DEVELOPMENT OF SPACE STATION LOADS DUE TO ON-ORBIT THERMAL ENVIRONMENTS

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ABSTRACT

The International Space Station (ISS) primary structural elements are to be assembled and operated in the severe on-orbit thermal environment. This environment is widely varying, resulting in a broad range of structural load conditions defined by parameters such as spacecraft articulating geometry, orbit inclination, flight attitude and altitude, and the annual solar cycle. This paper describes the integrated analysis approach developed using detailed MSC/NASTRAN structural models, to compute thermally induced loads and deflections specifications for the ISS pre-integrated truss (PIT) segments. Fatigue load spectra development due to orbital thermal cycling is also described. Aspects of interface attachment mechanisms to accommodate thermal expansion and contraction and allow autonomous alignment and mating of the ISS PIT segments are described. An approach is also presented for evaluating thermal/structural effects for the large array of thermal conditions under which on-orbit assembly operations can occur.

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INTRODUCTION

The International Space Station (ISS) primary elements are to be assembled and operated in the severe on-orbit thermal environment. This environment is widely varying, resulting in a broad range of thermally induced structural load conditions defined by parameters such as spacecraft articulating geometry, orbit inclination, flight attitude and altitude, and the annual solar cycle. The ISS Assembly Complete (AC) configuration is shown in Figure 1 [1]. The ISS primary structure consists of pressurized and unpressurized elements. The pressurized elements are thermally controlled to maintain specified interior temperature limits. The unpressurized elements, such as the pre-integrated truss (PIT) segments, are exposed to the natural thermal environment without active temperature control. Segment structural element temperatures may range from about -200°F to +200°F within the annual solar beta angle spectrum.

This paper is an overview of the integrated analysis approach that has been developed using detailed MSC/NASTRAN structural models to produce thermally induced loads and deflections of the integrated ISS. A unique substructuring approach, implemented to manage the voluminous structural model and temperature data required for ISS integrated analysis, is described. A two step approach based on linear superposition is presented to circumvent the limitations of standard thermal loads analysis methods, that typically assume uniform material reference temperatures at the time of structural assembly. The present approach correctly accounts for effects of on-orbit alignment and bolt-up of PIT segments under the range of assembly thermal conditions. Development of fatigue load spectra associated with orbital thermal cycling is also described.

PROBLEM DEFINITION

ISS On-orbit Thermal Environment

The solar thermal radiation environment of ISS is the dominant driver for on-orbit thermo-structural behavior. The environment model of this study used a direct solar radiation flux of 451.23 BTU/Hr-Ft^2, earth-emitted infrared of 86.56 BTU/Hr-Ft^2, and albedo of 0.27. To characterize the thermal environment in a simple way, the solar beta angle, β, has been defined. It is the angle from ISS orbit plane to the sun, i.e., the complement of the angle between the sun vector and the orbital angular momentum vector. The greatest magnitude of β occurs when the sun is at a solstice (23.5° measured from the earth's equator). The ISS will fly at a 51.6° orbital inclination, which equates to a β variation between approximately ±75°. For orbits with solar beta angles exceeding a range of about ±70°, the spacecraft does not experience solar eclipse due to earth shading.

Figure 2 shows the variation of the solar beta angle over one year, where the starting point has been selected to guarantee orbits near the extreme β. The actual date of occurrence of the extreme β is determined by launch date. The presence of the higher frequency β variations is a result of orbit nodal regression, caused by the non-sphericity of the earth.

ISS On-orbit Thermally Induced Loads

In the standard approach to thermally induced loads analysis, reference temperatures are specified for which the structural finite element members are undeformed; for example, temperatures at time of fabrication or assembly. A reference temperature is specified as a finite element material property. In practice, reference temperatures are typically assumed to be uniform over the entire finite element model. An equivalent static load is then developed corresponding to unconstrained deformations of the finite elements, associated with variation of applied temperatures from the reference temperature [2]. The static solution is obtained by applying the equivalent load vector to the constrained structural model. This approach is also standard for analysis of combined or merged structural systems, e.g., Superelement analysis [3].

The integrated ISS model is formed from several large finite element models that are conditioned and then combined. The assembly of ISS structural components in the on-orbit environment invalidates the standard assumption of a uniform reference temperature for combined structural systems. The temperatures at the time of assembly can vary widely with time due to the solar beta angle, flight attitude and other environmental effects. To illustrate this problem, consider combining two typical ISS segments, the S0 and S1 pre-integrated truss (PIT) segments. The ISS S0 and S1 PIT segments are identified in Figure 3, and computer generated plots of the finite element models are shown in Figures 4 and 5.

The ultimate goal of the thermal loads analyst is to determine internal member loads and deflections of the models due to the applied loading. Using the standard approach, i.e., with a uniform reference temperature, equations governing the internal loads of the combined S0 and S1 segments can be expressed individually as:

$$K_{S0}x_{S0} = P_{S0} + F_{S0} \tag{1a}$$

$$K_{S1}x_{S1} = P_{S1} + F_{S1} \tag{1b}$$

and

$$F_{S0} = -F_{S1} \tag{1c}$$

These are the static solution equations, where P_{S0} and P_{S1} are the equivalent static loads due to applied temperatures, and F_{S0} and F_{S1} are equal and opposite interface loads between the S0 and S1 segments.

During ISS assembly, the S1 segment is positioned for berthing to S0 using the Shuttle Remote Manipulator System (SRMS) robotic arm. The Segment to Segment Attach System (SSAS) mechanism mounted at the segment interface bulkheads allows for interim berthing and final mating operations. The SSAS must accommodate thermally induced relative deflections of the interfaces by self aligning prior to bolt-up for any and all environmental conditions. The SSAS mechanism shear axes self alignment provisions are depicted in Figure 6. ISS truss segment interface loads and deflections of interest in this study are in the shear directions, i.e., in the Xss-Zss plane (Figure 1) at the truss segment attachment fittings. The reference flight attitude is designated Local Vertical Local Horizontal (LVLH). In this attitude the Xss-axis points along the velocity vector, the Yss-axis points outboard along the starboard truss, and the Zss-axis points to the center of the earth.

Self alignment in the shear directions, which has the effect of initializing the interface shear forces to approximately zero at time of assembly and bolt-up, is not properly represented with the standard solution formulation of Equation 1. Alignment of the attachment mechanism at assembly can be modeled as an interface preload effect which can be the dominant contributor to peak loads developed later in the ISS service life. A two step approach based on linear superposition has been implemented to include the effective assembly preload. This procedure is described in the Analysis Section.

ISS Thermally Induced Fatigue Load Spectra

The ISS is designed for a service life of 15 years. A solar beta angle histogram for the 15 year service life is shown in Figure 7. The general shape and bimodal character are preserved over the ISS range of orbit inclination and altitude, with the peaks occurring at β near $\pm 30°$.

Thermally induced load spectra are developed by determining percentage of maximum load versus solar beta angle and counting the number of cycles (orbits) in incremental beta angle buckets. Altitude cycling, orbiter approach and docking operations, attitude variations, shading of articulating surfaces, etc., have secondary effects on the 15 year beta angle distribution and the load spectra.

ANALYSIS

A two step approach that correctly accounts for thermal conditions at the time of on-orbit assembly has been implemented to predict thermally induced loads of the ISS PIT segments. The approach involves combining integrated analysis results associated with the configurations/conditions during assembly of the segments with integrated analysis results associated with future configurations/conditions of interest: Assembly Complete in this case.

Temperature cases representing both the assembly flight scenario and AC ISS integrated model configurations are developed from high fidelity TRASYS/SINDA models and analyses. A procedure to convert thermal model temperature predictions to the MSC/NASTRAN structural elements, called mapping, results in the production of MSC/NASTRAN temperature BULK DATA cards. When this procedure is accomplished for each of the ISS PIT segments, the integrated model static analysis is run.

Step 1: On-orbit Assembly Integrated Analysis

The ISS assembly flight 9A is used herein as an example of on-orbit assembly integrated thermal loads analysis. During flight 9A, the S1 segment is delivered to the ISS and mated to the orbiting S0 segment.

A nominal assembly flight timeline [4] was assumed for the thermal analysis of flight 9A. For the nominal timeline the orbiter is docked with ISS at L+48 hours (launch time plus 48 hours). The S1 segment remains in the orbiter payload bay until L+64.5 hours. Over the next 90 minutes the SRMS deploys S1 from the orbiter and effects a series of maneuvers to position it for berthing. Because the thermal conditions at assembly are highly dependent on solar beta angle (launch date) and flight attitude, which are usually uncertain well in advance of the flight, a range of flight attitudes and solar beta angles are included in the assembly analysis. A summary of flight 9A assembly analysis conditions is described in Table 1. The code for flight attitude represents values for the sequence of roll, pitch and yaw flight angles measured from LVLH in degrees, where M = -15°, T = +25°, P = +15°, and Z = 0°. For example, MZM represents -15° roll, 0° pitch, -15° yaw flight attitude.

Table 1. Flight 9A Assembly Thermal Load Cases

Description	Case Summary
No. Orbits/Condition	3
No. Static cases/Orbit	13
No. Static Cases/Condition	39 (=3x13)
No. Solar Beta Angle Conditions -75, -52, -26, 0, 26, 52, 75 (deg.)	7
No. Flight Attitudes (roll, pitch, yaw) MZM, MZP, MTM, MTP, PZM, PZP, PTM, PTP	8
Total No. of Conditions	56 (=7x8)
Total No. of Assembly Static Cases	2184 (=39x56)

Example S0 to S1 interface shear (Zss) loads for the -52° solar beta, MZM flight attitude, 9A assembly condition are shown in Figure 8. The interface loads were calculated using the standard method, i.e., representing the models combined at uniform temperature (70° F).

Step 2: Assembly Complete Integrated Truss Analysis

ISS AC configuration thermally induced loads and deflections are required for strength and fatigue load assessments and to support flight control instrumentation sensing and equipment pointing objectives. In the normal LVLH flight attitude, the Photo Voltaic (PV) arrays continually track the sun, resulting in a complete cycle of the Solar Alpha Rotary Joint (SARJ) rotation angle, α, during each orbit cycle. To represent the ISS AC configuration, eight primary structural element MSC/NASTRAN models, including the mated S0 segment/U.S. Laboratory Module, and truss segments P4, P3/SARJ, P1, S1, S3/SARJ, S4, were assembled. The segments are identified in Figure 3. For sun tracking PV array conditions, at each orbit position analyzed around the orbit, the outboard half of the two SARJ models along with S4 and P4 rotate relative to the inboard truss segments.

The PIT segment models range in size from 17000 degrees of freedom (DOF) to over 95000 DOF with a combined total of about 350000 DOF for the segments incorporated into the AC truss model. The segment finite element models were developed separately by several organizations without governing requirements to facilitate integrated thermal loads analysis. A unique substructuring analytical approach was implemented to a) manage the extensive data associated with high resolution temperature data files and detailed articulating geometry finite element models, and 2) to obviate the need for developing special simplified and mutually compatible models for the ensuing integrated analysis. In the approach, the models were initially reduced to the adjoining segment boundaries, i.e., conditioned individually, thereby reducing the stiffness model and load vector data to minimal quantity. The models were later merged as required to assemble the desired integrated model configuration. The approach had the additional benefit of enabling calculation of internal member loads, in the detailed finite element models provided by the segment developers, that were case consistent with the interface fitting loads specifications.

The AC truss model was assembled by the process shown in Figure 9. The symbol **R** designates static reduction [5] of the segment models from the G-set (global-set) to the A-set (analysis-set) [6] displacement coordinate systems. The process of successive reductions produces a unique integrated model for selected positions around the orbit, associated with a corresponding SARJ rotation angle, α. The static solution of the integrated model proceeds in the S0 G-set coordinate system and interface loads and deflections of each of the segments are obtained by application of recovery transformations.

For this study seven AC solar beta angle conditions were run, one orbit each, with twelve orbit positions (30° increments) per orbit. AC orbital temperatures are steady state, i.e., cyclic from one orbit to the next.

A 70° F uniform reference temperature was assumed for the static solution of the integrated model. Interface loads, selected deflections and internal member loads of each of the primary structural elements were calculated. Examples of the S0 to S1 segment interface shear loads (Zss) are shown in Figure 10. Deflections were calculated relative to the ISS Navigation Base reference point, located approximately in the center of S0, which served as the grounding constraint point of the model for the static solution.

Once the assembly condition interface preloads are calculated for superposition with the AC interface loads, the segment internal loads can be computed in MSC/NASTRAN. This is done for the assembly complete conditions for each segment individually using a DMAP ALTER of MSC/NASTRAN Solution 101. The purpose of the DMAP ALTER is to combine both the assembly complete interface force at the segment boundaries, F_{S0}, and the assembly interface force preload, F_{PL}, to the temperature load for the static solution. For example, segment S0 internal loads for assembly complete condition i, assembled under assembly condition j, can be calculated as follows:

$$K_{S0} x_{S0_{ij}} = P_{S0_i} + F_{S0_i} - F_{PL_j} \qquad (2)$$

Examples of thermally induced load spectra associated with orbital cycling of the segment interface loads are presented in Figures 11 and 12. These figures were selected to show the variation in distributions observed in the analysis. The location of the statistical mode varied from less than 50% of maximum to greater than 90% of maximum with other multimodal examples found also.

DISCUSSIONS

Figure 13 illustrates how results from Figures 8 and 10 can be used to obtain combined AC loads plus assembly preloads. The example is for Zss axis shear at the S0/S1 interface fitting grid point identification number 261001. Note that the uniform reference temperature is effectively canceled from the analytical solution. The procedure properly represents mechanical alignment of the berthing mechanism and properly represents AC interface loads. Since any of the assembly conditions are possible, then all of the interface loads calculated for the assembly conditions are possible preloads for AC and other later occurring conditions. Figure 14 provides a way to evaluate the maximum interface shear loads at assembly complete for all possible preloads. The figure shows how thermal conditioning prior to assembly tends to reduce maximum peak loads at assembly complete. The figure has also been used to illustrate the tradeoff between designing the segment interfaces for worst case loads versus mitigating the worst case loads by operationally adjusting the on-orbit assembly timeline.

CONCLUSIONS

The mechanical assembly of space structures in the on-orbit thermal environment presents interesting problems to the structural designer and analyst. The attachment mechanisms must be able to accommodate significantly large thermal distortions. Attachment of structures under extreme temperature conditions can result in severe peak loads that may not manifest themselves until months later. A two step approach to account for effective preloads due to assembly temperature conditions has been developed that overcomes the limiting assumption of uniform temperatures at structural assembly. The approach utilizes the powerful MSC/NASTRAN DMAP and data recovery features and has been instrumental in development of ISS load specifications and on-orbit structural design loads and loads spectra.

ACKNOWLEDGMENTS

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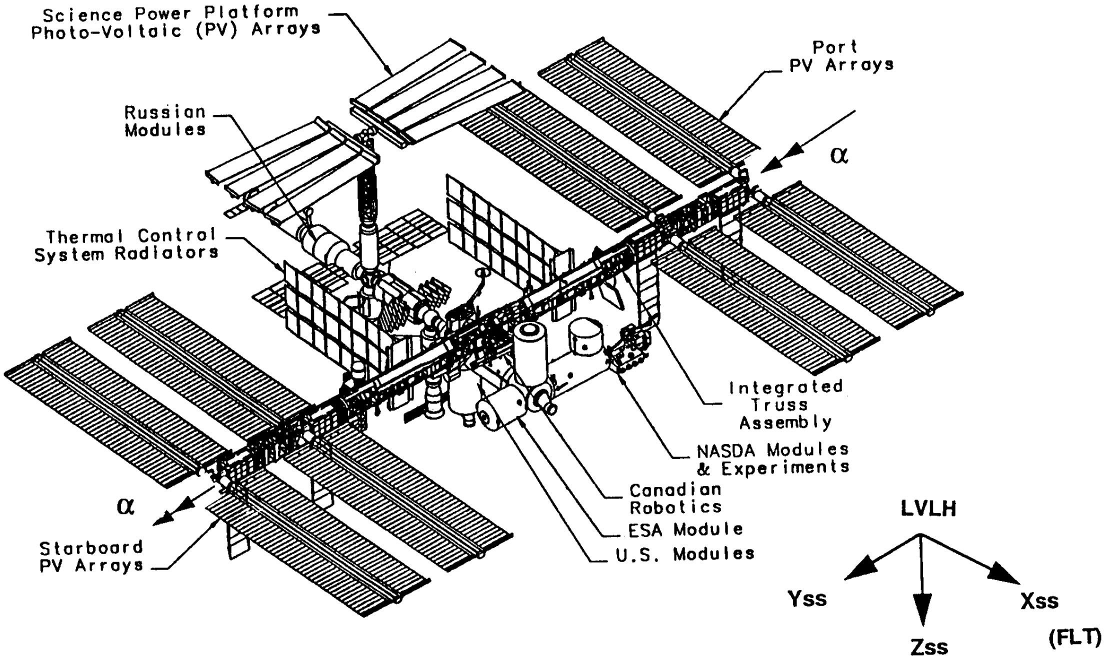


Figure 1. International Space Station (ISS) Assembly Complete (AC) Configuration

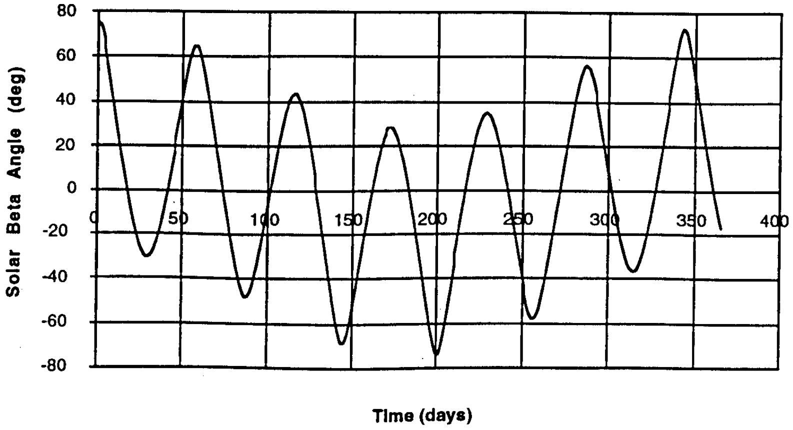


Figure 2. Solar Beta Angle Cycle, 51.6 Deg Inclination, 150 NM Altitude

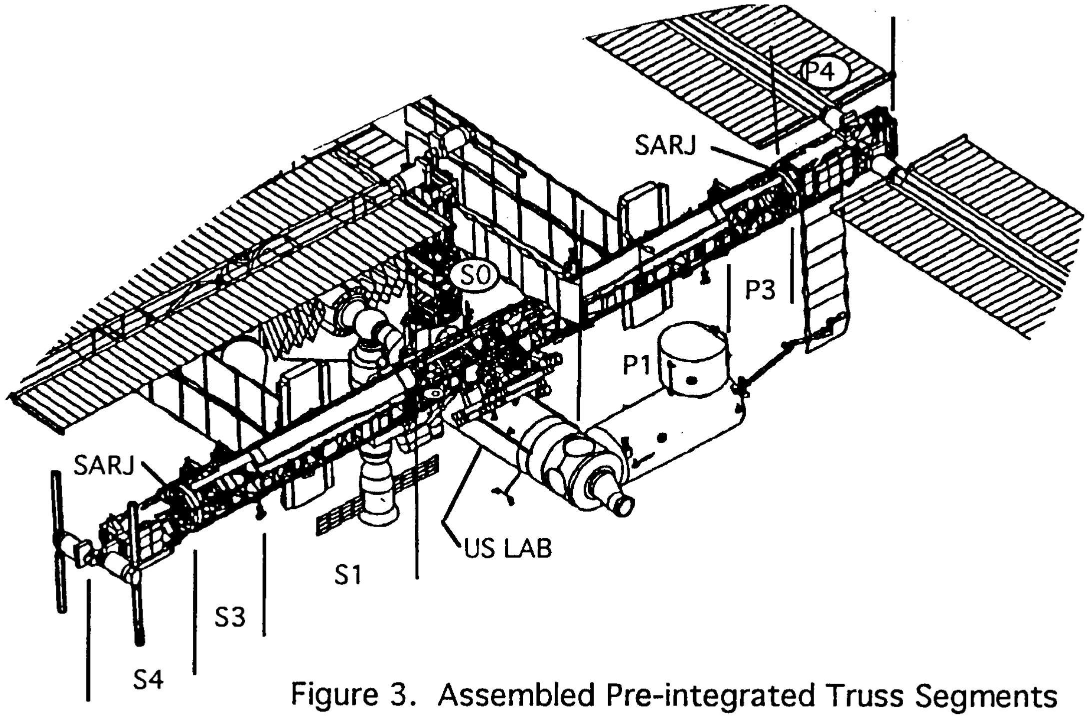


Figure 3. Assembled Pre-integrated Truss Segments

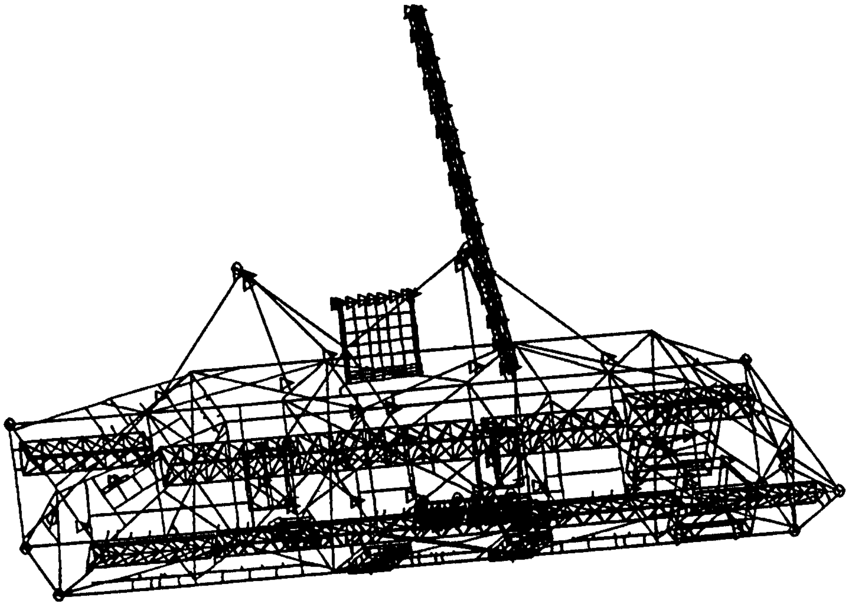


Figure 4. S0 Segment Finite Element Model

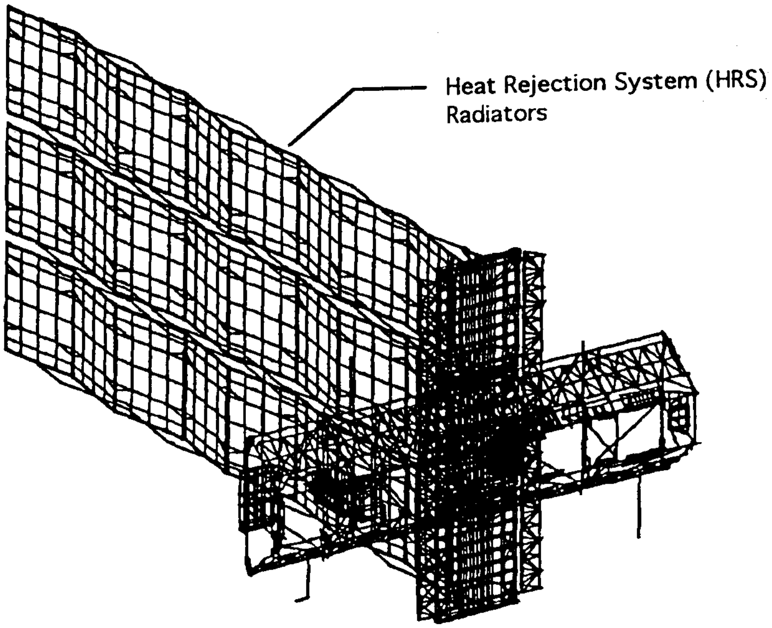


Figure 5. S1 Segment Finite Element Model

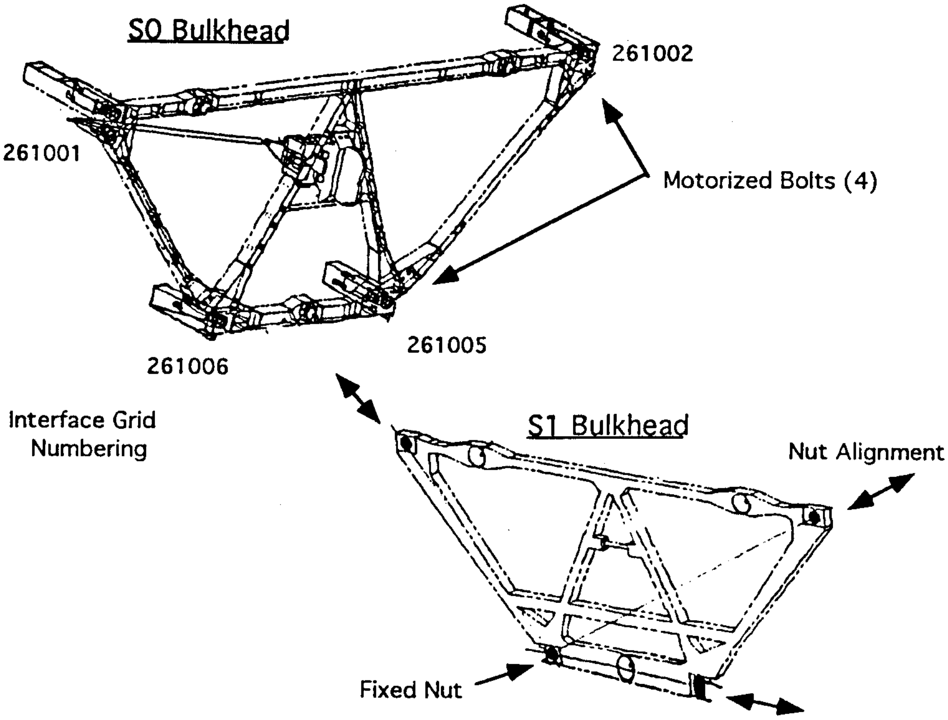


Figure 6. Segment to Segment Attach System (SSAS)

Figure 7. Solar Beta Angle Distribution (15 Years)

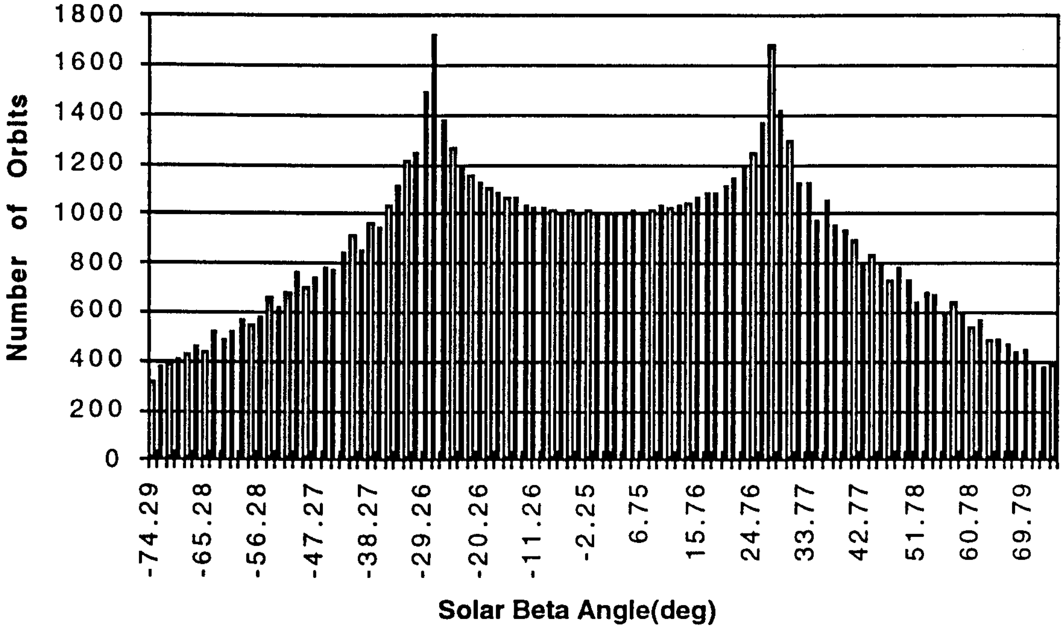


Figure 8.
Assembly Condition Solar Beta =-52, MZM, S0/S1 Interface Shear (Zss), 70F Degree Ref.

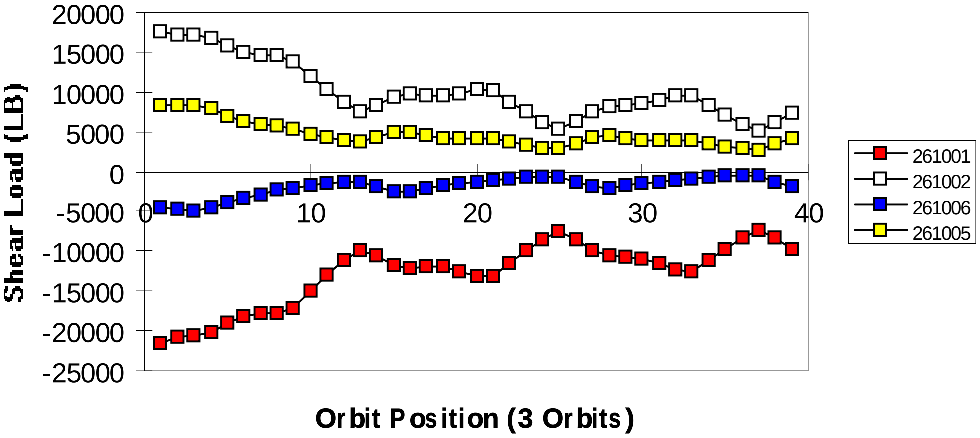
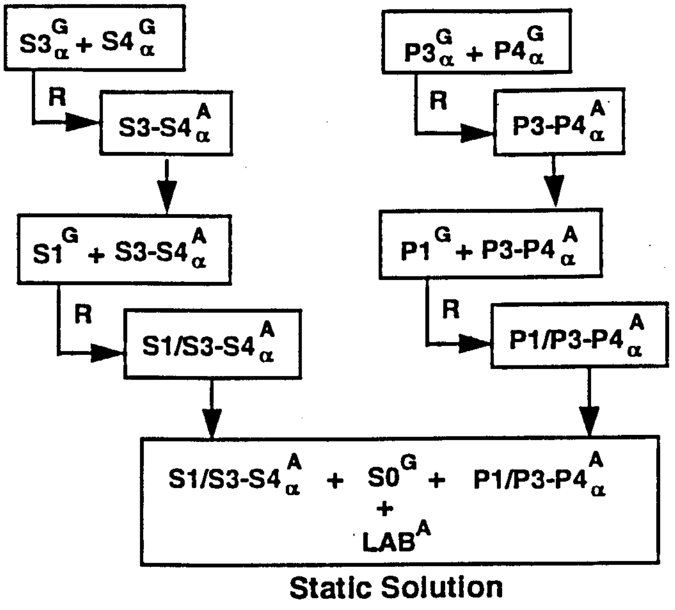
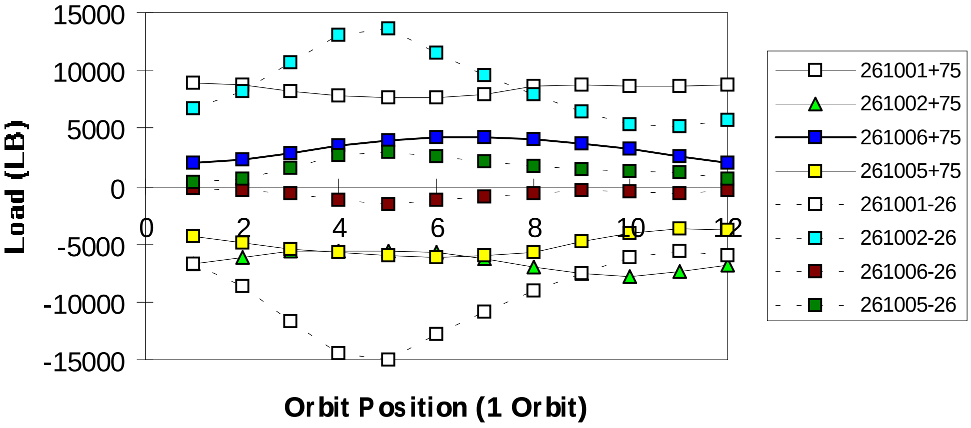


Figure 9. ISS Assembly Complete Integrated Model Conditioning and Assembly



Note: R -> Static Reduction; α -> SARJ Rot. Angle;
G -> G displacement set; A -> A displacement set

Figure 10.
S0/S1 Interface Shear Loads (Zss), +75 Beta and -26 Beta, Assembly Complete, 70F Degree Ref.



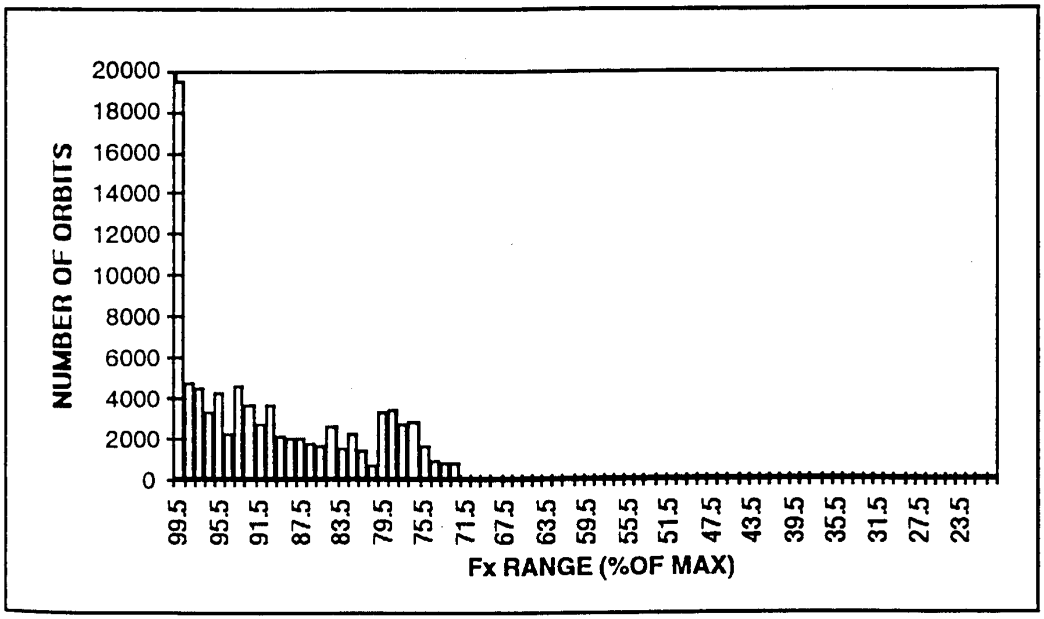


Figure 11. Sample Shear (Xss) Interface Load Spectrum

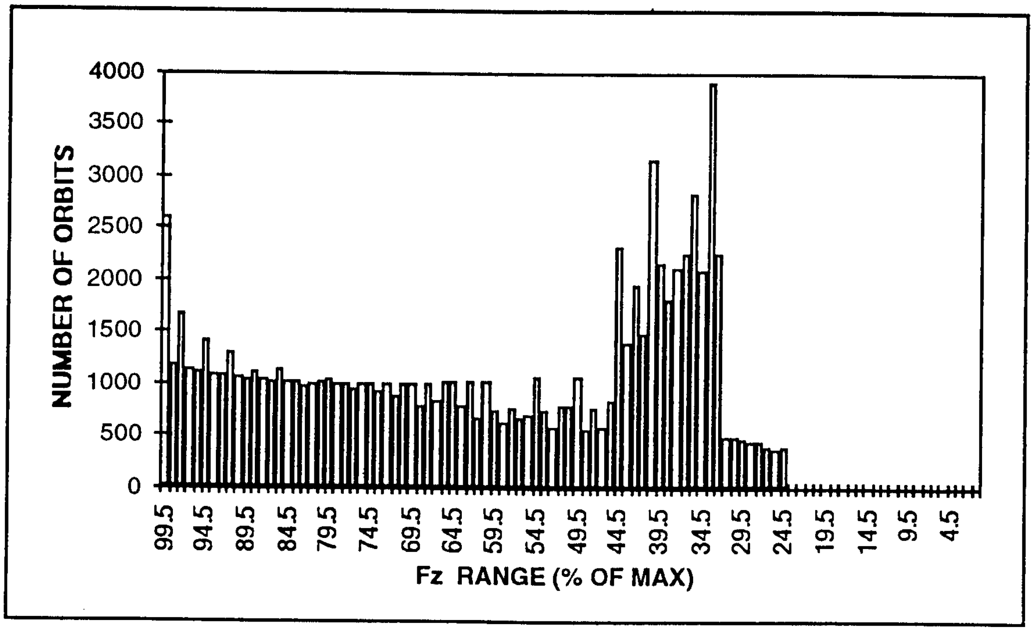


Figure 12. Sample Shear (Zss) Interface Load Spectrum

Figure 13. Combining Assembly Orbit Interface Preloads with Assembly Complete Orbit Interface Loads

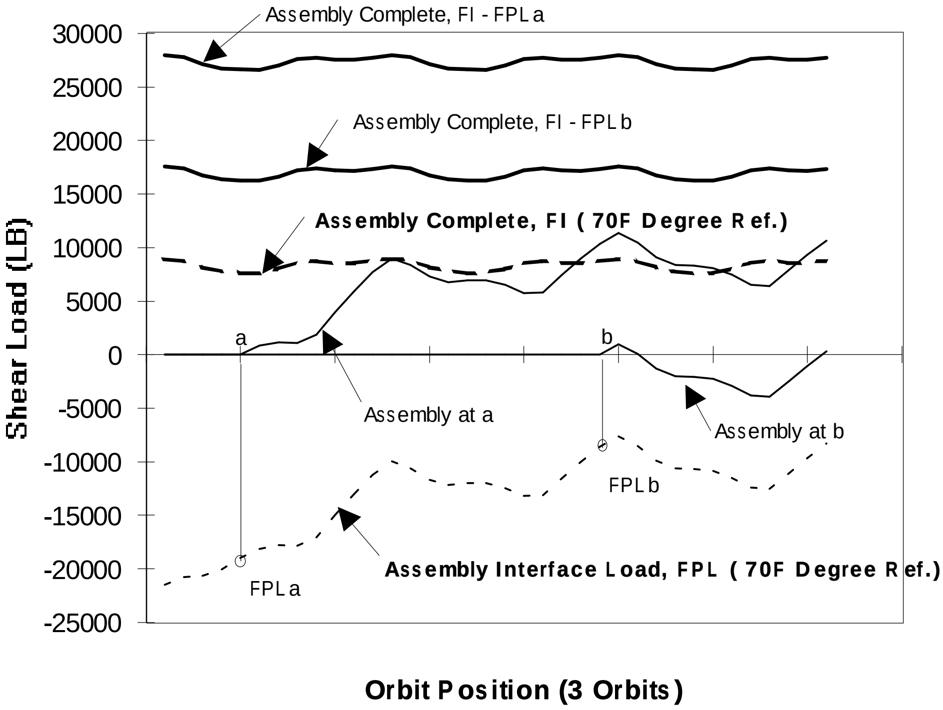


Figure 14. Maximum Assembly Complete Segment Interface Shear Loads (Zss) (Plus Assembly Preloads)