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Design and Verification of Space Station EVA-Operated Truss Attachment System

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Abstract

This paper describes the design and verification of a system used to attach two segments of the International Space Station (ISS). This system was first used in space to mate the P6 and Z1 trusses together in December 2000, through a combination of robotic and Extra-Vehicular tasks. Features that provided capture, coarse alignment, and fine alignment during the berthing process are described. Attachment of this high value hardware was critical to the ISS's sequential assembly, necessitating the inclusion of backup design and operational features. Astronauts checked for the proper performance of the alignment and bolting features during on-orbit operations. During berthing, the system accommodates truss-to-truss relative displacements that are caused by manufacturing tolerances and on-orbit thermal gradients. After bolt installation, the truss interface becomes statically determinate with respect to in-plane shear loads and isolates attach bolts from bending moments. The approach used to estimate relative displacements and the means of accommodating them is explained. Confidence in system performance was achieved through a cost-effective collection of tests and analyses, including thermal, structural, vibration, misalignment, contact dynamics, underwater simulation, and full-scale functional testing. Design considerations that have potential application to other mechanisms include accommodating variations of friction coefficients in the on-orbit joints, wrench torque tolerances, joint preload, moving element clearances at temperature extremes, and bolt-nut torque reaction.

Introduction

The construction of the ISS presents many challenges due to its large size and complexity. Multiple segments are brought to orbit via the Space Shuttle. Once on-orbit, the segments must be unberthed from the Orbiter's cargo bay, moved to the ISS, then attached to the ISS. In other applications, it makes sense to accomplish these tasks solely via autonomous and robotic tasks. Due to the critical nature of the ISS power system segments, however, a new attachment system was designed to be operated by spacewalking astronauts who could quickly react to any problems encountered during assembly. The system was first used to mate the P6 and Z1 trusses together. This paper describes the many design considerations associated with the new attachment system and the unique verification approach used to gain confidence in system performance.

The P6 Long Spacer is an integrated truss structure that will provide the ISS with power, using solar arrays and batteries, and communications for voice and telemetry. The P6 was carried into orbit on STS-97, ISS flight 4A, where it was attached to the rest of the ISS through the Z1 Truss. The Z1 is an integrated truss structure that provides a mating location for the P6 Long Spacer, attitude control hardware, and communication hardware for the ISS. The Z1 was carried into orbit on STS-92, ISS flight 3A, where it was attached to Node 1 of the ISS. Figure 1 shows the Z1 element in its launch configuration while Figure 2 shows the P6 element in its launch configuration. Figure 3 is a photograph of the ISS at the conclusion of STS-97, showing the P6 attached to the Z1.

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Design and Operations Overview

The truss attachment system is the hardware used to align, mate, and attach the P6 Long Spacer to the Z1 Integrated Truss Assembly. The mating is accomplished with the use of the Shuttle Remote Manipulator System (SRMS) and Extra-Vehicular Activity (EVA). The system, shown in Figures 4 and 5, consists of four sets of coarse alignment cones/receptacles, four sets of fine alignment cones with integral bolt mechanisms and nuts, and a capture latch/capture bar mechanism to pull the interfaces together. Figure 4 shows the Z1 side of the interface plane. The Z1 zenith bulkhead supports the Capture Latch Assembly (CLA), four coarse alignment receptacles, and four fine alignment bolt mechanisms. Figure 6 shows the P6 side of the interface plane. The P6 nadir face contains the capture bar, four coarse alignment cones, and four fine alignment nut assemblies.

Operating Phases

The truss berthing and attachment has four distinct operating phases: Phase I-SRMS positioning, Phase II-interface alignment, Phase III-bolt down, and Phase IV-demating. Phase I consists of manipulating the P6 into position near the Z1, using the SRMS. The P6 is positioned using the Space Vision System (SVS) so that all four P6 coarse alignment cones have their cylindrical tips at or below the plane of the Z1 coarse alignment bushing faces. Meeting that Ready to Latch (RTL) criteria ensures that the P6 segment's capture bar is placed within the capture envelope of the Z1 capture latch. The EVA astronauts visually verify that the ready to latch condition has been achieved, completing Phase I operations.

In Phase II, astronauts use the electric wrench to close the Z1 capture latch. As the latch claws close upon the P6 capture bar the Z1 and P6 segments are pulled together, the fine alignment features engage, and the P6 moves laterally with respect to the Z1. The SRMS is placed in its Test mode during Phase II to reduce resistance to the fine alignment. SRMS Test mode is a "limped" mode in which the joint servos have no control authority and the SRMS joints are relatively compliant to end effector motion. The Z1 fine alignment/bolt mechanism is shown in Figure 6. The P6 long spacer nut installation is shown in Figure 7. When the fine alignment cones (shear cylinders) on the Z1 side fully seat in their receptacles on the P6, the capture bar is approximately 1/4" from fully seated in the capture latch. Continuing to close the capture latch deflects the capture bar's backup structure, which produces a small preload between the Z1 and P6 structures.

To complete Phase III, the EVA astronauts first verify the fine alignment features are fully seated by checking the gap between the P6 and Z1 housings, using a convenient tool of a known width. Next, the crew tightens the primary structural attach bolts to fasten the truss segments to each other in the sequence noted in Figure 5. The resulting configuration is shown in Figure 8. The bolt design incorporates a "self-feeding feature" which provides a small axial force to initiate bolt thread engagement so that the crewmember does not have to push on the end of the bolt during tightening. During tightening, the crew checks that the bolt is turning, advancing, and the running torque is low. The bolt preload is controlled by torque alone. Primary bolt installation torque is reacted by two pins in the Z1 shear cylinder engaging matching slots in the P6 primary balls. After the bolts are fully tightened, the preload applied by the capture latch is released by EVA actuation, the SRMS ungrapples the P6, and the attachment process (Phase III) is complete. Later in the ISS assembly sequence, the P6 is removed from the Z1 and moved to a permanent location on the outboard truss, at P5. The Phase IV tasks associated with the demating operation are the reverse of Phases I through III.

Where possible, the three phases associated with truss berthing and mating are separate and have distinct, identifiable beginning and ending points. In addition, confidence for proceeding with the next phase can be gained by establishing specific verification criteria. For example, the interface alignment phase is verified complete prior to initiating bolt operations, by checking that the fine alignment features have accomplished the lateral positioning, and that the capture latch has accomplished the axial positioning. The practical means of determining that the alignment has been achieved to within the design limits of the system is by having the EVA crew check the Z1 to P6 housing distance. The gap check confirms that the lateral offset is within the capability of the bolt threads to engage the nut, even with the nut rotated within its spherical bearing.

Capture Latch Description

The Capture Latch Assembly, mounted on the Z1 truss, consists of two opposing claws connected to a series of linkages, a drive screw, and a geared drive train (Figure 9). The input shaft to the drive train, when driven at a constant 15 RPM, will cause the claw to rotate from fully open to fully closed in approximately 6 minutes 45 seconds, although it may be driven faster or slower. Assuming the capture bar, a solid steel cylindrical shaft mounted on the P6 truss, is within the sweep area of the claws, the claws will then pull the bar, and the attached P6 truss, towards the Z1 truss, forcing the two interfaces to comply. For use on the Z1, the CLA's input is extended by a tube to the outer edge of the truss where the astronaut has good access.

Contingency Design and Operational Features

In Phase II, if the capture latch fails to close, the astronauts have contingency procedures for routing special straps between the trusses and with a winch, they temporarily hold the interface together during bolt engagement[1]. To accommodate failures in Phase III, bolt-down, each fine alignment device incorporates two contingency attachment bolt/nut combinations to allow a structural connection to be made in the event the primary bolt cannot be engaged (see Figure 8). At each corner of the truss, the mechanism is two fault tolerant for achieving structural integrity. Therefore if the primary bolt cannot be engaged, one contingency bolt can be engaged. If that contingency bolt cannot be engaged, the second contingency bolt can be employed.

Specific operational procedures were prepared through the development of flowcharts that addressed potential anomalous on-orbit conditions[2]. Manufacturing tolerances and thermal-structural deflections may create an offset between the capture bar and the capture latch (see Figure 10). These offsets affect latch preload and the ability to fully seat the shear cylinders at the shear carrying corners of the truss. Procedures were devised to loosen the capture latch if the bar/latch offset causes excessive Z1 bolt to P6 nut misalignment, as detected by the truss-to-truss gap check. An analysis was conducted to derive the number of turns the latch would need to be loosened.

Contingency bolts and associated threaded spacers are launched with the Z1 in the position shown in Figure 6. EVA astronauts extend the spacer sleeve. The spacer serves to maintain the gap between the Z1 fine alignment housing and the P6 corner fitting so that no bending moments are created due to the distance between the fine alignment shear cylinder's centerline and the contingency bolt's centerline. A special lock tool is installed over the spacer sleeve to keep it from turning during contingency bolt operations (see Figure 11). The tool incorporates an additional feature for use in contingency operations to measure the gap between Z1 and P6 housings[3]. If needed, the tool's tapered protrusion is placed between the housings until the edges contact the housings. The housing gap is indicated by graduated lines on the protrusion, which are visible to the crew.

All contingency nuts in P6 fine alignment device slide in Y-Z plane. Even if the primary bolt fails to engage, shear is transferred through the shear cylinders on primary bolt at the two truss corners that are intended to react shear. Operational procedures ensure the shear cylinder is seated even if the primary bolt is not completely engaged.

Contingency bolt installation torque is reacted by a locking plate on the P6 assembly (see Figure 12). After contingency bolt torqueing, this plate is removed by EVA and stowed for future use. A pry bar can be used to assist in plate removal while the contingency ball flats press against the plate's slotted hole. Plate removal allows the contingency ball/nut races to slide and rotate as required to accommodate thermal-structural deflections.

If the capture latch cannot be released nominally, there are backup means to release the preload by turning the P6 capture bar in its eccentric bushings, and releasing the Z1 capture latch claws via EVA handles on the Z1 zenith bulkhead[2].

For demating (Phase IV), the device includes a release mechanism, an EVA operated lock pin, to allow disconnect of the P6 from the Z1 should the primary EVA bolt become stuck in the P6 sleeved nut (see Figure 12) during engagement. If the nut gets stuck, contingency tools and means exist to replace the nut (threaded sleeve) in the P6 fine alignment assembly, thereby restoring the original fault-tolerance of the joint for connection of P6 to P5. The self-feeding nut in the Z1 bolt assembly is made of plastic which will shear off as the bolt/nut together are unscrewed, if the bolt has stuck to the nut at a significant engagement depth. This feature is required because there is a small difference in thread pitch between the outer and inner diameters of the P6 sleeve/nut.

Thermal-Structural Analysis

The accommodation of structural deflections caused by the temperature gradients was one of the most important considerations in designing the truss attachment system. Estimates of the temperature distributions were made using ISS thermal models of both the pre-mate and post-mated conditions. Transient thermal analysis was used to determine truss temperatures at the point in time when the mating was expected to occur. Numerous flight attitudes, sun angles, hardware configurations, shadowing, and truss thermal properties were evaluated in the analyses. Once temperatures were determined from the thermal models, they were mapped onto the corresponding elements of the structural finite element models. Finite element analysis was then performed to determine structural deflections. Through further processing, the relative deflections of corresponding P6 to Z1 attach points were calculated. To determine the deflections in a relative sense, the fixed corner was the origin of a coordinate system that was positioned angularly by +/-Y sliding corner[4].

Attachment Restraint

Figure 5 indicates the degrees of freedom in the fine alignment assembly's primary nuts located at each corner of the P6. Figure 8 shows a cross section of a fine alignment mechanism with the Z1 primary EVA bolt engaged into the P6 long spacer primary nut. Spherical bearings are used around both the primary and contingency nuts to provide a limited rotational freedom about the Y and Z axes. This bearing arrangement provides relief for on-orbit differential thermal expansion and distortion that may occur between the Z1 and P6 during on-orbit operations. The arrangement also accommodates angular misalignments due to manufacturing tolerances.

In addition to the rotational degree of freedom in the primary nut assemblies, there are provisions for sliding in the Y-Z plane to allow for differential thermal expansion of the P6 and Z1. One corner of the P6 incorporates a fine alignment nut assembly that is fixed from sliding in the Y-Z plane. A second corner incorporates a nut assembly that is allowed to slide in the Y-direction only. The two remaining corners incorporate nut assemblies that are allowed to slide in the Y-Z plane. This arrangement allows the bolts to react shear and torsional loads, while still allowing the structures to expand and contract thermally.

The sliding degrees of freedom in the P6 nut side of the fine alignment mechanism is accomplished by incorporating a gap between the bearing race and the truss corner fitting. The magnitude of these gaps is established based upon both part tolerances and predicted thermal displacements. All of the contingency nuts in the P6 fine alignment device are allowed to slide in the Y-Z plane. The shear cylinder at the primary bolt locations still carry shear loads even when the contingency bolt is installed.

After the structural connection is made, loads are transmitted across the Z1-P6 interface as follows:

+/- Z in-plane shear load - reacted by fixed truss joint & truss joint that is free to slide in the +/-Y direction
+/- Y in-plane shear load - reacted by fixed truss joint only
+/- X axial load - reacted by all four truss joint corners

Race-Nut Centering

The P6 primary races contain springs that keep the ball/nut elements centered for entry of the Z1 fine alignment shear cylinder (see Figure 13). The P6 ball opening, Z1 shear cylinder tip, and the P6 centering spring geometries ensure fine alignment feature engagement when lateral misalignments are present, as limited by coarse alignment feature clearances. Such misalignments may be due to thermal gradients and manufacturing tolerances. The P6 contingency races contain springs that keep the ball/nut elements centered for Z1 contingency spacer seating (see Figure 14).

Bolt Installation Torque Reaction

Primary bolt installation torque is reacted by two pins in the Z1 shear cylinder engaging matching slots in the P6 primary balls. These features keep the P6 nut from turning during installation of the Z1 bolts. In addition, the nut is free to slide and rotate after full torque is applied. The torque reaction features were designed to engage with the P6 primary ball/nut rotated to its limits, translated to its limits, and with the maximum gap predicted from the thermal and manufacturing tolerance studies. Figure 15 shows a layout of the Z1 shear cylinder entering the P6 ball/nut with the Z1 torque reaction pin capable of resisting torque against the P6 ball's slot. The layout shows the shear cylinder axially separated from the P6 ball a distance equal to the maximum expected gap predicted from the thermal and manufacturing tolerance studies. The shape of the slot in the P6 ball and the positioning of the pin in the Z1 shear cylinder were critical, having been derived from a series of layouts reflecting the expected relative misalignments. Those layouts ensured that the Z1 pin would enter the P6 primary ball even with the ball rotated to its limit.

Joint Preload Considerations

The primary and contingency bolts must be tightened to a sufficiently high torque to create a preload that prevents joint separation under the influence of external loads. The maximum torque is limited by strength, fracture and fatigue considerations. With upper and lower limits defined, a range of permitted torque values is therefore determined. Typically, another factor must be taken into account- the change in preload associated with tightening the bolt at the various predicted on-orbit temperatures, due to the difference in thermal expansion coefficients between the bolt and clamped materials. In the case of the subject attach system, however, the bolt, shear cylinder, retaining nut, and threaded sleeve are all stainless steel alloys with similar coefficients of thermal expansion. Variations in bolt-nut interface friction coefficients are examined in the joint analysis that place additional constraints on the bolt torque allowable range. Development tests were conducted to characterize the friction coefficients associated with the specific materials, sizes, surface finishes, and lubricants of the truss attach system joints[5]. These tests were conducted in air, and at vacuum, over the expected temperature range. The attach bolts, races, balls and nuts are dry film lubricated with Molybdenum Disulfide.

The primary bolt sizing calculations included misalignment loads associated with closing a maximum axial gap that may exist at the time of bolt-up, due to truss-to-truss interface out-of-plane manufacturing tolerances and thermal-structural deflections. The contingency bolt sizing did not include this misalignment load because the contingency spacer sleeve bridges, but does not close, the axial gap. On-orbit mechanical loads are also part of the joint design loads.

After the preload range was computed, the torque range was determined and a wrench with adequate torque accuracy was selected[6]. In the case of the subject truss attachment system, the final tightening of the bolts was accomplished using a manual torque wrench that had an accuracy of +/-10% in the expected operating and torque ranges.

Design Tolerance Studies

A large number of tolerance analyses were performed to ensure that the selected design dimensions of the truss attachment system features provide the required performance in the different operating phases[7]. This section describes the evaluations of truss in-plane differential displacement, out-of-plane relative displacement, and relative rotations due to warpage. In addition, studies of the clearances of the moving elements are addressed. During and after mating, temperature gradients exist within the P6 and Z1 trusses. Such gradients cause the structure to deflect from its nominal shape. The tolerance assessment included thermal conditions that exist during pre-mate and post-mate configurations.

In-Plane Differential Displacements

Analysis was performed to predict the maximum thermal-structural displacements in the mating plane, across the Z1-P6 interface. Relative displacements were predicted between each of the four corner fine alignment features, between each of the four coarse alignment features, and between the coarse and fine alignment features.

A check was made to ensure radial clearance exists between the coarse alignment P6 cone's cylindrical body and Z1 coarse alignment bushing inside surface when displacements are at their extremes. The coarse alignment features must have clearance post-mating, so that shear loads are only transmitted at the fine alignment connections. The analysis was repeated for both nominal and worst case detail part dimensions, and overall positional tolerances. Clearances for pre-mate and post-mate thermal conditions were examined.

The clearance between the P6 fine alignment primary ball/race and the P6 corner fitting bore for each of the four corners, one to another, was analyzed as well. Race clearances must exist, post-mating to ensure that shear loads are reacted by the intended statically determinate system.

A calculation was made to determine the radial clearance between the fine alignment Z1 shear cylinder and the P6 receptacle (nut) when these two items first begin to engage (by capture latch closure). The calculation was repeated with the items displaced by thermal-structural gradients and manufacturing tolerances. A detailed layout revealed that the shear cylinder would enter the ball properly.

Selection of the minimum clearance between the coarse cone and bushing was driven by the thermal-structural displacements between the coarse alignment features that are furthest from the fixed fine alignment nut. Once this selection was made, a calculation showed that entry of the fine alignment features would always occur with the maximum clearance between the coarse alignment features.

Analysis confirmed that with the predicted thermal displacements, dimensional tolerances, and positional tolerances, when the coarse alignment features engage, the fine alignment always begin to engage, even considering the potential for free play associated with the primary race centering springs.

Out of Plane Relative Displacements

Manufacturing tolerances and temperature gradients in and between the Z1 and P6 trusses shift the out-of-plane (X-direction) positions of the fine alignment features when the Z1 capture latch is closed on the P6 capture bar, prior to structural bolt engagement. Stated another way, three of the four shear cylinders will seat, but the fourth might not be seated. The primary attach bolt's stroke, bolt strength, contingency attach sleeve stroke, and contingency attach bolt strength were found to be sufficient to seat the fine alignment Z1 shear cylinders in the P6 receptacles (nuts). For this truss attachment system, the capture latch preload is not sufficient to seat the fine alignment Z1 shear cylinder in the P6 receptacle (nut).

With the shear cylinder not fully seated, there could be a bolt to nut centerline offset that must be accommodated by attach bolt's lead-in. Analysis and test confirmed the capability to engage the threads in this offset condition.

Relative Rotations Due to Warpage

Temperature differences between the Z1 and P6 might produce warpage that creates relative rotation between the Z1 bolt and P6 nut assemblies. The amount of the rotations due to thermal effects was analytically predicted. Rotational freedom was provided in the design, in the form of spherical bearings for both the primary and contingency nut assemblies sufficient to accommodate the predicted rotations due to thermal gradients and manufacturing tolerances. In addition, an analysis concluded that the on-orbit mechanical loads do not rotate the bearing to its travel limit, thereby confirming that local moments remain released.

Moving Element Clearances

Analysis was performed to ensure clearance exists, with worst case predicted temperatures, and with worst case dimensions, between the following components: Z1 shear cylinder outer surface to P6 primary ball inside surface, Z1 contingency bolt spacer to contingency bolt, Z1 microconical fitting to primary bolt, Z1 spring retainer nut to primary bolt, Z1 shear cylinder to primary bolt, Z1 launch restraint cap to housing, Z1 launch restraint cap to shear cylinder, Z1 shear cylinder to self-feeding nut, P6 ball to race spherical diameters, P6 race width to housing, and Z1 primary bolt to self-feeding nut. The Z1 launch restraint nut, shown in Figure 16, secures the primary bolt from rattling during launch, and is removed by the EVA crew on the mission prior to berthing.

Verification Program

Confidence in system performance was achieved through a cost-effective collection of tests and analyses, including thermal, static loads, vibration, misalignment, contact dynamics, underwater simulation, and full-scale functional testing[8]. A balance between tests and analyses at the component and system levels resulted in an integrated verification approach. The relationship between component level testing and system level characteristics is described for each test in the following sections.

Qualification Vibration Test

A qualification vibration test was performed to demonstrate the ability of Z1 & P6 fine alignment assemblies to withstand the maximum expected launch vibration environment with a qualification margin. This component level test correlated to system level performance in that the vibration spectrums used for the test were derived from system (cargo element) level acoustic tests. The fine alignment bolt and nut assemblies passed all functional tests after being exposed to the vibration environments[9].

Qualification Thermal Cycle Test

A qualification thermal cycle test was performed to demonstrate the ability of the fine alignment assemblies to perform in the ISS space environment, meeting all thermal and mechanical performance requirements[10]. This component level test correlated to system level performance in that the temperatures used for test were predicted from system level (truss) thermal analysis. The component test partly verifies ability of the P6 primary and contingency nuts to comply with the predicted system borne misalignments relative to Z1 fine alignment features. The test also evaluated bearing rotation and race sliding at temperature extremes.

With regard to nut rotation/sliding performance, results of this ambient pressure test correlate well with results of an earlier Human Thermal Vacuum (HTV) test[11]. In the HTV test, a misalignment test was performed at temperature extremes, simulating both overall truss thermal-structural deflections and local mechanism thermal-structural deflections (clearance changes due to differential coefficients of thermal expansion between mechanism moving elements). Functional testing at several points of this test was successful, including confirmation that the primary bolt did not loosen as a result of thermal cycling, and visual inspection revealed no change occurred. The test also verified that the fine alignment features, bolts, launch restraint cap, etc. have sufficient clearance to engage/disengage at temperature extremes.

Qualification Misalignment Test

A qualification misalignment test was performed to verify that the Z1 and P6 fine alignment interfaces engage and can be bolted together when there is an angular misalignment between the two structures, when there is a lateral offset between the Z1 and P6 assemblies, and when there is a gap between the Z1 shear cylinder and the face of the sleeve in the P6 ball/receptacle[12].

This component level test correlated to system level performance in that the thermal-structural deflections that the mechanism's degrees of freedom are designed to accommodate, are the truss deflections. These truss deflections are due to overall Z1 to P6 truss temperature differences, not local temperatures of the mechanisms themselves. Test gaps and misalignments simulate those that may occur between the P6 and Z1 due to worst case system level on-orbit thermal effects and manufacturing tolerances. This component test also correlated to system level performance in that the test fixture simulated the P6 truss backup structure stiffness. The P6 finite element model was used to calculate required fixture stiffness. Fixture stiffness was test verified prior to use in the misalignment test. A graphical view of the misalignment test setup is shown in Figure 17.

In the qualification misalignment test, performed at room temperature, only simulated overall truss thermal-structural deflections were addressed. However, in the HTV test, the misalignment test was performed at temperature extremes, simulating both overall truss thermal-structural deflections, and local mechanism thermal-structural deflections (clearance changes due to differential coefficients of thermal expansion between mechanism moving elements). Therefore, results of both the qualification and HTV misalignment tests provided confidence that the mechanism would perform as required in the space environment.

Qualification Static Loads Test

The qualification static loads test was performed to verify the functionality of the test articles after the application of 1.0 times the design limit on-orbit loads[13]. An additional objective was to measure the force required to slide the P6 assembly under applied limit loads. The strength of the test article was verified for 1.5 times the design limit on-orbit loads. This component level test correlated to system level performance in that the structural test load values were derived from system-level analyses. These loads include on-orbit mechanical loads, thermal loads, and misalignment loads due to manufacturing tolerances. Test cases included configurations with only the primary bolt engaged, and cases with only the contingency bolt engaged. After the application of limit loads, no damage was found and the units passed the mechanical functional tests. No failure occurred after application of ultimate loads. Load versus deflection data was recorded for each load case and was used to determine joint stiffnesses.

Qualification Contact Dynamics Test

A special contact dynamics test was performed to validate the mathematical model of the truss attachment's fine alignment features, comprising the ball-nut and shear cylinder at one truss corner[14]. This model, together with the SRMS and CLA models made up the system level model, or full simulation as it has been called. The intent of the simulation, using the system model, was to predict the behavior of the truss interface and the SRMS as the CLA draws the P6 and Z1 trusses together to a mated, pre-loaded condition, after which the primary bolt attach features are engaged. The testing of a single corner's fine alignment feature, i.e., the component level, allowed identification of detailed alignment characteristics that would otherwise be masked by system level testing.

A specially designed test setup was created consisting of a platform supported by struts that were each instrumented with a displacement and axial load transducer. The platform held the ball-nut half of the fine alignment feature and an XYZ table held the shear cylinder feature above the ball-nut (see Figure 18). The XYZ table was used to create a lateral misalignment between the two features while they were apart from each other. The table was then driven down, causing the two features to engage and forcing the platform to comply via displacement of the struts. Strut loads and displacements were recorded as a function of time for correlation with a simulation of the entire test setup.

After being correlated to the contact dynamics test results, the system model was developed and used for several studies[15]. First, hand selected initial misalignment conditions were used to examine the boundaries of the capture envelope. Then, treating the maximum misalignment values as three-sigma conditions generated probabilistic initial conditions. The initial conditions were screened for meeting the ready to latch criteria. The RTL criteria itself was determined through a series of studies which ultimately resulted in the one used on-orbit, i.e. that all four P6 coarse alignment cone tips be placed at or below the plane of the Z1 coarse alignment bushings. In all the simulated cases, the P6 and Z1 trusses were successfully brought together by the CLA and the interfaces fully seated, even with the SRMS in Brakes On Mode. The coarse and fine alignment features of the interfaces were always able to remove initial misalignments completely, followed by pre-loading of the interface by the CLA. The worst case travel paths defined by the simulations were used to perform a computer aided design clearance study. This analysis confirmed that no interference to berthing exists. Additional berthing simulations were performed to show that berthing can be achieved using the straps and winches, mentioned earlier, in the event the capture latch cannot be operated[1].

Underwater Testing

Full scale Z1 & P6 segment mockups were built to physically simulate truss module interfaces and the capture mechanism. These mockups were made neutrally buoyant and placed underwater in a massive tank. Space suited astronauts demonstrated they could conveniently reach and operate the truss attachment mechanisms in simulated weightless conditions[16]. This demonstration provided confidence that the mechanism would work in the Z1 to P6 application.

Acceptance Phase Component Testing

Functional tests were performed during assembly of the individual Z1 bolt assemblies. Checks on the Z1 bolt assemblies included verifying lock pin operation in the primary bolt launch restraint, operation of the contingency spacer lock, and operation of the contingency spacer. Because the P6 nut elements are integral with the truss corner fitting, they were verified after installation in the P6 truss. Careful dimensional inspections during detail part fabrication and during assembly ensured mechanism performance was as intended. Such inspections were possible, and therefore the usual mechanism thermal vacuum and vibration acceptance tests were not needed.

Acceptance Phase Full Scale Testing

Functional tests and inspections were performed after the bolt assemblies were installed on the Z1 and after the nut elements are installed in the P6. Many of these checks were performed using the Mating Mechanism Simulators (MMS). The Z1 MMS is an inspection tool that contains simulated Z1 features for checking the P6 flight article (see Figure 19). The P6 MMS is an inspection tool that contains simulated P6 coarse and fine alignment features and is used to check the Z1 flight unit features (see Figure 20). Measurements taken using the MMS units verified that the manufacturing tolerances on the flight article's alignment features were within the allocated values. With that confirmation, confidence was gained that there would be sufficient race float and coarse alignment feature clearance to accommodate the expected on-orbit thermal deflections. The MMS measurements were augmented with laser theodolite and camera-computer system measurements[17].

Conclusions

This paper reviewed the design and verification of a Space Station truss attachment system that was successfully used for the first time to mate the ISS Z1 and P6 segments, in December 2000. The mechanisms were designed and used in a manner that, as much as possible, kept the berthing, interface alignment, and bolt-down phases separate. Contingency procedures were developed for the EVA astronauts to use in response to on-orbit anomalies. A robust system was developed which accommodated interface misalignment caused by manufacturing tolerances and thermal gradients. The verification approach resulted from a balance between tests and analyses at the component and system levels.

References

1. “Z1 to P6 Berthing Using Payload Retention Devices”, Gabriel Katell, The Boeing Company, Rocketdyne Propulsion & Power, April 16, 1999, EID-03968.
2. “Evaluation of Z1 Capture Latch to P6 Capture Bar Preload”, Gabriel Katell, The Boeing Company, Rocketdyne Propulsion & Power, November 22, 1999, EID-05257.
3. “Rocketdyne Truss Attachment System (RTAS) Design/Verification Technical Interchange Meeting”, Gabriel Katell, The Boeing Company, Rocketdyne Propulsion & Power, April 29, 1999, EID-03899.
4. “Z1-Stack Flight 4A IDR3 Z1/P6 and P6LS/P6IEA Interface Loads”, Robert Rudd, The Boeing Company, February 16, 1998, A92-J195-STD-M-RAR-9800016.
5. “Rocketdyne Truss Attachment System (RTAS) Bolt Development Torque-Preload Test”, George Raquelsantos, The Boeing Company, Rocketdyne Propulsion & Power, May 17, 1999, ETD-MD4-C01178.
6. “RTAS Mechanism- Z1 Side (P6 to Z1) Stress Report”, Bill Ng, The Boeing Company, Rocketdyne Propulsion & Power, June 23, 1999, EPS-S-PV-16-01-017.
7. “Rocketdyne Truss Attachment System (RTAS) Design Tolerance Analysis”, Gabriel Katell & Stanley Gordon, The Boeing Company, Rocketdyne Propulsion & Power, July 12, 2000, EID-03256.
8. “Rocketdyne Truss Attachment System (RTAS) Verification Plan”, Gabriel Katell, The Boeing Company, Rocketdyne Propulsion & Power, March 26, 1998, EID-02267.
9. “Rocketdyne Truss Attachment System Fine Alignment Bolt/Nut Qualification Vibration Test Report”, Frank Chang & Keli Asato, The Boeing Company, Rocketdyne Propulsion & Power, March 12, 1999, ETD-PQ4-C01180.
10. “Rocketdyne Truss Attachment System Fine Alignment Bolt/Nut Qualification Thermal Cycle Test Report”, Gabriel Katell & Keli Asato, The Boeing Company, Rocketdyne Propulsion & Power, March 31, 1999, ETD-PQ4-C01181.
11. “HTV #7 Test Results- BMRRM Dual Latch, RTAS Bolts, Z1 Keel, Russian Tools”, John Maddux, The Boeing Company, Rocketdyne Propulsion & Power, October 15, 1999, EID-00722-103.
12. “Rocketdyne Truss Attachment System Fine Alignment Bolt/Nut Misalignment Qualification Test Report”, Gabriel Katell & Keli Asato, The Boeing Company, Rocketdyne Propulsion & Power, April 8, 1999, ETD-PQ4-C01189.
13. “Rocketdyne Truss Attachment System Fine Alignment Bolt/Nut Qualification Static Test and Z1 Contingency Spacer Lock Tool Strength Test Report”, Gabriel Katell & Alfred Lewis, The Boeing Company, Rocketdyne Propulsion & Power, May 13, 1999, ETD-PQ4-C01191.
14. “Rocketdyne Truss Attachment System Fine Alignment Hardware Contact Dynamics Test/Analysis Correlation Report”, Gabriel Katell, The Boeing Company, Rocketdyne Propulsion & Power, April 20, 1999, EID-03970.
15. “Rocketdyne Truss Attachment System Full Simulation Report”, Teri Krene, The Boeing Company, Rocketdyne Propulsion & Power, August 2, 1999, EID-03954.
16. “Crew Consensus Test Report”, Cathy Therrien, The Boeing Company, Rocketdyne Propulsion & Power, June 22, 1998, EID-00722-51.
17. “P6 RTAS Race Concentricity Assessment”, Gabriel Katell, The Boeing Company, Rocketdyne Propulsion & Power, October 10, 2000, EID-05780.

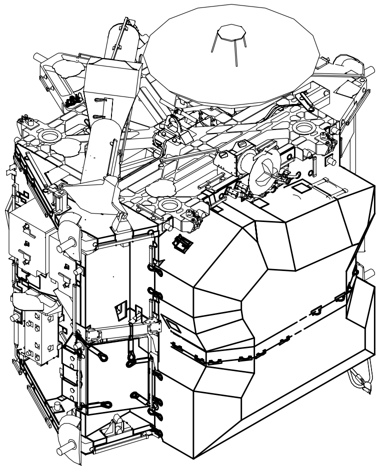

Figure 1. Z1 Cargo Element

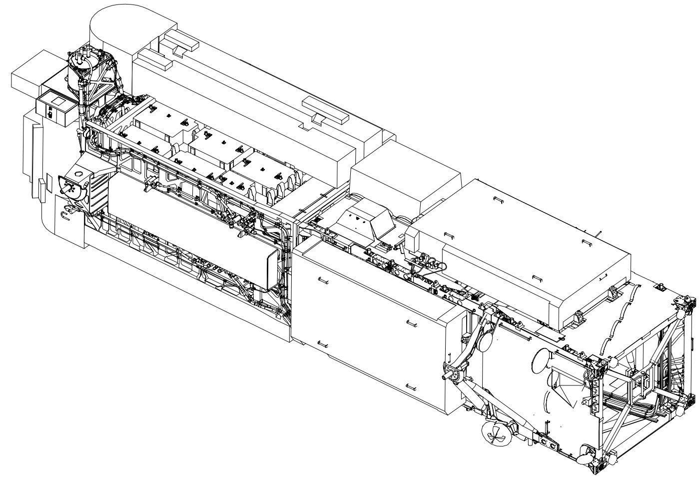

Figure 2. P6 Cargo Element

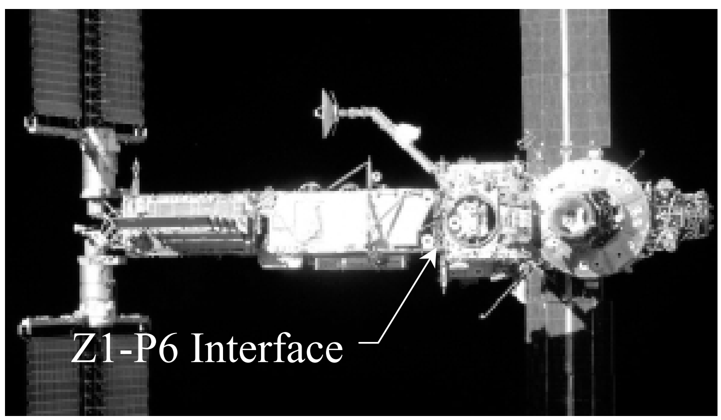

Figure 3. ISS at STS-97 Conclusion

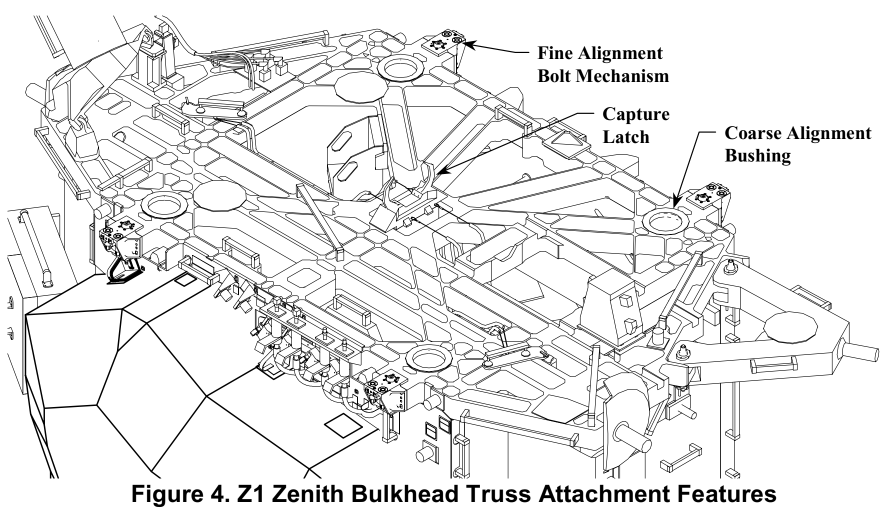

Figure 4. Z1 Zenith Bulkhead Truss Attachment Features

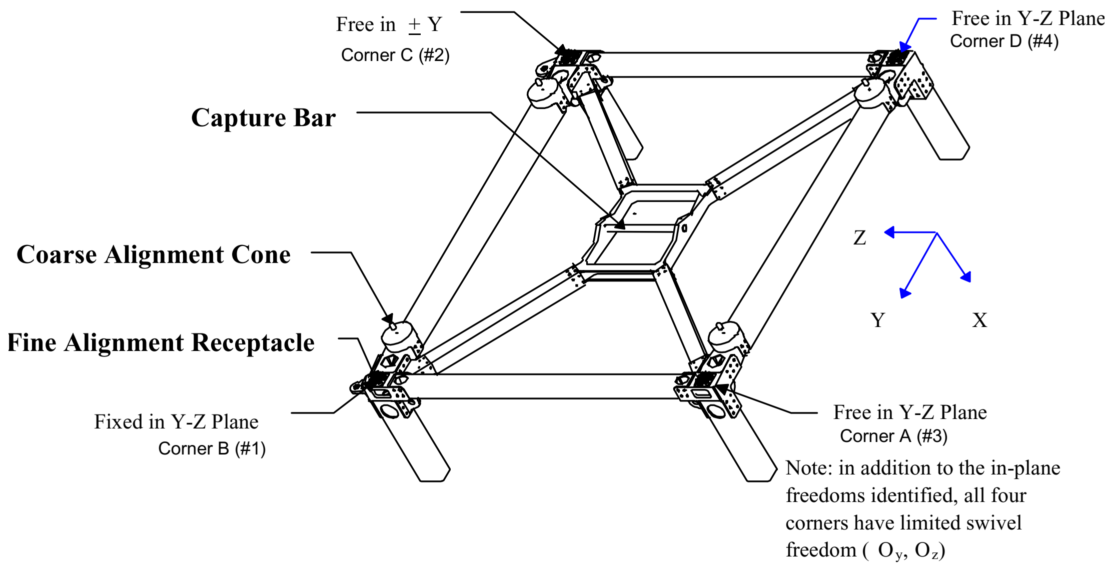

Figure 5. P6 Long Spacer Truss Attachment Features

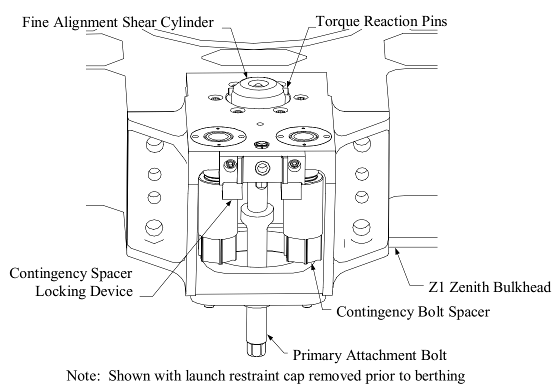

Figure 6. Z1 Fine Alignment/Bolt Installation

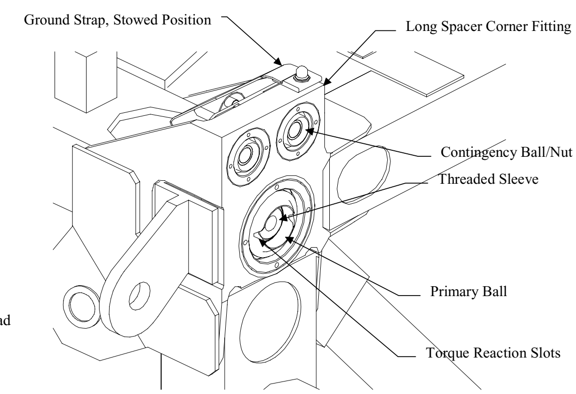

Figure 7. P6 Fine Alignment/Nut Installation

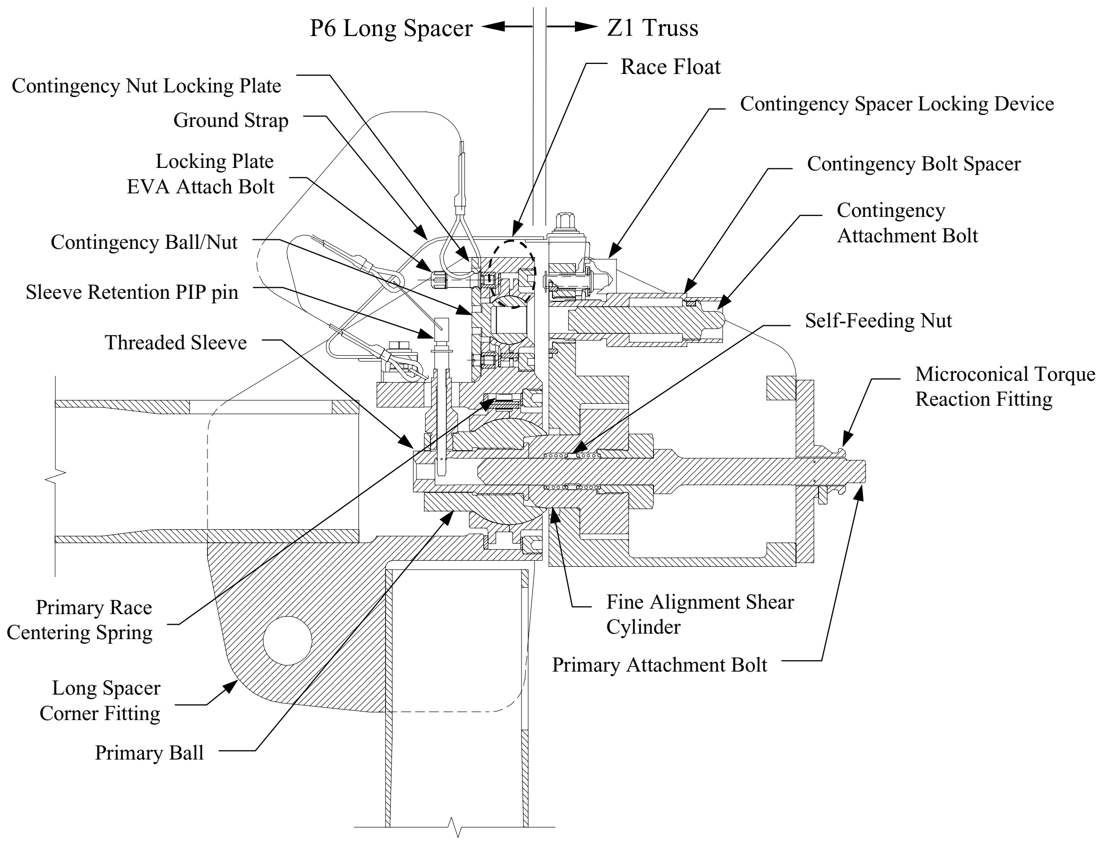

Figure 8. P6-Z1 Mated Configuration

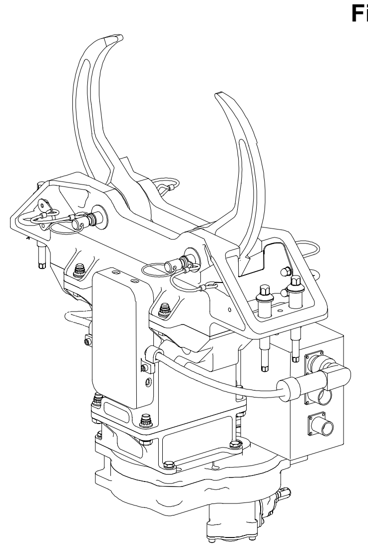

Figure 9. Capture Latch Assembly

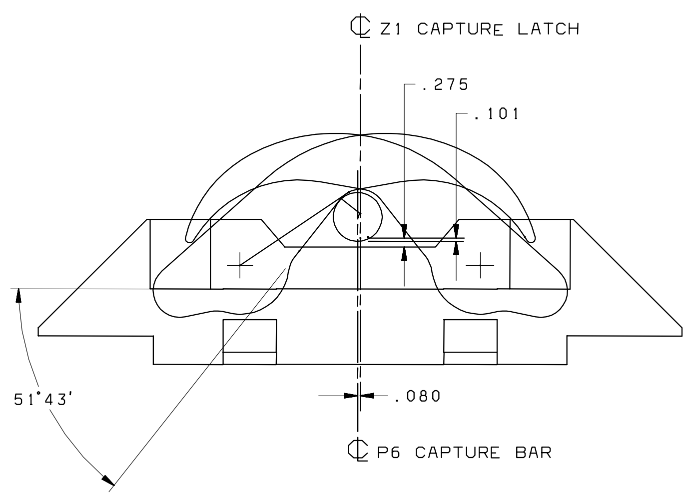

Figure 10. Capture Latch-Capture Bar Offset

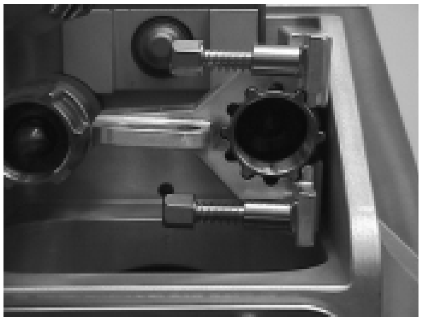

Figure 11. Z1 Congingency Spacer Lock Tool

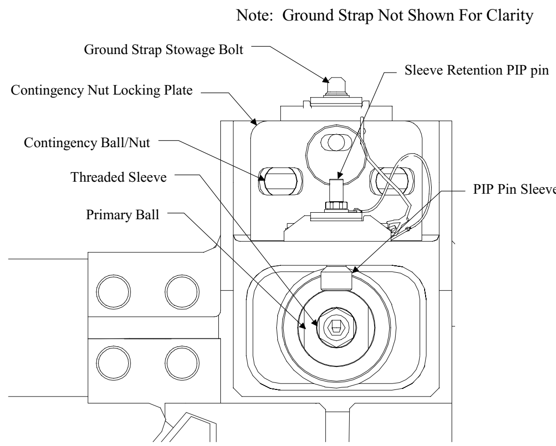

Figure 12. P6 Fine Alignment/Nut Installation Rear View

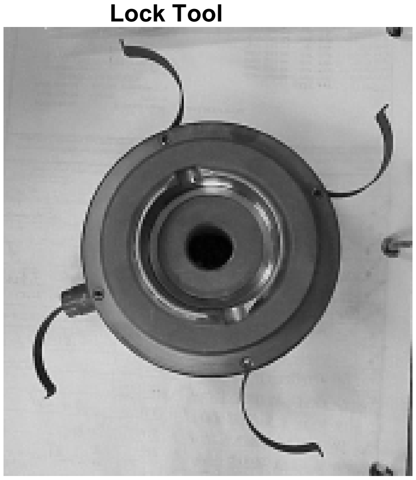

Figure 13. P6 Primary Race with Centering Springs

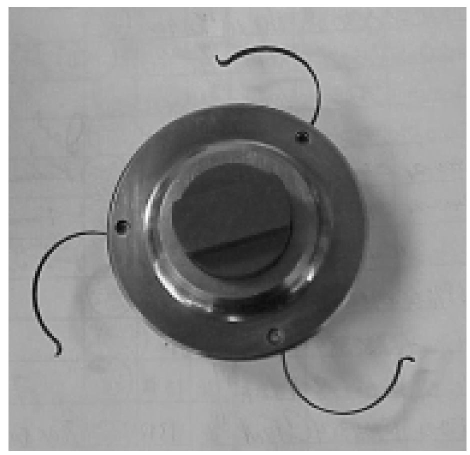

Figure 14. P6 Contingency Race with Centering Springs

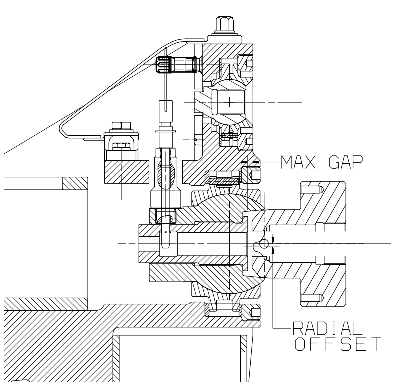

Figure 15. Z1 Shear Cylinder Entering P6 Ball/Nut, at Ready to Bolt Configuration

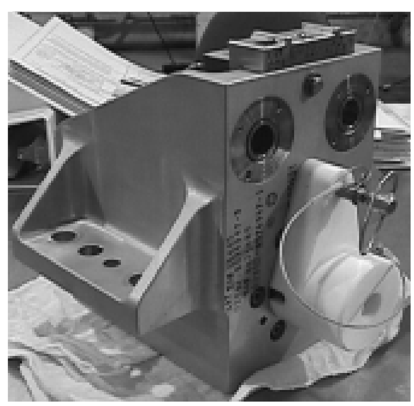

Figure 16. Z1 Fine Alignment/Bolt Assembly

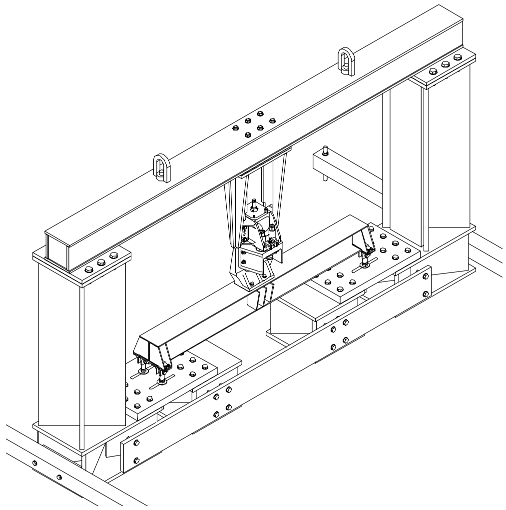

Figure 17. Misalignment Test Setup

Figure 18. Contact Dynamics Test Setup

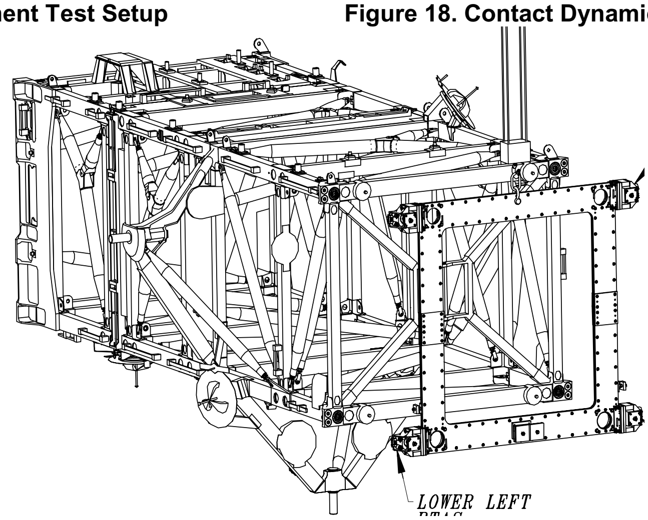

Figure 19. Z1 MMS Checkout of P6 Flight Article

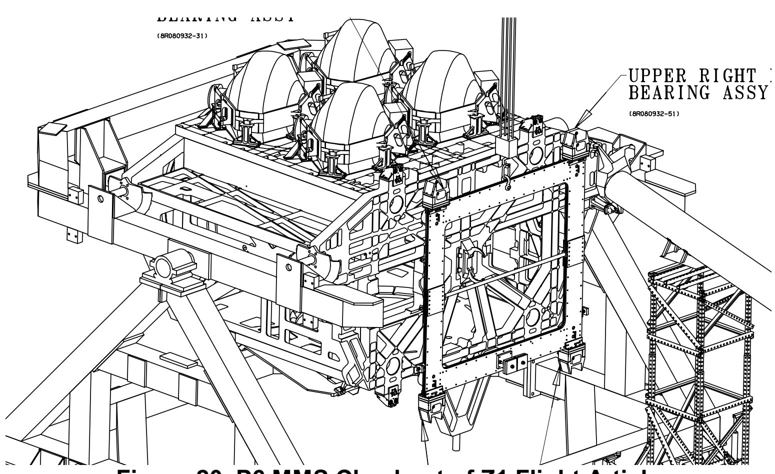

Figure 20. P6 MMS Checkout of Z1 Flight Article