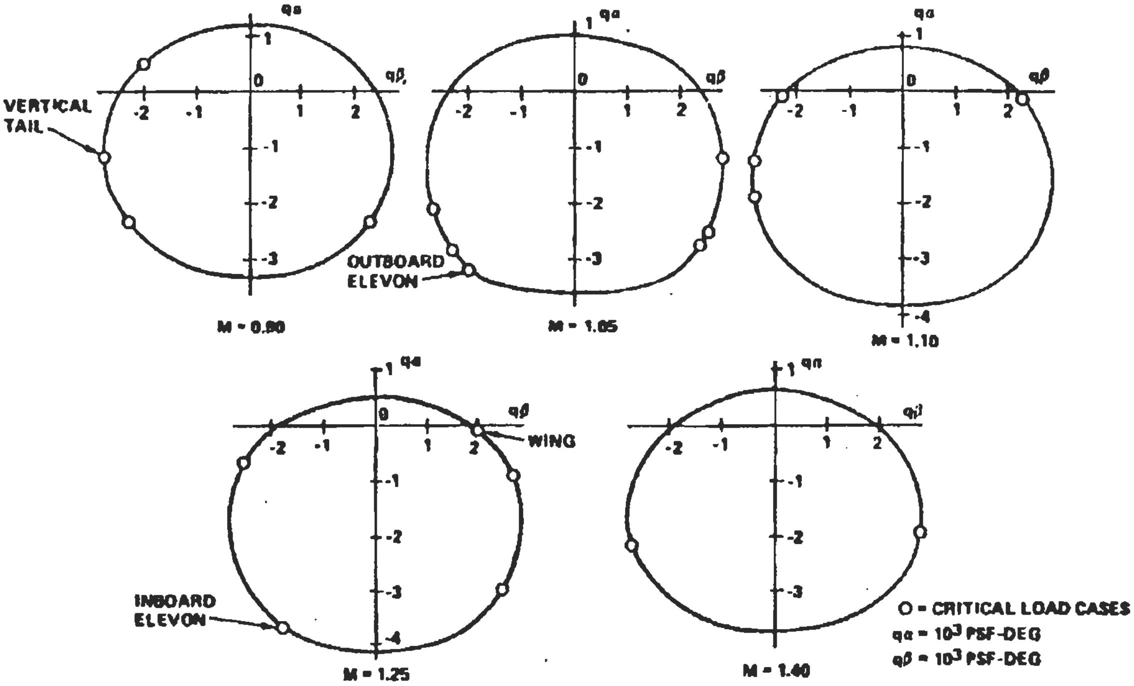

FIGURE 10.- SQUATCHELOIDS WITH CRITICAL LOAD CASES.

LIFT-OFF FLIGHT TEST RESULTS

The most notable result pertaining to lift-off occurred on STS-1. The ignition overpressure wave from the SRB's was much more severe than predicted. The resulting transient loads caused damage to a strut supporting a tank in the Orbiter forward reaction control system. The subscale model testing that had been used to predict the overpressure environment was deficient in predicting the full-scale pressure wave. After STS-1, additional modified subscale testing led to modifications to the launch pad to attenuate the overpressure wave. These steps were strikingly successful in eliminating overpressure as a contributor to dynamic loads. In all subsequent flights beginning with STS-2, nominal lift-off loads that are well within design limits have occurred. Shown in figure 11 are examples of the generally excellent correlation between the analytical reconstruction and the measured flight data.

HIGH-q BOOST FLIGHT TEST RESULTS

An unanticipated result during high-q boost also occurred on STS-1. The trajectory was "lofted"; i.e., the flightpath deviated from the planned trajectory. In postflight evaluations, this phenomenon was attributed to a discrepancy in the aerodynamic data pertaining to interactions with the rocket plumes. In the design data base, the aerodynamic interaction with the plumes was based on subscale wind-tunnel tests. In the following flights in the OFT program, adjustment of the aerodynamic data for consistency with flight measurements effectively eliminated the lofting phenomenon. These adjustments were also included in postflight reconstructions of the structural loads. Some examples are shown in figure 12. In the lower portion of the figure, the correlation of an interface load between the Orbiter and the ET illustrates the generally good correlation of total vehicle characteristics; i.e., aerodynamics, thrust, and mass properties. In the upper portion of the figure, the correlation of a wing load indicator illustrates an area in which further update is required in the local pressure distributions.

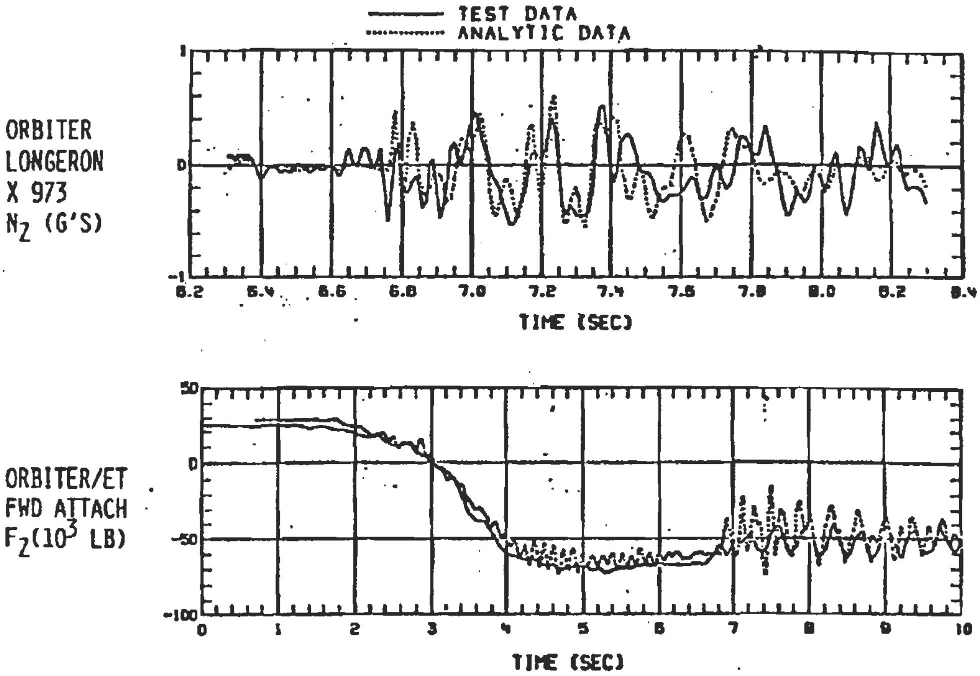

FIGURE 11.- STS-2 LIFT-OFF MEASURED LOADS VERSUS RECONSTRUCTION.

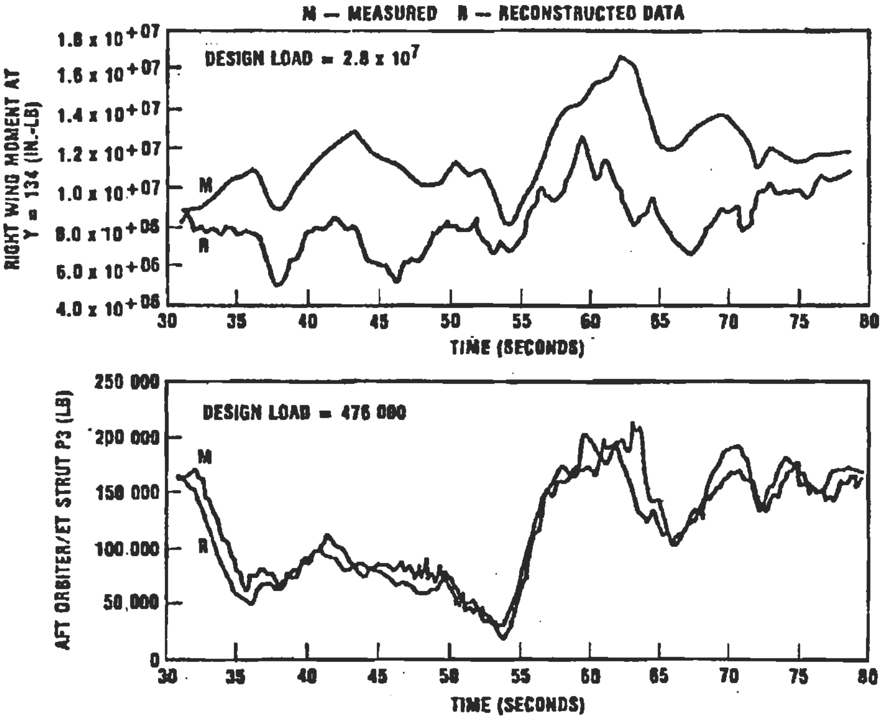

FIGURE 12.- HIGH-q BOOST LOADS, MEASURED LOADS VERSUS RECONSTRUCTED LOADS.

CONCLUSIONS

Because of its sensitivity to changes in environmental data, the Shuttle configuration presented unique challenges to the structural loads analyst. Results of the Orbital Flight Test program have generally verified the design analysis. However, subscale testing was found to be deficient in predicting full-scale results in two areas: the ignition overpressure at lift-off and the aerodynamics/plume interactions at high-q boost. In these areas, the results of the flight test program have been accommodated with no impact to the vehicle design. The challenge of developing a structural system which meets the Shuttle program goal has been met. The analytical tools and data which accrued during Shuttle development remain as significant contributions to structural analysis technology.

REFERENCE

1. Modlin, C. Thomas, Jr.; and Zupp, George A., Jr.: Shuttle Structural Dynamics Characteristics -- The Analysis and Verification. Space Shuttle Program Technical Conference, Johnson Space Center, Houston, Texas, June 28-30.