NASA/TM–2013-217996 (Corrected Copy)
NESC-RP-12-00768

Structural Analysis Peer Review for the Static Display of the Orbiter Atlantis at the Kennedy Space Center Visitors Center

Stephen J. Minute/NESC
Langley Research Center, Hampton, Virginia

May 2013

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National Aeronautics and
Space Administration

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Structural Analysis Peer Review of the Kennedy Space Center Visitors Center Orbiter Atlantis Static Display

March 14, 2013

Report Approval and Revision History

NOTE: This document was approved at the March 14, 2013, NRB. This document was submitted to the NESC Director on March 22, 2013, for configuration control.

Approved:	*Original Signature on File*	3/25/13
	NESC Director	Date

Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Mr. Stephen Minute, NESC Chief Engineer, KSC	3/14/13

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Technical Assessment Report

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Technical Assessment Report

1.0 Notification and Authorization

Mr. Christopher Miller with the NASA Safety & Mission Assurance (S&MA) at the Kennedy Space Center (KSC), in conjunction with the KSC Education and External Relations Directorate, requested an independent peer review of the Orbiter Atlantis static display structural analysis for display at the KSC Visitors Center. The principal focus of the assessment was to review the engineering firm's structural analysis for lifting and aligning the orbiter and its static display configuration.

A NASA Engineering and Safety Center (NESC) initial evaluation was approved to proceed by the NESC Review Board (NRB) on March 22, 2012. Mr. Steve Minute, NESC Chief Engineer at KSC, was assigned to lead this assessment. A preliminary stakeholder summary was approved by the NRB on September 27, 2012.

The key stakeholders for this assessment are the KSC S&MA, KSC Education and External Relations Directorate, Shuttle Transition and Retirement (T&R) Project, and the NESC.

2.0 Signature Page

Submitted by:

Team Signature Page on File – 4-15-13

Mr. Stephen A. Minute   Date

Significant Contributors:

Dr. Ivatury S. Raju   Date

Mr. Kevin Roscoe   Date

Dr. Curtis E. Larsen   Date

Mr. David A. Hamilton   Date

Dr. Kenny B. Elliott   Date

Signatories declare the findings, observations, and NESC recommendations compiled in the report are factually based from data extracted from program/project documents, contractor reports, and open literature, and/or generated from independently conducted tests, analyses, and inspections.

3.0 Team List

Name	Discipline	Organization
Core Team		
Steve Minute	NESC Lead	KSC
Kenny Elliott	NASA Deputy Discipline Expert for Structures	LaRC
Curt Larsen	NASA Technical Fellow for Loads & Dynamics	JSC
Patricia Pahlavani	MTSO Program Analyst	LaRC
Ivatury Raju	NASA Technical Fellow for Structures	LaRC
Kevin Roscoe	Structures Discipline Expert	LaRC
Mark Terrone	NESC Systems Engineer	KSC
Consultant		
Dave Hamilton	Structures Discipline Expert	Consultant
Administrative Support		
Erin Moran	Technical Writer	LaRC/AMA

4.0 Executive Summary

Mr. Christopher Miller with the Kennedy Space Center (KSC) NASA Safety & Mission Assurance (S&MA) office requested the NASA Engineering and Safety Center's (NESC) technical support on March 15, 2012, to review and make recommendations on the structural analysis being performed for the Orbiter Atlantis static display at the KSC Visitor Center. The S&MA office requested the NESC to consider three parts to this review:

1. Final static display – minimal dynamic loads (i.e., indoors, no internal access).
2. Lifting and handling to get orbiter onto final stands – potential dynamic loads on orbiter and support stands.
3. Payload bay door support – Atlantis will be displayed with doors open.

The primary interfaces for NESC team during this review were with the KSC S&MA office and with the KSC Shuttle Transition & Retirement (T&R) Program via their KSC Engineering Project engineering representative. However, there were numerous telecons and meetings convened with participation from NESC, KSC S&MA, KSC Shuttle T&R, KSC Engineering, Delaware North Companies (DNC), BRPH Engineering, and United Space Alliance (USA).

Numerous drawings, analysis, design, and data packages were provided to the NESC team. Because this was a peer review of the engineering analysis, a formal independent NESC assessment was not performed due to time constraints. The NESC team reviewed the existing work with technical experts asking questions about methodology and assumptions, and performing hand and finite element calculations as deemed appropriate. The NESC questions and comments were exchanged directly with the cognizant engineers in a real-time and effective technical interchange.

Throughout the review there were comments and concerns that centered around four specific areas of the proposed design and process.

1. Compliance of attach points primarily for thermal expansion.
2. Sufficient control of the load while on the lifting jacks.
3. Payload bay door support beam support structure strength.
4. Payload bay door opening operations.

DNC, BRPH Engineering, and USA were responsive to the NESC team inquiries and took action to improve their analysis and design, where appropriate. Details of these technical exchanges are discussed in this report. Based on the data and information provided, the NESC team found the DNC, BRPH Engineering, and USA designs and analysis to be appropriate and acceptable.

One observation was noted during the review. In general, there was a lack of "procedures" that NASA engineers are accustomed to seeing, such as detailed documentation on how a structure goes from one position to another, and how the load is transitioned from one support system to another. The contractor captured the general processes in the drawing system and drawing notes to convey the activities. To assess the activities involving structures and the orbiter without procedures, assumptions were made on the NESC team's part that the vendor would safely execute the activity as discussed.

However since the conclusion of the NESC peer review activities, the contractors demonstrated the lifting and rotation processes using an orbiter mass simulator. The NESC team contacted KSC S&MA office to confirm that no issues were encountered during the tests.

5.0 Assessment Plan

Since this was a peer review, the assessment plan was waived.

6.0 Problem Description, Scope, Proposed Activities

Mr. Christopher Miller with the KSC S&MA office requested NESC technical support on March 15, 2012, to review and make recommendations on the structural analysis being performed for the Orbiter Atlantis static display at the KSC Visitor Center. In particular, Mr. Miller requested the NESC to consider three parts to the scope of this review and comment effort:

1. Orbiter final static display design and engineering analysis with the assumption that there would be minimal dynamic loads after the orbiter was in place (i.e., indoors – no wind loading, no internal access).
2. Lifting and handling processes to move the orbiter onto the final stands – potential dynamic loads on orbiter and support stands.
3. Process to open the payload bay doors and provide static support of the doors in the open position.[1]

The primary interfaces for the NESC team during this review were with the KSC S&MA office and with the KSC Shuttle T&R Program via their KSC Engineering Project engineering representative.

This peer review was an iterative process. Numerous drawings, analysis, design, and data packages were provided to the NESC team in different drops (See Reference Documents 1-10). The NESC held internal telecons to assess the engineering analysis and formulate questions and comments. In most instances, the NESC questions and comments were transmitted to Mr. John Dillon with the KSC S&MA office, who forwarded the questions to the appropriate responsible contractor personnel. Some of the responses were handled via e-mail but, in some cases, it was more appropriate to have telecons with cognizant Atlantis Display project personnel. The primary organizations included, as appropriate, the NESC, KSC S&MA, KSC Shuttle T&R, KSC Engineering, DNC, BRPH Engineering, and USA.

Because this was a peer review of the engineering analysis, the NESC team did not perform a formal independent modeling and analyses due to time constraints. The NESC reviewed the existing work with technical experts asking questions about methodology and assumptions, and performing hand and finite element calculations as deemed appropriate.

A stakeholder outbrief of the NESC team's activities was approved at the NESC Review Board on September 27, 2012 (Appendix A). It was subsequently shared with KSC S&MA, KSC

[1] Activity not performed. See Section 7.4.

T&R, and KSC Education & External Relations organizations in preparation for their readiness reviews.

7.0 Data Analysis

The review focused around several general areas of the proposed design and analysis process with comments and concerns on the first four areas.

1. Compliance of attach points for thermal expansion and dynamic loading (i.e., rotation).
2. Sufficient control of the load while on the lifting jacks.
3. Payload bay door support beam factors of safety (FoS).
4. Payload bay door opening operations.
5. Reaction loads for static display.
6. FoS.

DNC, BRPH Engineering, and USA were responsive to the NESC team inquiries and took appropriate action to modify and improve their analysis and design, where appropriate. Details of these items are discussed in more detail in the following sub-sections.

7.1 Compliance of Attach Points for Thermal Expansion

BRPH assessments (References 8 and 9) were provided to NASA as part of an ongoing process to show that the orbiter final display configuration was safe to construction personnel and the public, and would not damage the Orbiter Atlantis. A review of Reference (8) showed that the attachment points on the orbiter and the attachment hardware to be sufficient for the 43 degrees, port wing down roll display configuration. This sufficiency is contingent on the support structure/attachment hardware providing the adequate compliance, especially for thermal expansion. (See Figure 7.1-1 for the aircraft/orbiter (AO)-2 attach point.) The fore/aft direction should be compliant at the AO-1 forward support point, and the lateral direction should be compliant at the AO-2 aft port support point. Without these compliances, there is a risk to exceed the design loads in ICD-2-17001 Table 3.2.3-1.2 of Reference (1). A summary of the telecom to discuss this concern is included in Appendix B, Appendix H, items 1 and 2, and Appendix I, item 1. Comments, concerns, and questions are provided in Appendix C with subsequent responses from BRPH Engineering in Appendix D.

<u>NESC Concern (Roscoe, August 17)</u>: The orbiter installation was to be performed in November and without environmental control (i.e., without the building's roof installed). Given a change in temperature event during installation or while on display, differential thermal expansion between the orbiter and the support structure drove the need for compliance between the two articles. The DNC calculations (Appendix E) predicted forces at the AO joints with perfectly compliant (i.e., zero stiffness) support structure. The DNC used Fluorogold® bearing elements to add

compliance. However, these bearings were not "perfectly" compliant. The non-zero compliant bearings would result in additional shear forces at the AO joints during thermal events. Also, the thermal events would have a zero relative velocity starting point at the Fluorogold® interface. The joint would tend to stick until sufficient shear force would overcome static friction.

BRPH Response (Paquette, August 20): "We have been looking at the concerns about differential thermal expansion between the Orbiter and the Orbiter Support frame and had the following response.

a. According to the slide bearing manufacturers, the static coefficient of friction to break away is anywhere from nearly the same as the dynamic friction (0.07) to a maximum of 0.1. So at AO2 the maximum breaking frictional resistance Yo = 93.1(0.1) = 9.31 kips which we used in our calculations. To assure the 0.07 coefficient of friction in the short term, lubricants are used according to the bearing manufacturers, we are specifying them for the jacking and rotation. The coefficient of friction is also improved with bearing pressures above a minimum of 75 psi according to the slide bearing manufacturers - so for the slide bearings under the spacers, the bottom plate bearing surface was reduced where required to assure that the bearing pressures are above 75 psi for applicable Orbiter orientations. (The Orbiter when level was a controlling factor at the aft slide bearings.)
b. We have also added high capacity slide bearings at the edges of the shear lugs at the spacers to reduce friction at AO3 and AO1 in the Xo direction from the Yo loads and at AO2 in the Zo direction and we have considered the breakaway friction at the edge slide bearings in our calculations as well.
c. After rotation, the support frame between the Aft and Forward AO supports is intended to be removed, so differential thermal expansion of the Orbiter versus the horizontal support frame between the forward and aft Orbiter supports will not be applicable. The forward support frame is capable of deflecting because it is not braced in the Xo direction.
d. We identified as much as 10.2 kips of uplift at AO3, which isn't very much for all 8 bolts (1.5 inch diameter A325) in the spacer to resist. We have removed the torque requirements after jacking and rotation from the contact documents.
e. We have analyzed and provided a table considering the Orbiter loads combined with friction developed on the slide bearings prior to movement and differential thermal expansion for cases that include in the level or rotated condition during jacking and rotation."

Static Display Compliance Summary:

The NESC team assessed this item has been satisfactorily addressed, assuming compatibility of the lubricant and Fluorogold®, and believing 0.10 is the maximum coefficient of friction per the manufacturer. Both assumptions would rate as a low risk. The contractor team has sufficiently engineered the joint (e.g., contacted the manufacturer to estimate break-away friction, reduced bearing area to increase pressure load to the minimum recommended, added slide bearings to the shear lugs, removed post-installation bolt torque, and calculated predicted max break-away shear loads due to thermal expansion). The contractor team could have (or may have) tried to determine the structural compliance between AO-2 and AO-3 for the small thermal expansion difference. However, the 16,300-lb limit may have been too low for the Support Frame. Either way the bearing solution works. Once a slide bearing was introduced under AO-1, the contractor team solved the biggest threat to the thermal expansion issue. Refer to in-depth question and response discussion in Appendix F.

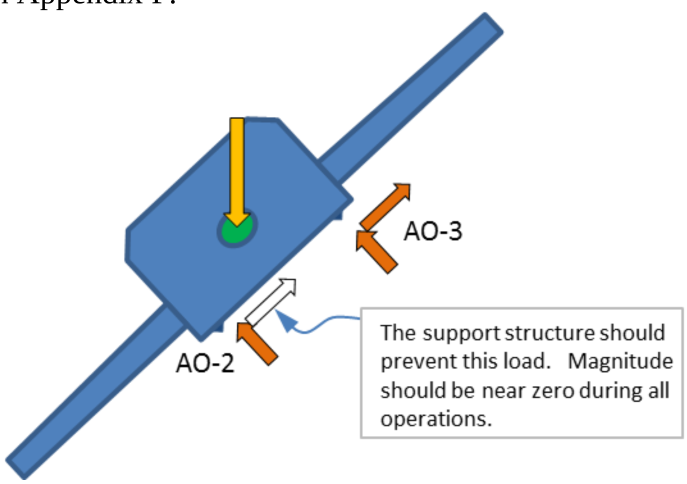


Figure 7.1-1. Orbiter Attach Point Compliance (Weight and Reaction Loads)

7.2 Sufficient Control of the Load While On the Lifting Jacks

The NESC team had an initial concern that the jacks will experience a moment as the orbiter is being rotated to final position i.e., 43 degrees, port wing down) (See Figures 7.2-1, 7.2-2, and 7.2-3, and Appendix G and Appendix H, items 3 and 4).

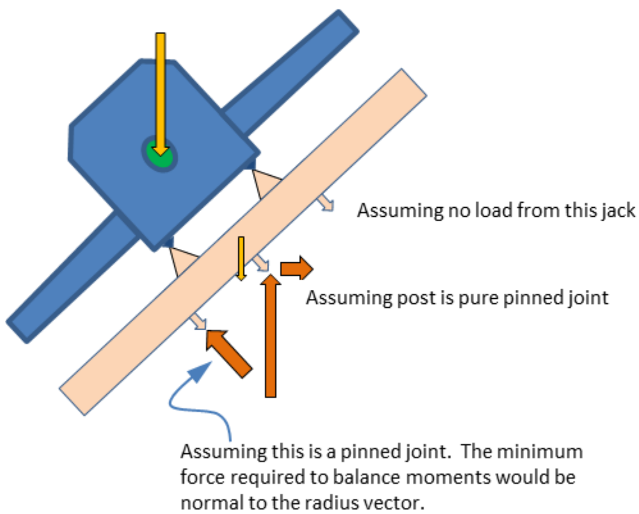


Figure 7.2-1. Free Body Diagram of Loads to the Support Structure

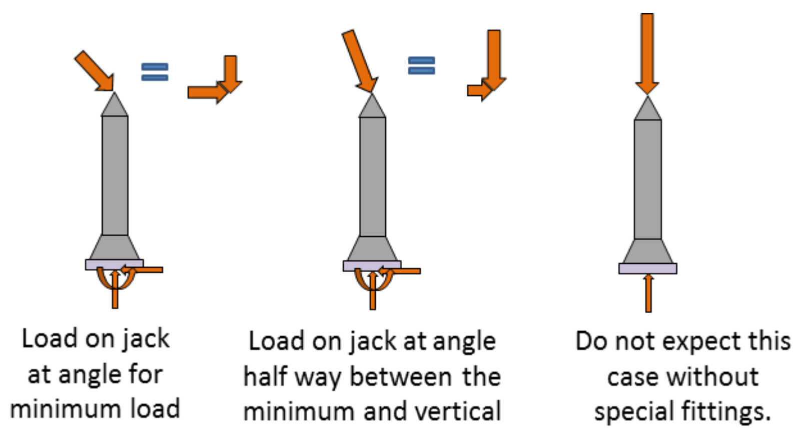


Figure 7.2-2. Free Body Diagram of Loads to the Jacks

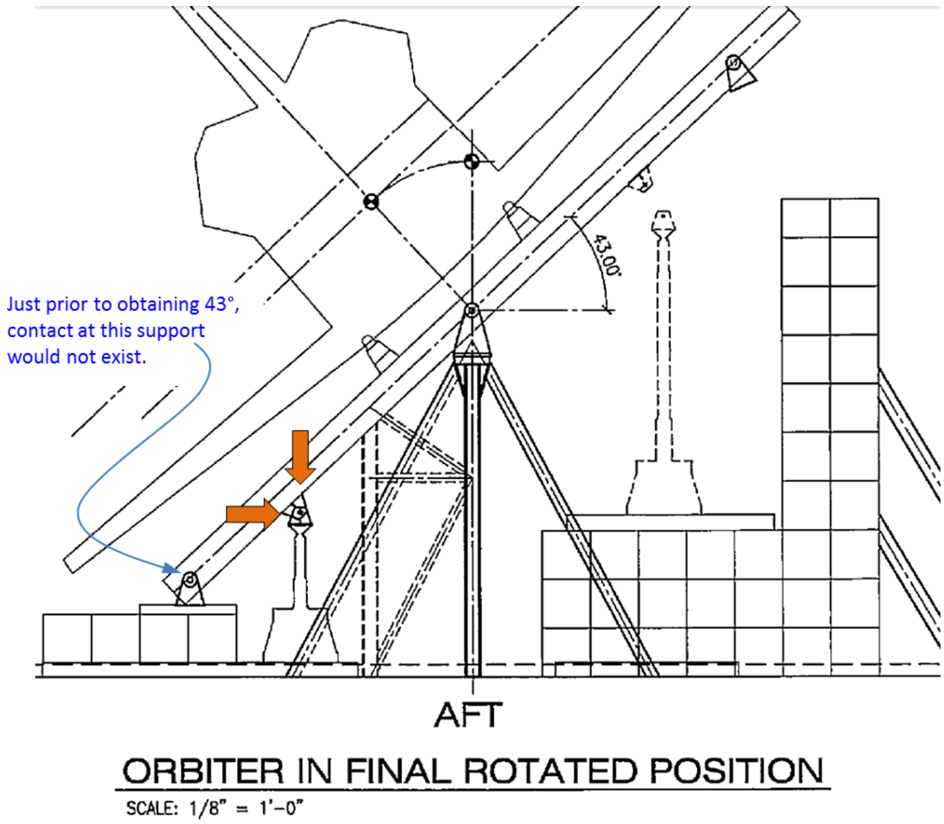


Figure 7.2-3. BRPH Drawing of Orbiter in Final Rotated Position with Loads Applied to Jacks

The following response was provided to the initial NESC team's comments and concerns via an email from Mr. Ken Paquette, BRPH to Mr. John Dillon, KSC-Safety & Mission Assurance Support Services (SMASS), dated July 10, 2012:

Response to Atlantis-Pivot.xlsx Load Diagrams in Appendix G

"Beyel Brothers has the bottom of the jacks stabilized by (propel) hydraulic cylinders that are attached to the jack alignment runway tracks. (See attachments – Propel Jack Cylinder.pdf and Lift Systems Jack Runway.pdf; Appendix J) The hydraulic cylinder allows controlled horizontal movement. Leveling systems are being used to keep the jack straight. The top of the jacks are attached to a hinged connection on the orbiter support beam. There are diagonal braces that extend from the aft jack locations on the orbiter support beam to spreader beams between the aft and forward supports for the orbiter. The rotation procedure will be performed slowly to allow for adjustment to keep the jacks vertical."

BRPH Engineering and DNC provided jack stability analysis (Reference 10). However, during the telecon on July 27, 2012, the NESC team and DNC agreed that there was insufficient jack data to perform a thorough analysis. DNC agreed to develop a test fixture with an orbiter mass simulator to demonstrate capability and provide a pathfinder test for future processes. DNC modified their design to include load cells at the top of the jack. With the load cells, DNC were able to monitor jack side loads and improve the load control (Appendix I, item 2).

Subsequent to the peer review and stakeholder outbrief, DNC performed a pathfinder demonstration with an orbiter mass simulator. (Figures 7.2-4, 7.2-5, and 7.2-6) No issues were identified as a result of the test. The pathfinder test satisfied the concerns raised in this section.

BRPH Engineering incorporated bracing, sliding tracks for jacks, dunnage, and moved in 2-inch increments to control the load. (Figures 7.2-4, 7.2-5, and 7.2-6)

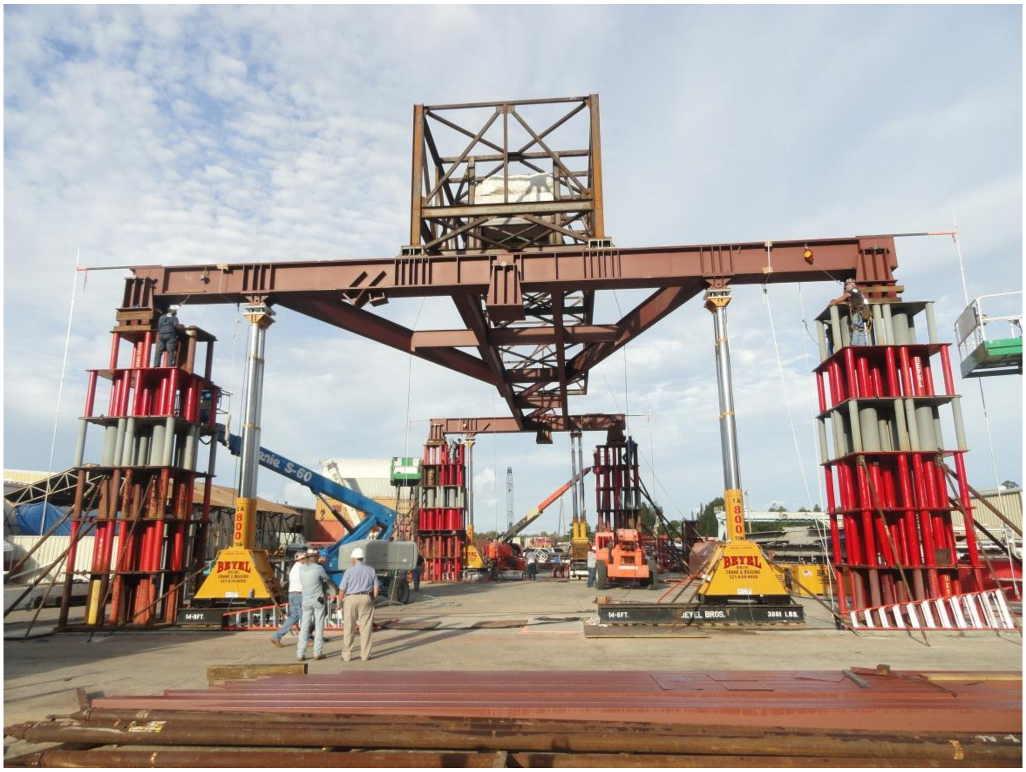


Figure 7.2-4. Pathfinder Demonstration – Initial Lift

Figure 7.2-5. Pathfinder Demonstration – Rotation (aft view)

Figure 7.2-6. Pathfinder Demonstration – Rotation (side view)

Beyel Brothers completed the lift and rotation demonstration test at their Rigging and Heavy Equipment Yard on October 11, 2012. The test used a mass simulator and equivalent support structure to demonstrate the planned process for lifting and rotating the orbiter at the KSC Visitor Center display site. The contractor demonstrated a well-choreographed process using a combination of lifting jacks and support cribbing/dunnage to lift and rotate the orbiter to its final display configuration (i.e., 43 degrees, port wing down).

Dunnage was used to support the port side jacks, the frame at the 43-degree position, and the load in the event of a jack casualty (loss of hydraulics). The dunnage load capacity was based on an aligned stacking configuration (concentric pipes axis) per page 92 of Volume I, Reference 7. The aft port location had staggered dunnage where the pipes were not aligned and a load capacity rating was not defined. The NESC team performed an assessment of dunnage for this configuration (Appendix K) and found it to be sufficient for this application. No issues were identified from the NESC team.

7.3 Payload Bay Door Support Beam Support Structure Strength

The DNC/USA bolt calculation showed a FoS of 3 on yield and 5 on ultimate (see Appendices L, M, and N). However, the DNC/USA calculations were in error because they did not account for the prying/lever action of the two-piece support arm on the bolt. It was assumed all the cable load would go directly to the bolt. The NESC bolt force load estimation, assuming only one bolt was active out of the six, was 1,591 lbs, versus the DNC/USA value of 679 lbs (1,357/2) (see Appendices O, P, and Q). DNC/USA subsequently revised their analysis and agreed to improve the design by increasing the bolt strength to achieve a FoS of 5 (MP-35N 240KSI tensile strength versus 90-100 KSI for the original bolt).

No further concerns were generated from the NESC team.

7.4 Payload Bay Door Opening Operations

Initially, a review of the payload bay door opening operations was included in the initial NESC request. The engineering and operational expertise associated with payload bay door operations for the Space Shuttle Program resides with KSC Engineering, USA, KSC S&MA, and the Shuttle T&R personnel at KSC. It was agreed with all parties, including KSC Education and External Relations Directorate, that the NESC was not the appropriate organization to peer review those operations.

7.5 Miscellaneous

There were other items the NESC team reviewed. They were not significant items, but are included in this section for completeness. The NESC considers these items accepted and closed.

1. The DNC orbiter support frame with respect to the orbiter and the test fixture, including center of gravity measurements and checks of critical dimensions of the orbiter-to-shuttle carrier aircraft interfaces as found in the interface control document (ICD).
2. The shuttle documentation for the external tank (ET)-to-orbiter limit loads allowed during ascent flight. Those allowable loads were more severe than the ferry flight ICD limits used in designing the DNC static display structure. The demonstrated ascent loads reflect the true orbiter interface load capability and give additional comfort in accepting the loads to be imposed by the static display structure (Appendix R).

8.0 Findings and NESC Recommendations

Because of the iterative nature of this peer review there were no formal findings or NESC recommendations. All comments and concerns were addressed in real-time discussions and e-mail and captured as best as practical in this report. Based on the data and information provided, the NESC finds the DNC, BRPH Engineering, and USA design and analysis results to be appropriate and acceptable.

One observation was noted during this review and documented in the stakeholder outbrief (Appendix A). In general, there was a lack of "operational procedures" that NASA as an Agency are accustomed to, such as detailed documentation on how a structure goes from one position to another, and how the load is transitioned from one support system to another. The contractor captured the general processes in the drawing system and drawing notes to convey the activities. To assess the activities involving structures and the orbiter without procedures, assumptions were made on the NESC team's part that the vendor would safely execute the activity as discussed. Subsequent to the peer review and stakeholder outbrief, DNC performed a pathfinder demonstration with an orbiter mass simulator (Figures 7.2-4, 7.2-5, and 7.2-6). No issues were identified to the NESC as a result of the test. The pathfinder satisfies the concerns raised in this observation.

9.0 Alternate Viewpoint

There were no alternate viewpoints identified during the course of this assessment by the NESC team or the NESC Review Board quorum.

10.0 Acronyms List

AO	Aircraft/Orbiter
DNC	Delaware North Companies
ET	External Tank
FoS	Factor of Safety
ICD	interface control document
KSC	Kennedy Space Center
MTSO	Management Technical Support Office
NASA	National Aeronautics and Space Administration
NESC	NASA Engineering and Safety Center
S&MA	Safety & Mission Assurance
SMASS	Safety & Mission Assurance Support Services
T&R	Transition & Retirement
USA	United Space Alliance

11.0 References

1. Atlantis Loads Assessment, KSC Visitor Complex Analysis Report, Final Submittal, BRPH No. 5636.45, dated July 5, 2012 (pdf)
2. KSC Visitor Complex Atlantis Support Dwg., 60% Submittal, BRPH No. 5636.44, dated June 18. 2012 (pdf)
3. KSC Visitor Complex Atlantis Support Dwg., 90% Submittal, BRPH No. 79K39277, dated August 22, 2012 (pdf)

4. Atlantis Support Orbiter Opening Doors, Pre-100% Submittal, BRPH 79K39277, dated September 12, 2012 (pdf)
5. KSC Visitor Complex Atlantis Support Dwg., 100% Submittal, BRPH No. 79K39277, dated September 19, 2012 (pdf)
6. Test Fixture Design, 100% Submittal, BRPH Drawing 6701.01, dated August 9, 2012 (pdf)
7. 100% Structural Calculations Volumes I & II, BRPH No. 5636.44, dated January 19, 2012 (pdf)
8. Atlantis Loads Assessment, KSC Visitor Complex Analysis Report, 90% Submittal, BRPH No. 5636.45, dated May 3, 2012 (pdf)
9. Atlantis Support Concept, KSC Visitor Complex, 100% Submittal, BRPH No. 5636.44, dated February 17, 2012 (pdf)
10. Orbiter Rotation Frame 7-9-2012.pdf (STAAD Analysis FilePropel Jack Cylinder.pdf (Jacks to be used for lift and Orbiter Rotation Frame 7-9-2012.pdf (STAAD Analysis File)

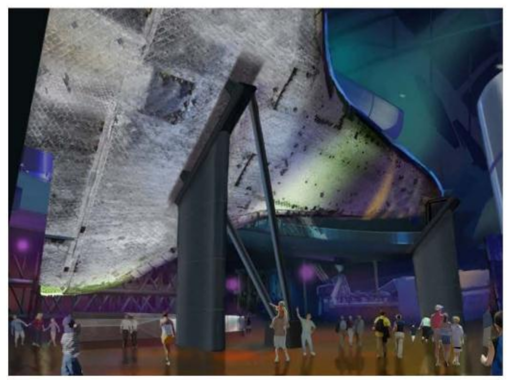
12.0 Appendices

A. NESC Stakeholder Outbrief
B. Atlantis_Review-Executive_Summary-060112[1].docx (Notes from Telecon held 6/1/2012)
C. AtlantisLoadsAssess_Comments.xlsx (K. Roscoe Comments from NESC Review of Reference Documents: Attachments D of Ref. 1, Ref. 8, and Ref. 9)
D. AtlantisLoadsAssess_Comments RBPH Response.pdf (Response to NESC comments in Appendix C - AtlantisLoadsAssess_Comments.xlsx)
E. Orbiter Loads 155K Xo = 159 On SCA Connections.pdf
F. Email from K. Roscoe to S. Minute on 9/3/2012: 5636.44 RE: Atlantis Support Structure - Additional Design Calculations
G. Atlantis-Pivot.xlsx (K. Roscoe’s Free Body Diagrams)
H. AtlantisItemsFor072712meeting.docx (Discussion items for telecon held 7/27/2012)
I. AtlantisReview072712-Summary.docx (Summary of telecon on 7/27/2012)
J. Propel Jack Cylinder.pdf (jacks to be used for lift and rotation)
K. Atlantis DunnageRevA.pptx (Assessment of dunnage to be used in lift and rotation procedure)
L. PLBD Support-C.pdf
M. G-Ops Support.pdf
N. Mathcad - OV-104_Door_Support_Analysis_3.pdf
O. PLBD Comments.pptx (K. Roscoe’s assessment of PLBD analysis)
P. PLBD Attach Beam calcs.xlsx (K. Roscoe’s analysis)
Q. AttachBeamBolts.xlsx (K. Roscoe’s analysis)
R. Email from C. Larsen to Minute, et. al. on September 5, 2012: Re: Atlantis Support Structure – Orbiter allowable loads.

Appendix A. NESC Stakeholder Outbrief

		Presenter: S. Minute
		Date 9/27/2012

Stakeholder Briefing:
Atlantis Static Display Structural Analysis Review
T-12-00768



Steve Minute
September 27, 2012

This briefing is for status only and does not represent complete engineering data analysis 1

NESC Document No: NESC-PSS-12-00768

Scope of Assessment

Presenter: S. Minute

Date 9/27/2012

An engineering firm is performing the structural analysis for the static display of Orbiter Atlantis at the KSC Visitor Center

Because of the significance and visibility of this national asset, S&MA wanted an independent peer review of the engineering analysis

NESC considered three parts to this review

- Final static display of Orbiter to support stands – minimal dynamic loads (i.e. indoors, no internal access)
- Lifting and handling to get orbiter onto final stands
- Assess payload bay door support and connection to support wires - Orbiter will be displayed with doors open (analysis of door structure not provided)
- Did not review the Payload Bay Door opening procedure and required GSE – KSC engineering better suited to review that operation

Peer Review Activities

Presenter: S. Minute

Date 9/27/2012

- Team Membership:
  - Steve Minute (NESC CE - KSC)
  - Ivatury Raju (NASA Tech Fellow – Structures)
  - Kevin Roscoe (NASA LaRC Discipline Expert – Structures & GSE)
  - Kenny Elliott (NASA LaRC Discipline Expert – Structures)
  - Curt Larsen (NASA Tech Fellow – Loads & Dynamics)
  - Dave Hamilton (Structural Engineering Consultant – JSC)
  - Mark Terrone (NESC Systems Engineer)
- NESC was requested to peer review the design in March, 2012.
- Over the course of the review period NESC was provided multiple design and analysis packages.
- Held 4 internal team meetings and 2 external meetings (with Delaware North, BRPH, NASA, S&MA, and USA)
- Upcoming - Rollout and Program Readiness Reviews

This briefing is for status only and does not represent complete engineering data analysis

3

NESC Document No: NESC-PSS-12-00768

	Data Analysis	Presenter: S. Minute
		Date 9/27/2012

- Data, Designs, and Drawings provided were reviewed.
- Because this was a peer review the NESC questions and comments were fed directly to the program and contractors for consideration.
- Four areas for further discussion/concern developed:
  1. Compliance of attach points for thermal expansion
  2. Sufficient lateral stiffness of the lifting jacks
  3. Payload Bay Door Support Beam Factor of Safety
  4. Payload Bay Door opening operations

This briefing is for status only and does not represent complete engineering data analysis 4

NESC Document No: NESC-PSS-12-00768

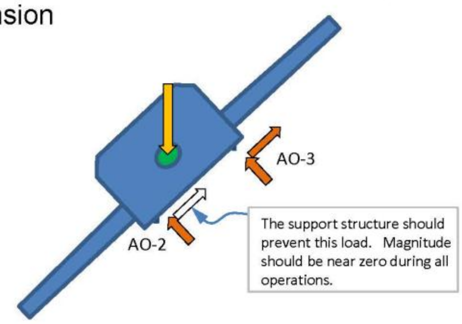
Data Analysis (cont.)

Presenter: S. Minute

Date 9/27/2012

1. Compliance of attach points for thermal expansion

- BRPH has re-engineered their Flourogold® slide bearing design to better accommodate thermal issues as a result of NESC inquiries:
  - Contacted Flourogold® to estimate break-away friction
  - Reduced bearing area to increase pressure load to minimum recommended (overcomes static friction)
  - Removed post-installation bolt torque
  - Added slide bearings to side of shear lugs (effective when rotated)
  - Calculated predicted max break-away shear loads due to thermal expansion



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NESC Document No: NESC-PSS-12-00768

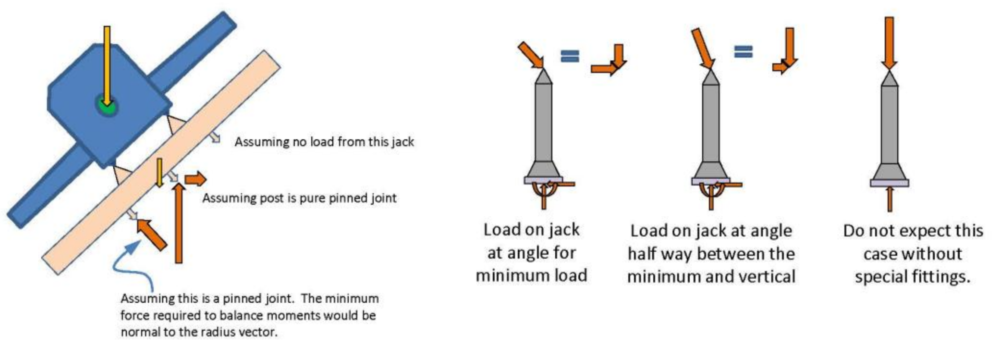
Data Analysis (cont.)

Presenter: S. Minute

Date 9/27/2012

2. Sufficient lateral stiffness of the lifting jacks

- Concern that jacks will experience a moment as the orbiter is being rotated to final position (starboard side 43 deg. down)
  - BRPH incorporating bracing, sliding tracks for jacks, and dunnage in 2" increments to control rotation.
  - Insufficient jack data to do analysis – but will demonstrate capability with testing (open work). Plan to use an orbiter mass simulator to perform pathfinder test.



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NESC Document No: NESC-PSS-12-00768

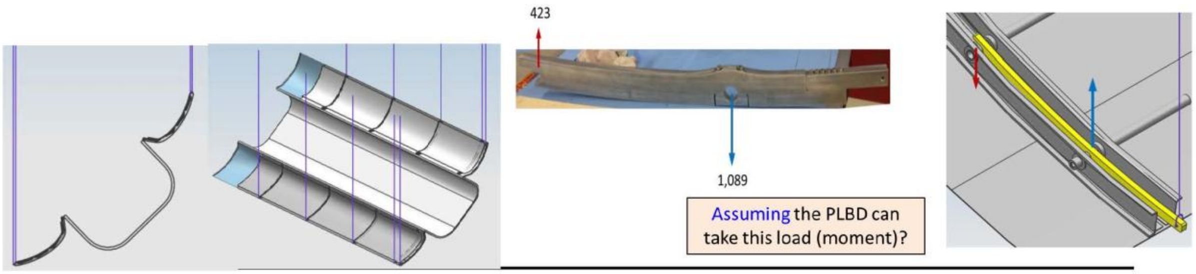
Data Analysis (cont.)

Presenter: S. Minute

Date 9/27/2012

3. Payload Bay Door (PLBD) Support Beam Factor of Safety (FoS)

- PLBD Support Beam design was based on FoS of 2
- NESC concerned with transition of PLBDs from existing GSE to support beam & cables.
  - Weight of GSE still attached; Strongbacks make doors semi-rigid
  - Planned method to transfer load to support cables via turnbuckles
  - Should consider Support beam and cables as lifting devices during transition (NASA Standard required FoS of 5)
- USA opted to use stronger bolts and improve their analysis resulting in FOS greater than 5.



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NESC Document No: NESC-PSS-12-00768

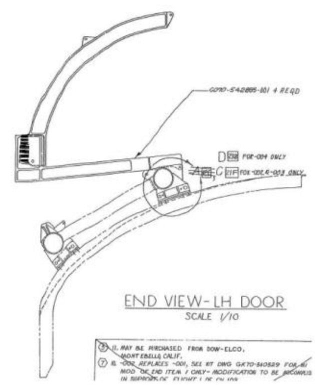
Data Analysis (cont.)

Presenter: S. Minute

Date 9/27/2012

4. Payload Bay Door opening operations

- The NESC team did not have the expertise to assess the PLBD opening operation with modified orbiter GSE (C-hook, etc.)
- Communicated concern back to S&MA and program. NASA and USA Program personnel are reviewing those activities



This briefing is for status only and does not represent complete engineering data analysis

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NESC Document No: NESC-PSS-12-00768

Findings/Recommendations

Presenter: S. Minute

Date 9/27/2012

Based on the data and information provided to NESC we find the Delaware North, BRPH, and USA designs and analysis (as stated in the scope) to be appropriate and acceptable.

- The contractors responded to our NESC inquiries.
- Where appropriate, they improved their analysis and design

In general, there was a lack of "procedures" as we in NASA are accustomed to seeing, like detail on documenting how a structure goes from one position to another, and how the load is transitioned from one support system to another. The contractor captured the general processes in the drawing system and drawing notes to convey the activities. To assess the activities involving structures and the orbiter without procedures, assumptions were made on our part that the vendor would safely execute the activity as discussed. The planned lifting and rotation tests will be helpful in demonstrating the process.

This was communicated to the Stakeholders

This briefing is for status only and does not represent complete engineering data analysis

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NESC Document No: NESC-PSS-12-00768

Appendix B. Atlantis_Review-Executive_Summary-060112[1].docx (Notes from Telecon held 6/1/2012)

Subject: Display of Atlantis in the KSC Visitor Complex

References (1) and (2) were provided to NASA as part of an ongoing process to show that all procedural steps from transporting the orbiter to the final display configuration are safe and will not damage the Orbiter Atlantis. A review of Reference (1) shows that the attachment points on the orbiter and the attachment hardware to be sufficient for the 43° roll display configuration. This sufficiency is contingent on the support structure / attachment hardware providing the proper compliance. At the forward support point, AO-1 the fore/aft direction should be compliant. At the aft port support point, AO-2 the lateral direction should be compliant. Without these compliances it could be relatively easy to exceed the design loads in Table 3.2.3-1.2 of Reference (3).

To complete the review and assessment of the process, the following documents are needed:

1. The structural steel support frame (display structure) assessment, including the appropriate support structure / attachment hardware compliances.
2. Payload Bay Door procedure and hardware assessment (crane operations (opening), and supporting)
3. Orbiter lifting / jacking procedure onto the display structure and hardware assessment
4. Orbiter rotation procedure and hardware assessment

Confirmation should be provided stating that all hardware and procedures used for handling the orbiter are the same as those used for the flight articles. If not, an assessment of the variances should be provided for review.

Note: Reference (2) contains operations that conflict with those in Reference (1). These conflicts need to be addressed and resolved.

References:

1. Atlantis Loads Assessment, KSC Visitor Complex Analysis Report, 90% Submittal, BRPH No. 5636.45, dated May 3, 2012
2. Atlantis Support Concept, KSC Visitor Complex, 100% Submittal, BRPH No. 5636.44, dated February 17, 2012
3. ICD-2-17001, rev G-1, Orbiter Vehicle / Carrier Aircraft, Dated March 5, 2007

Appendix C. AtlantisLoadsAssess_Comments.xlsx (K. Roscoe Comments from NESC Review of Reference Documents: Attachments D of Ref. 1, Ref. 8, and Ref. 9):

Atlantis Review

brph *Atlantis* *Loads Assessment*

Section	Paragraph	Comments or Notes
1	2	Do not need to make an exception. Comparison to the worst case tensile condition is not applicable. See ICD-2-17001, Section 3.2.3
1.2	2	Bullet 6: Cannot have a rigid support frame. All loading in contingent on AO-2 not transmitting lateral loads.
1.3	4	Support frame analysis is TBD
2.2	Figure	Sideslip Maneuver Forces: shows vertical tensile force of 128 kips. This case was used to size the bolt preload. See ICD-2-17001, Section 3.2.3
2.4	Last	Statement that they will design the support stand with AO-2 lateral compliance.
3	1	Don't need exception
3	3	Disagree with their Z load at AO-3. See Figure in 2.1 and "Loads" sheet
4.1		Orbiter support structure: AO-1 should be compliant in fore/aft direction A0-2 should be compliant in lateral direction
4.2	all	Don't need FEA when all the dofs are released.
4.3	all	Don't need FEA when all the dofs are released.
4.4		ICD-2-17001 rev G-1
	Figure	1.2-1.1 has the attachment coordinates
	3.2.3	Shows sideslip maneuver only used to derive preload
	Table	3.2.3-1.2 shows worst case loads on attachment hardware
	Table	3.2.3-1.3 shows sideslip maneuver loads
4.5	Figure 1	Figure is different from brph *Atlantis Support Concept* 2/17/12
	Step 2	Does not describe how they are going to install Atlantis on support frame
	Step 3	Does not describe how they are going to rotate frame
	Assumptions	Bullet 3: Only applies to attach points (not doors) and needs to have a FS Bullet 6: Frame must be appropriately compliant, not "rigid"
	Limitations	Assumption that there will be no differences between normal lifting and handling of the Orbiter and landing the Orbiter on the support stand.
4.6	email	Analysis weight appears to be conservative.
End		

Appendix D. AtlantisLoadsAssess_Comments RBPH Response.pdf (Response to NESC comments in Appendix C - AtlantisLoadsAssess_Comments.xlsx)

ATLANTIS LOAD ANALYSIS - Project # 5636.45

DNC Parks & Recreation

Atlantis Review (06-26-2012)

brph *Atlantis* *Loads Assessment*

Section	Paragraph	Comments or Notes	BRPH Response
1	2	Do not need to make an exception. Comparison to the worst case tensile condition is not applicable. See ICD-2-17001, Section 3.2.3	Accept - Will remove exception from report
1.2	2	Bullet 6: Cannot have a rigid support frame. All loading in contingent on AO-2 not transmitting lateral loads.	Accept - Will remove bullet 6 from report
1.3	4	Support frame analysis is TBD	60% Atlantis Support Package will have the support
2.2	Figure	Sideslip Maneuver Forces: shows vertical tensile force of 128 kips. This case was used to size the bolt preload. See ICD-2-17001, Section 3.2.3	Information - no action required
2.4	Last	Statement that they will design the support stand with AO-2 lateral compliance.	60% Atlantis Support Package will show spacers with slide bearings under the A02 and A03 Aft SCA Bases
3	1	Don't need exception	Accept - Will remove exception from report
3	3	Disagree with their Z load at AO-3. See Figure in 2.1 and "Loads" sheet	BRPH value is slightly higher -9.36 vs 2.712 This is due to the Analysis Software and method used and is more conservative than the reviewers result. The conservative results were used in the Orbiter Support frame analysis.
4.1		Orbiter support structure: AO-1 should be compliant in fore/aft direction A0-2 should be compliant in lateral direction	The Teepee for the forward flight ferry is capable of rotating, so special conections for the Teepee to the support are are not anticipated. 60% Atlantis Support Package will show spacers with slide bearings under the A02 and A03 Aft SCA Bases
4.2	all	Don't need FEA when all the dofs are released.	FEA was not performed, plates were added to an Orbiter model to change the stiffness to review the affect of allowing A03 to support loads in the Xo direction. This lead to not allowing A03 to support Xo loads.
4.3	all	Don't need FEA when all the dofs are released.	
4.4		ICD-2-17001 rev G-1	
	Figure	1.2-1.1 has the attachment coordinates	
	3.2.3	Shows sideslip maneuver only used to derive preload	Information - no action required
	Table	3.2.3-1.2 shows worst case loads on attachment hardware	
	Table	3.2.3-1.3 shows sideslip maneuver loads	
4.5	Figure 1	Figure is different from brph *Atlantis Support Concept* 2/17/12	If you are referring to "Figure- Orbiter Support Plan" this figure just gives a simple reference horizontal plan location of the connection attachments. This figure is not indicating the support frame.
	Step 2	Does not describe how they are going to install Atlantis on support frame	60% Atlantis Support Package will basic method. USA will make the ferry flight attachments to the Orbiter. Rigging plans from the Contractor will provide a detailed full procedure and equipment used.

Section	Paragraph	Comments or Notes	BRPH Response
	Step 3	Does not describe how they are going to rotate frame	60% Atlantis Support Package will basic method. Rigging plans from the Contractor will provide a detailed full procedure and equipment used.
	Assumptions	Bullet 3: Only applies to attach points (not doors) and needs to have a FS	Assuming that this is referring to the Approach section, approximately 1/2 of the final door weight should be supported from the roof structure above.
	Limitations	Bullet 6: Frame must be appropriately compliant, not "rigid" Assumption that there will be no differences between normal lifting and handling of the Orbiter and landing the Orbiter on the support stand.	See 60% Atlantis Support package for Orbiter installation. Framing between the aft and forward vertical support frames will be removed after Orbiter rotation.
4.6 End	email	Analysis weight appears to be conservative.	We haven't been able to get sufficiently detailed information to make any reductions.

Atlantis Review

brph *Atlantis Loads Assessment*

Pinned-Pinned Load Distribution

43 deg

	ICD-2-17001, Fig 1.2-1.1			Transform Coordinates: Relative to AO-1 X & AO-2 Y&Z			Transform Coordinates: Pivot about AO-2	
Location	Xo	Yo	Zo	Xo'	Yo'	Zo'	Yo"	Zo"
AO-1	388.045	0	283.841	0	96.5	16.285	59.47	77.72
AO-2	1317	-96.5	267.556	928.955	0	0	0	0
AO-3	1317	96.5	267.556	928.955	193	0	141.15	131.63
CG*	1082.6	0	364.9	694.555	96.5	97.344	4.19	137.01

* Per brph Loads assessment, Attach F

Load Distribution

X-Direction	
Fwd	25.23%
Aft	74.77%

Aft = 694 / 929
Fwd = 1 - Aft

Y-Direction	
AO-2	97.03%
AO-3	2.97%

AO-3 = 4.19 / 141
AO-2 = 1 - AO-3

Loads

Atlantis Weight 167,216

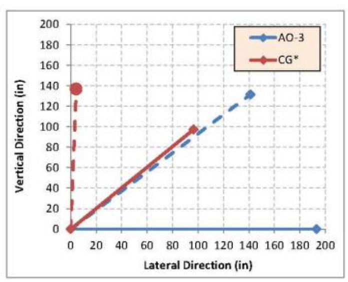
		Analysis Loads**			Limit Loads		Factor of Safety	
		X - Dir	Yo	Zo	Yo	Zo	Yo	Zo
Aft	AO-2&3	125,023	85,265	91,436				
Fwd	AO-1	42,193	28,776	30,858	95,300	190,400	3.31	6.17
	AO-2		0	88,724	16,300	355,000		4.00
	AO-3		85,265	2,712	248,400	355,000	2.91	131

**Analysis Xo loads were all zero

Graphical Display of Rotation

AO-3	
193	0
0	0
141.15	131.63

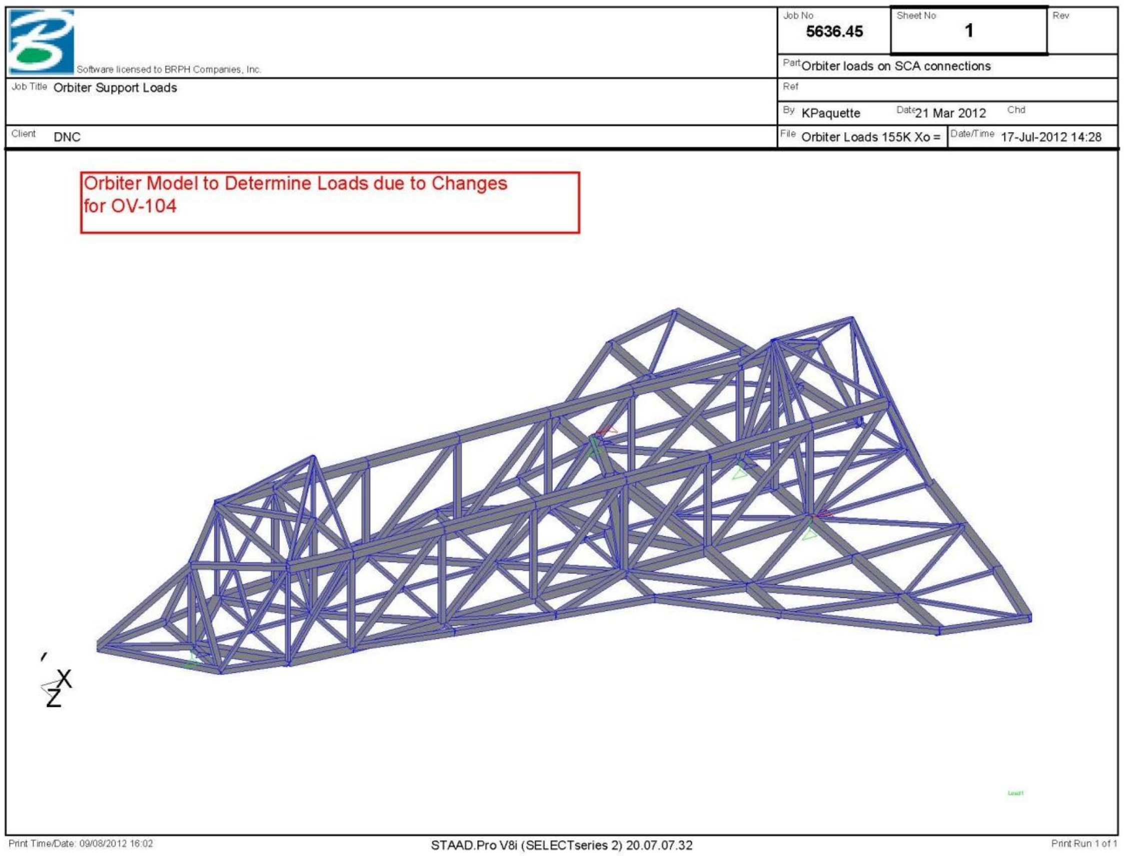
CG*	
96.5	97.344
0	0
4.19	137.01



Atlantis Review
brph *Atlantis* *Support Concept*

Section	Paragraph	Comments or Notes	BRPH Response
1.2	Step 2-7	Assume: brph *Atlantis Loads Assessment* section 4.5, limitations applies and they will not need steps 2-7.	Steps 2 to 7 are required to get the Orbiter up to the vertical height needed to rotate the Orbiter.
1.2	Step 8	Assume: brph *Atlantis Loads Assessment* section 4.5, Figure 1 is different from Step 8 (pivot point). Rotation not shown. Step 8 "as-is" is appears unstable.	See 60% Atlantis Support package. Dunnage has been added on the port side and bracing to the dunnage has been added at all of the dunnage.
1.2	Step 9	Dunnage will not likely work in this configuration.	See 60% Atlantis Support package.
1.3	Step 1	Port door CG and lift point appear to be in-line with or on the port side of the hinge (eyeball). Crane would need to pull sideways to open.	A detailed Orbiter door opening procedure is being developed by USA.
	Step 2 & 6	Door going over top dead center will want to bounce. Coordinating crane translation with cable tension likely needed.	A detailed Orbiter door opening procedure is being developed by USA.
		Preference: rather ground, support structure, or vehicle support doors. Storms will move rafters and a small cable easier to vandalize.	
4.1	Appendix A	Is the "Forward Jack" still needed with the current lift plan? Concerns with structure: Clevis ring on post, Foot Plates can't take moments, Lateral braces are flexible.	Yes - Unless USA comes up with something, there is inadequate clearance from the forward landing gear to the Ferry Flight Teepee support beam.
4.9	Appendix I	"C-Frame": Flange is not continuous at corner.	Illustration provided by NASA. Additional drawings from USA have only recently been obtained.
End			

Appendix E. Orbiter Loads 155K Xo = 159 On SCA Connections.pdf



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10132 TO 10135 10138 TO 10142 10144 TABLE ST TUB80806
10149 TO 10155 TABLE ST TUB80806
10160 TO 10164 TABLE ST TUB80806
10192 TO 10213 TABLE ST TUB80806
10214 TO 10218 TABLE ST TUB80806
10251 TABLE ST TUB80806
10222 TABLE ST TUB50506
10220 10225 10227 TABLE ST TUB80806
10229 TABLE ST TUB50506
10241 TO 10244 TABLE ST TUB50506
10245 TO 10247 TABLE ST TUB50506
10248 10249 TABLE ST TUB50506
10254 10257 TABLE ST TUB50506
10252 10253 10255 10256 TABLE ST TUB80806
10180 TO 10184 10223 10232 TABLE ST TUB1201205
10185 TO 10189 10224 10231 TABLE ST TUB1201205
10036 TO 10041 10083 10084 TABLE ST TUB80806
10049 10050 10114 10145 TABLE ST TUB50506
10117 10118 10148 TABLE ST TUB50506
10092 10112 10115 10116 10123 10143 10146 10147 TABLE ST TUB50506
10097 10128 TABLE ST TUB50506
10159 10165 TO 10167 10235 TO 10238 TABLE ST TUB50506
10190 10191 TABLE ST TUB50506
10168 10169 10233 10234 10239 10240 TABLE ST TUB80806
10258 10259 TABLE ST TUB50506
10260 TABLE ST TUB80806
2003 10044 TO 10046 10094 TO 10096 10098 TO 10100 10105 10106 10125 TO 10127 -
10129 TO 10131 10136 10137 TABLE ST TUB1201205
DEFINE MATERIAL START
ISOTROPIC MATERIAL1
E 10000
POISSON 0.33
DENSITY 9.549E-005
ISOTROPIC STEEL
E 29000
POISSON 0.3
DENSITY 0.000283
ALPHA 6E-006
DAMP 0.03
TYPE STEEL
STRENGTH FY 36 FU 58 RY 1.5 RT 1.2
END DEFINE MATERIAL
CONSTANTS
MATERIAL MATERIAL1 ALL
```

K:\STRUCT\5636.44 Orbiter Installation Concept\Calcs for Kevin Roscoe\Orbiter Loads 155K Xo = 159 43 deg Flexible - No Xo Co

```
153. SUPPORTS
154. 2001 FIXED BUT FX MX MY MZ
155. 2002 FIXED BUT FZ MX MY MZ
156. 2003 FIXED BUT FX MX MY MZ
157. 10001 FIXED BUT MX MY MZ KFX 0.001 KFY 0.001 KFZ 0.001
158. LOAD 1 LOADTYPE NONE
159. MEMBER LOAD
160. 10001 CON X -155 0
161. PERFORM ANALYSIS


       P R O B L E M   S T A T I S T I C S
       -----------------------------------

  NUMBER OF JOINTS/MEMBER+ELEMENTS/SUPPORTS =    74/   209/     4

        SOLVER USED IS THE OUT-OF-CORE BASIC SOLVER

  ORIGINAL/FINAL BAND-WIDTH=    67/    14/     90 DOF
  TOTAL PRIMARY LOAD CASES =    1, TOTAL DEGREES OF FREEDOM =    438
  SIZE OF STIFFNESS MATRIX =       40 DOUBLE  KILO-WORDS
  REQRD/AVAIL. DISK SPACE  =     12.7/ 305323.7 MB


162. PRINT SUPPORT REACTION
```

```
SUPPORT REACTIONS -UNIT KIP  INCH    STRUCTURE TYPE = SPACE
-----------------

JOINT  LOAD   FORCE-X   FORCE-Y   FORCE-Z     MOM-X     MOM-Y     MOM Z

 2001    1      0.00     32.26    -30.09      0.00      0.00      0.00
 2002    1      0.00     91.33      0.00      0.00      0.00      0.00
 2003    1      0.00    -10.23    -75.62      0.00      0.00      0.00
10001    1      0.00      0.00      0.00      0.00      0.00      0.00

************** END OF LATEST ANALYSIS RESULT **************

163. FINISH

          *********** END OF THE STAAD.Pro RUN ***********

            **** DATE= JUL 17,2012   TIME= 14:28:31 ****
```

```
                                              Thursday, August 09, 2012, 03:58 PM
STAAD SPACE                                            -- PAGE NO.    6

     ************************************************************
     *        For questions on STAAD.Pro, please contact        *
     *        Bentley Systems or Partner offices                *
     *                                                          *
     *            Telephone              Web / Email            *
     *  USA       +1  (714) 974-2500                            *
     *  UK        +44 (0) 808 101 9246                          *
     *  SINGAPORE +65 6225-6158                                 *
     *  FRANCE    +33 (0) 1 55238400                            *
     *  GERMANY   +49 0931 40468                                *
     *  INDIA     +91 (033) 4006-2021                           *
     *  JAPAN     +81 (03)5952-6500    http://www.ctc-g.co.jp   *
     *  CHINA     +86 21 6288 4040                              *
     *  THAILAND  +66 (0)2645-1018/19 partha.p@reisoftwareth.com*
     *                                                          *
     *  Worldwide  http://selectservices.bentley.com/en-US/     *
     *                                                          *
     ************************************************************
```

Appendix F. Email from K. Roscoe to S. Minute on 9/3/2012: 5636.44 RE: Atlantis Support Structure - Additional Design Calculations

From: ROSCOE, KEVIN (LARC-D206)
Sent: Monday, September 03, 2012 4:19 PM
To: Minute, Stephen A. (KSC-C105)
Cc: Raju, Ivatury S. (LARC-C104); Elliott, Kenny B. (LARC-D210); Larsen, Curtis E. (JSC-C104); 'David Hamilton' (dave@lifethoughts.com)
Subject: RE: FW: 5636.44 RE: Atlantis Support Structure - Additional Design Calculations
Importance: High

Steve,
I think they closed this item, assuming compatibility of the lubricant and Flourogold, and believing 0.10 is the maximum coefficient of friction per the manufacture (we have margin if it is slightly higher). Both assumptions I would rate as a low risk.
Prior to this response they assumed it would work and didn't think about it (my opinion). Now they have engineered the joint (reduced bearing area to increase pressure load to the minimum recommended, removed post-installation bolt torque, added slide bearings to the shear lugs, contacted the manufacturer to estimate break-away friction, and calculated predicted max break-away shear loads due to thermal expansion).
They could have (or may have) tried to determine the structural compliance between AO-2 and -3 for the small thermal expansion difference. However, the 16,300 lb limit may have been too low for the massive Support Frame. Either way the bearing solution works.
Once they put a slide bearing under AO-1, they solved the biggest threat to the thermal expansion issue. The rest of this work is more or less good engineering (details).
Disclaimer: I haven't looked at the details in the analysis or the drawings, but BRPH gave the right response. I plan on looking at the details after I go thru the hot items in my inbox.
Sincerely,
Kevin Roscoe

Structural & Thermal Systems Branch
Engineering Directorate
NASA Langley Research Center, MS 431
1 N. Dryden Street / Hampton, VA 23681
Bldg. 1209, Rm. 150B, Off: 757-864-4173

From: Minute, Stephen A. (KSC-C105)
Sent: Wednesday, August 29, 2012 12:45 PM
To: Raju, Ivatury S. (LARC-C104); ROSCOE, KEVIN (LARC-D206); Elliott, Kenny B. (LARC-D210); Larsen, Curtis E. (JSC-C104); 'David Hamilton' (dave@lifethoughts.com)

Subject: FW: FW: 5636.44 RE: Atlantis Support Structure - Additional Design Calculations
Importance: High

I haven't read any of this yet – wanted to get it directly into your hands.

From: Dillon III, John Thurman Rascoe (KSC-SMASS-E)[Millennium Engineering and Integration Company]
Sent: Wednesday, August 29, 2012 12:24 PM
To: Minute, Stephen A. (KSC-C105)
Cc: Braden, Barry M. (KSC-SA000)
Subject: FW: FW: 5636.44 RE: Atlantis Support Structure - Additional Design Calculations
Importance: High

Steve,
Here is the response from BRPH.
John

From: Ken E. Paquette [mailto:kpaquette@brph.com]
Sent: Wednesday, August 29, 2012 12:01 PM
To: Dillon III, John Thurman Rascoe (KSC-SMASS-E)[Millennium Engineering and Integration Company]
Cc: Wohlert, William D. (KSC)[DELAWARE NORTH COMPANIES PARKS & RES]; Andrew H. Miller
Subject: RE: FW: 5636.44 RE: Atlantis Support Structure - Additional Design Calculations

John
See my responses in Red below and forward with my attachments to Mr. Roscoe.
Thanks Ken

KEN E. PAQUETTE | *Senior Structural Engineer*

BRPH | 5700 North Harbor City Boulevard, Suite 400 | Melbourne, Florida 32940
O: 321-751-3035 | **F:** 321-259-4703
KEP@brph.com | www.brph.com

ARCHITECTS | ENGINEERS | CONSTRUCTORS

From: ROSCOE, KEVIN (LARC-D206)
Sent: Monday, August 20, 2012 1:00 PM
To: Minute, Stephen A. (KSC-C105); Raju, Ivatury S. (LARC-C104); Elliott, Kenny B. (LARC-D210); 'David Hamilton' (dave@lifethoughts.com); Larsen, Curtis E. (JSC-C104)
Cc: Dillon III, John Thurman Rascoe (KSC-SMASS-E)[Millennium Engineering and Integration Company]
Subject: RE: 5636.44 RE: Atlantis Support Structure - Additional Design Calculations

Steve,

Great. Based on my understanding that takes care of the connection from AO-1 to AO-2 (and AO-3) in the X direction for the post installation condition. An estimate of shear force given the assumptions and calculations can be added to the predicted load summary for the AO joints, provided this is the worst case.

Is the connection situation identical for the AO-2 to AO-3 in the lateral direction?
There isn't a separate frame in between AO-2 and AO-3 so we considered the full breaking friction force in the Yo directions at the slide bearing at AO-2 for thermal stresses.
The Change in length of the Orbiter from AO2 to A03 due to a 30 degree temperature swing is approximately:
13x10^-6 (30 degrees)(96.25+96.25) = 0.075 inches
The change in length of the steel Orbiter support beam for the same length is:
6x10^-6(30)(96.25+96.25) = 0.03465 inches
The change in length difference is 0.0404 inches – a little more than 1/32 of an inch.
According to the slide bearing manufacturers, the static coefficient of friction to break away is anywhere from nearly the same as the dynamic friction (0.07) to a maximum of 0.1. So at AO2 the maximum breaking frictional resistance Yo = 93.1(0.1) = 9.31 kips which we used in our calculations. To assure the 0.07 coefficient of friction in the short term, lubricants are used according to the bearing manufacturers, we are specifying them for the jacking and rotation. The coefficient of friction is also improved with bearing pressures above a minimum of 75 psi according to the slide bearing manufacturers - so for the slide bearings under the spacers, the bottom plate bearing surface was reduced where required to assure that the bearing pressures are above 75 psi for applicable Orbiter orientations. (The Orbiter when level was a controlling factor at the aft slide bearings.)
We have also added high capacity slide bearings at the edges of the shear lugs at the spacers to reduce friction at AO3 and AO1 in the Xo direction from the Yo loads and at AO2 in the Zo direction, and we have considered the breakaway friction at the edge slide bearings in our calculations as well.
Also, does environmental control from the time the orbiter is secured to the support frame till the final display configuration exist?
Environmental control is not expected, however this procedure is intended to be done in November, when milder temperatures occur.
After the building is in use and conditioned, emergency systems to keep the artifacts at a constant temperature are part of the facility design.
If not, then there is a risk during this time (jacking and rotation) of an environmental load condition. The event could occur in the level or rotated condition.
We have analyzed and provided a table considering the Orbiter loads combined with friction developed on the slide bearings prior to movement and differential thermal expansion for cases that include in the level or rotated condition during jacking and rotation.

Preload:
We haven't had a lot of discussion concerning bolt torque after installation at the AO joints. The Fluorogold® slide bearings provide compliance once they start sliding. Until then, the bearings provide a rigid structural connection. The bearing's compliance begins once the static friction times the normal force acting on the bearing is exceeded. Bolt preload increases the normal load, thus reduces the compliance (higher break-away force).
The structural compliance as described in the email below should cover the reduction in bearing compliance due bolt preloading at the AO-1 joint. I don't think that is the case at the AO-2 and AO-3 joints. Is there a need to torque the bolts at both AO-2 and AO-3 joints?
We identified as much as 10.2 kips of uplift at AO3, which isn't very much for all 8 bolts (1.5 inch diameter A325) in the spacer to resist. We have removed the torque requirements after jacking and rotation from the contact documents.

Note: A rigid bearing joint would not meet the contingency per "Atlantis Review 6-1-12 - Summary.docx" (excerpt):

> "A review of Reference (1) shows the attachment points on the Orbiter and the attachment hardware to be sufficient for the 43° roll display configuration. This sufficiency is contingent on the support structure / attachment hardware providing the proper compliance."

It should be demostrated (calculated) that proper compliance exists.

We have included additional tabulated comparisons with the Interface loads from ICD-2-17001.

Sincerely,
Kevin Roscoe

Structural & Thermal Systems Branch
Engineering Directorate
NASA Langley Research Center, MS 431
1 N. Dryden Street / Hampton, VA 23681
Bldg. 1209, Rm. 150B, Off: 757-864-4173

From: Minute, Stephen A. (KSC-C105)
Sent: Monday, August 20, 2012 11:51 AM
To: Raju, Ivatury S. (LARC-C104); ROSCOE, KEVIN (LARC-D206); Elliott, Kenny B. (LARC-D210); 'David Hamilton' (dave@lifethoughts.com); Larsen, Curtis E. (JSC-C104)
Cc: Dillon III, John Thurman Rascoe (KSC-SMASS-E)[Millennium Engineering and Integration Company]
Subject: FW: 5636.44 RE: Atlantis Support Structure - Additional Design Calculations
Importance: High

Folks,

Please see included email and attachment.
Thanks John.

SM

From: Dillon III, John Thurman Rascoe (KSC-SMASS-E)[Millennium Engineering and Integration Company]
Sent: Monday, August 20, 2012 11:02 AM
To: Minute, Stephen A. (KSC-C105)
Subject: FW: 5636.44 RE: Atlantis Support Structure - Additional Design Calculations
Importance: High

Please forward.
Thanks!
John

From: Ken E. Paquette [mailto:kpaquette@brph.com]
Sent: Monday, August 20, 2012 10:51 AM
To: Dillon III, John Thurman Rascoe (KSC-SMASS-E)[Millennium Engineering and Integration Company]
Cc: Wohlert, William D. (KSC)[DELAWARE NORTH COMPANIES PARKS & RES]; Andrew H. Miller
Subject: RE: 5636.44 RE: Atlantis Support Structure - Additional Design Calculations

John – Please Forward to Mr. Roscoe

1. **We have been looking at the concerns about differential thermal expansion between the Orbiter and the Orbiter Support frame and have the following response.**

   a. **After rotation, the support frame between the Aft and Forward AO supports is intended to be removed, so differential thermal expansion of the Orbiter versus the horizontal support frame between the forward and aft Orbiter supports will not be applicable. The forward support frame is capable of deflecting because it is not braced in the Xo direction.**
   b. **We reviewed the lateral stiffness of the Orbiter forward support frame on its own, and determined that it would deflect about 1 inch for a 1000 lb force conservatively applied at the column below the Teepee support stand. We also determined that the change of length of the Orbiter due to a temperature change from 100 degrees to 70 degrees would be about 0.36 inches based on the coefficient of thermal expansion for Aluminum.**

      13.0 x 10^-6 (100-70)(1317-388.045) = 0.36 inches

So if the slide bearing is not effective for thermal movement, the forward Orbiter support frame will deflect in the Xo direction significantly under low lateral forces.

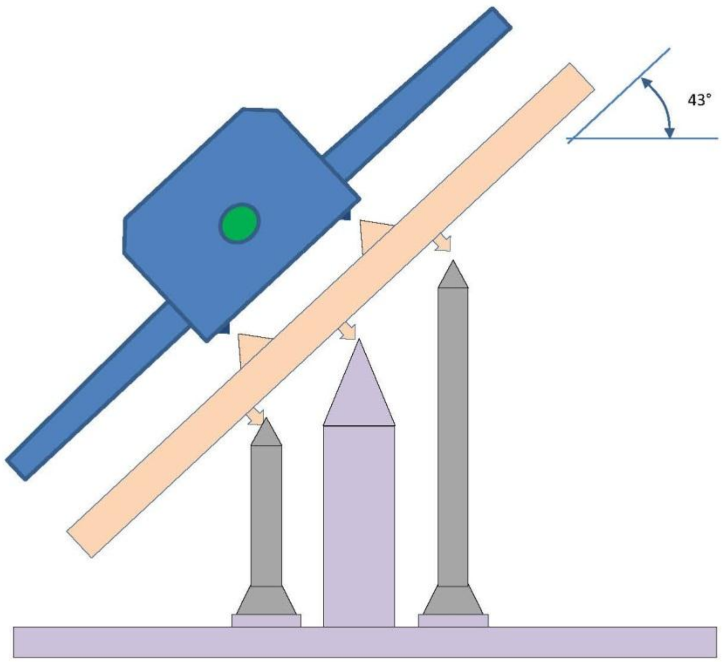
Thanks Ken

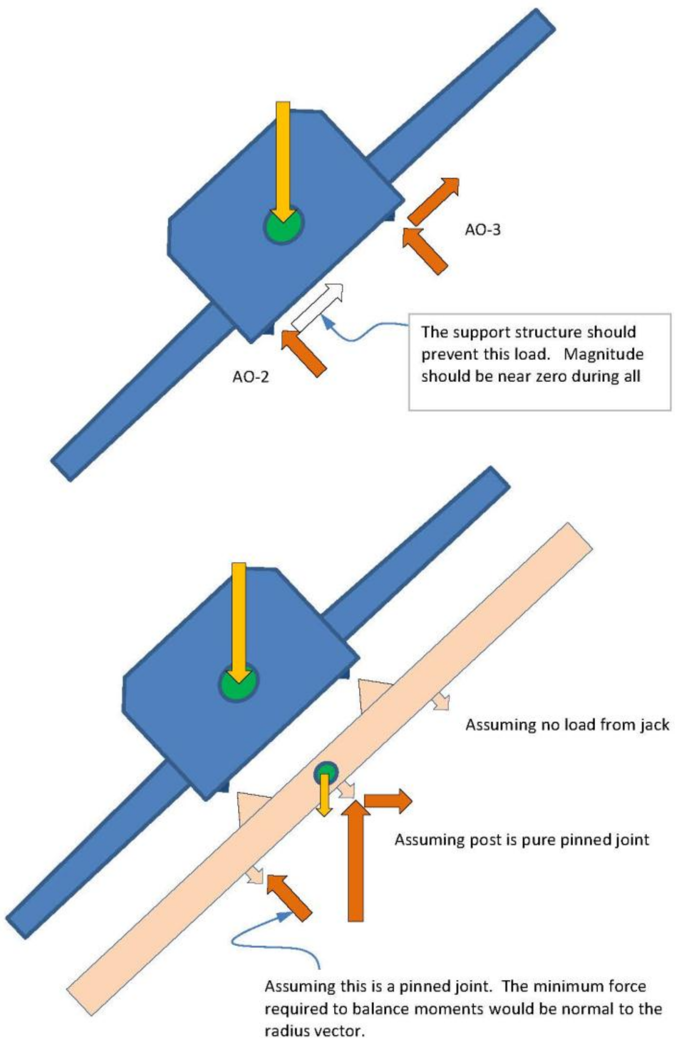
KEN E. PAQUETTE | *Senior Structural Engineer*

BRPH | 5700 North Harbor City Boulevard, Suite 400 | Melbourne, Florida 32940
O: 321-751-3035 | **F:** 321-259-4703
| www.brph.com

Appendix G. Atlantis-Pivot.xlsx (K. Roscoe's Free Body Diagrams)

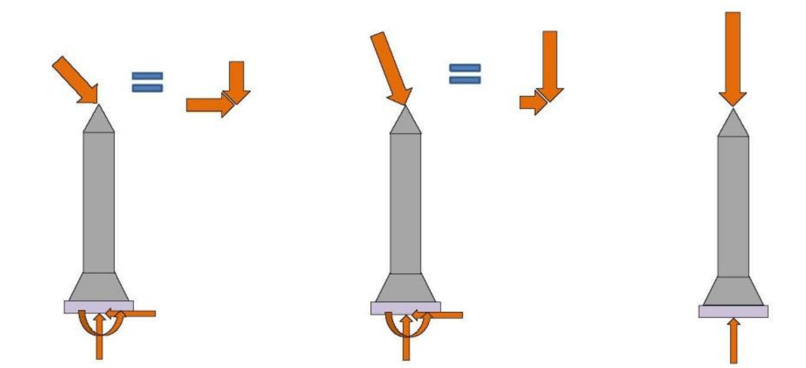
Enclosure (1) to Atlantis Review 7-5-12 - Summary.docx





AO-3
AO-2
The support structure should prevent this load. Magnitude should be near zero during all
Assuming no load from jack
Assuming post is pure pinned joint
Assuming this is a pinned joint. The minimum force required to balance moments would be normal to the radius vector.

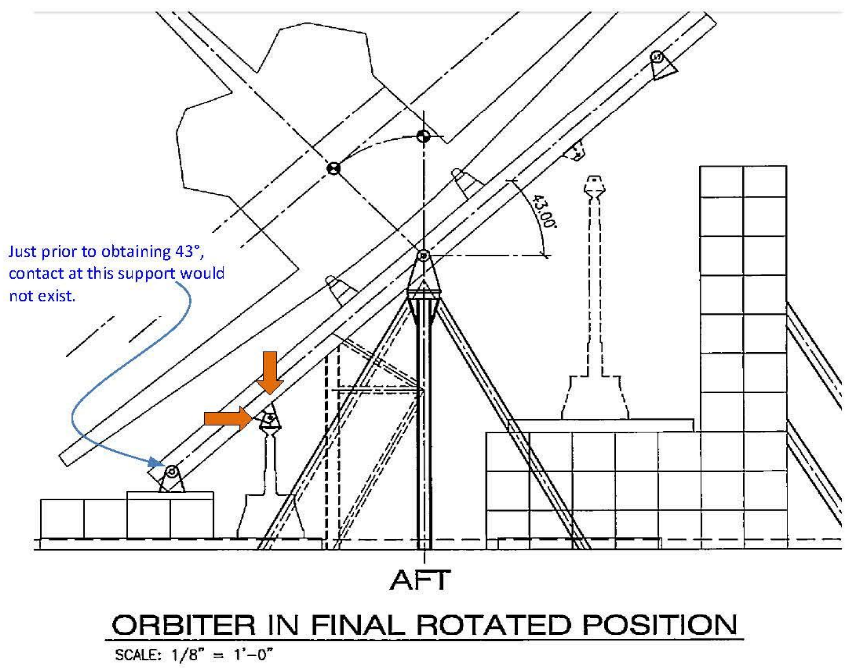
Load at top of left side jack depending on interaction of jack to frame:



If the jack is on a slide, then the horizontal component would be zero?

If that is the case, then the horizontal component load would push the jack inboard (couldn't remove dunnage) and wouldn't stop rotating until impacting dunnage.

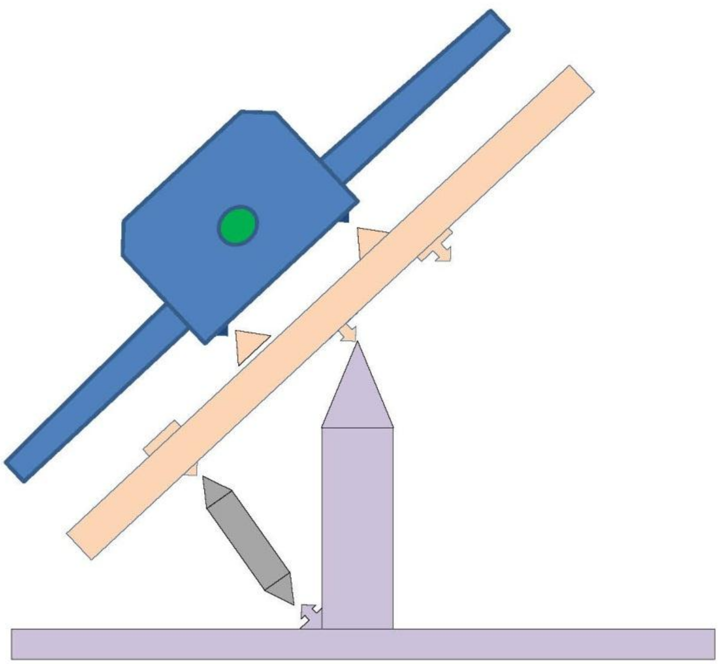
If there is a horizontal reaction, then the horizontal load would tend to bend the jack and tip it over.


Just prior to obtaining 43°, contact at this support would not exist.
43.00°
AFT
ORBITER IN FINAL ROTATED POSITION
SCALE: 1/8" = 1'-0"

Consider a pinned / pinned jack connected as shown. Once the shuttle is over top dead center, simply throttle the jack until 43°.

Use current planned jack on right side to push it over the top.

The peak load on the jack is when it is the shortest.



Appendix H. AtlantisItemsFor072712meeting.docx (Discussion items for telecon held 7/27/2012)

Discussion Items for Atlantis Display Meeting on July 27, 2012

1. Did not find calculations showing the design (including Flourogold) limits the loads at the AO-1 and AO-2 location to the allowable values.
    a. Found Flourogold coefficient of friction data in vendor brochure. Could not find data for zero velocity (stick/slip).
    b. Found Flourogold recommended pressure data, but no calculations showing it was not exceeded when torque is applied to bolts the 8 1½-inch bolts. Did not find the torque call-out.

2. Found space between Aft Support Spacer and Shear Lugs. Did not find shims to close the gap (sheet 18 in Atlantis Support.pdf).

3. Orbiter Rotation Frame Analysis:
    a. Sliding jack has 4 wheels contacting the XZ plane. The wheels will react translation loads in the Y direction (vertical) and moments about the X and Z axes. The Analysis released the moments at this joint, thus could not assess bending in the jack (line 91 of STAAD input deck and joint 3510 output on page 9 of analysis package. Could not find another method where the moments were assessed.
    b. Could not find documentation for jack vertical stiffness
    c. Could not find documentation for Propel cylinder stiffness.
        i. Propel cylinder line of action is in the YZ plane at a shallow horizontal angle. Could not find where the analysis accounted for this vector.
    d. Did not find lateral load strength or limitation for gantry system, nor lateral stiffness
    e. Beam model joins member of different size. Without joint releases, the joint is rigid where all degrees of freedom are transmitted. Did not find in Atlantis Support.pdf joint details that were consistent with the analysis method.
        i. For example, the long Fore/aft beams (X direction) were connected together in the Z direction with smaller beams. Could not find the joint detail.

4. Could not find the "Rigging plans from the Contractor will provide a detailed full procedure and equipment used" document.
    a. Cannot interpret the lifting note 1 on page 7 of Atlantis Support.pdf, zone F7 without "Rigging Plan". Alternate the lift fore/aft or port/starboard?

b. Could not find a plan to control the load
    i. Could not find position sensors or load indicators
c. Could not find lateral load limits for the gantry system
d. Cannot fully assess rotation operations without more detail

Appendix I. AtlantisReview072712-Summary.docx (Summary of telecon on 7/27/2012)

Subject: Display of Atlantis in the KSC Visitor Complex
Subject: 7/27/2012 Meeting minutes

Doug Wohlert opened the meeting by describing three tasks that DNC is performing:

1) Atlantis load assessment – 90% design review package released in May and transmitted to NASA on July 12.
2) Transportation of Orbiter Planning – the 90% transportation plan is released and they plan to move the orbiter in November.
3) Atlantis Structural Support – the concept was released on Feb 17, 30% design package was released in May, 60% released on June 21. They plan to release the 90% package on August 22 and hold a 2-week review period. The final package is planned to be released on Sept. 19.

This was followed by a review of the attachment to Reference (1) with the bulk of the conversation closing out the drawing comments. A portion of the content of the Reference (1) material was deferred and addressed in the discussion based on the comment in the attachment to Reference (2). The conversation about Reference (2) resulted in the following action items for DNC:

1) Redesign AO-1 joint to allow for axial displacement. Although the fitting to the orbiter allows rotation, it transmits forces. Thermal expansion could overload the joint with the current design.
    1. A calculation package showing the predicted loads at the orbiter supports (AO-1, AO-2 and AO-3) was requested. Although the design has elements to reduce the joint shear loads, the predicted values were not presented. The predicted loads would be compared to the orbiter limits to show margin in the design during operations.
2) Develop a test fixture, test plan, conduct qualification tests to demonstrate control of the load and provide the obiter operation plan. The test fixture would simulate the orbiter weight and center of gravity. The test plan would envelop the orbiter plan operation environment. The jacks would also be operated asynchronously to demonstrate control of the load.
    1. Due to lack of technical data such as jack lateral stiffness, DNC is not able to analytically show the design is sufficient.

The beam finite element model presented was too simplistic when it came to joint details and jack simulation. DNC stated they had separate detail analysis results for some critical joints and that they could provide a package for review.

References:

4. Email from Doug Wohlert [DWohlert@dncinc.com] on Mon 7/23/2012 at 11:09 AM with attachment "(2012-07-20) 60% Review Comments and Support Documentation.pdf".
5. Email from Raju, Ivatury S. (LARC-C104) on Fri 7/27/2012 with attachment "AtlantisItemsFor072712meeting.docx"

Appendix J. Propel Jack Cylinder.pdf (Jacks to be used for lift and rotation)

Propel Jack Cylinder.pdf is available at:
http://lift-systems.com/

PROPEL OPTIONS

For Hydraulic Gantry Systems

LIFT SYSTEMS, INC.

OFFICE:
1505 - 7th Street
East Moline, IL 61244

MAILING ADDRESS:
P.O. Box 906
Moline, IL 61266

TEL: +1-309-764-9842
FAX: +1-309-764-9848
EMAIL: liftit@lift-systems.com
WEB: www.lift-systems.com

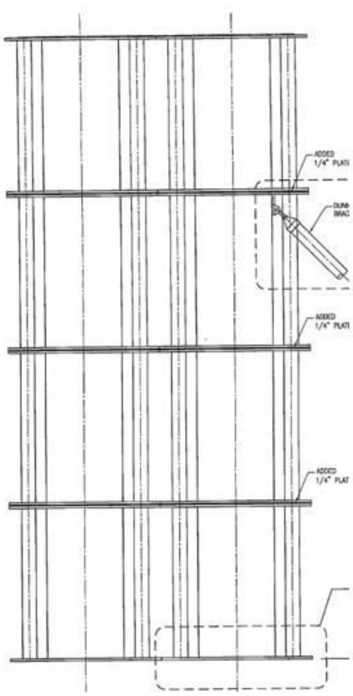
Appendix K. Atlantis DunnageRevA.pptx (Assessment of dunnage to be used in lift and rotation procedure)

Atlantis Dunnage

10/11/12

Dunnage: Actual

Dunnage: Drawing vs. Actual



1. Without a load spreader, all the load will be transmitted to the columns under the pivot.
   a) Flat plate will flex and not transmit loads laterally to adjacent columns
2. Drawing show identical units. Actual shows changes in pipe diameter and pipe center locations.
3. Not identified on drawing

Dunnage: Drawing vs. Actual

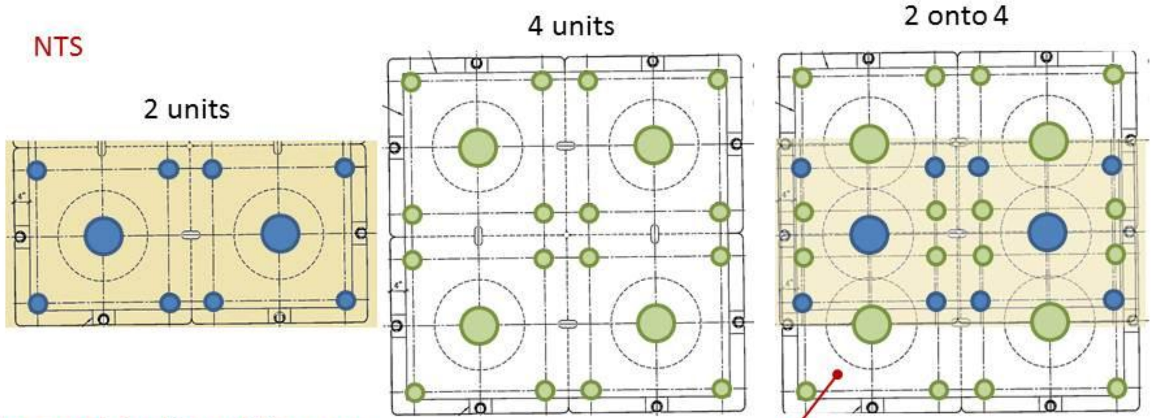
1. Load Path via flat plates?

Dunnage: Summary

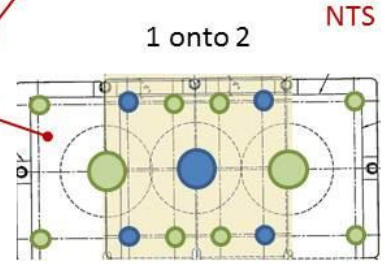
Questions:

1. Are they testing the dunnage?
    1. Load removed from jacks and without center pivot posts. If they missed the opportunity due to installation of the posts, they can test when they reverse the process.
2. Will the dunnage be in the identical configuration (each piece has an identification number, orientation and location, and includes bracing)?

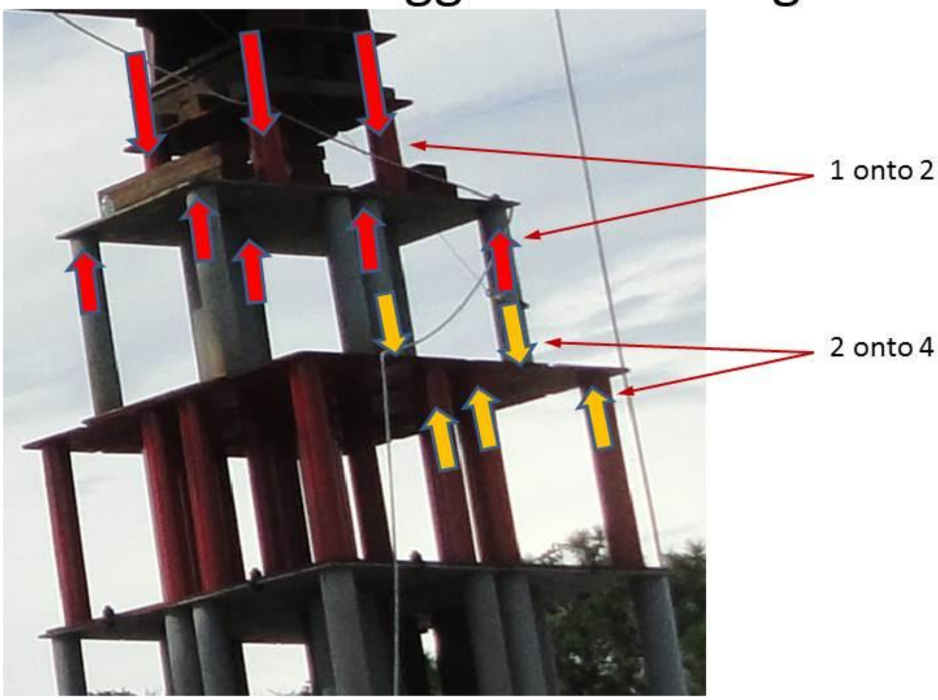
Dunnage Stacking



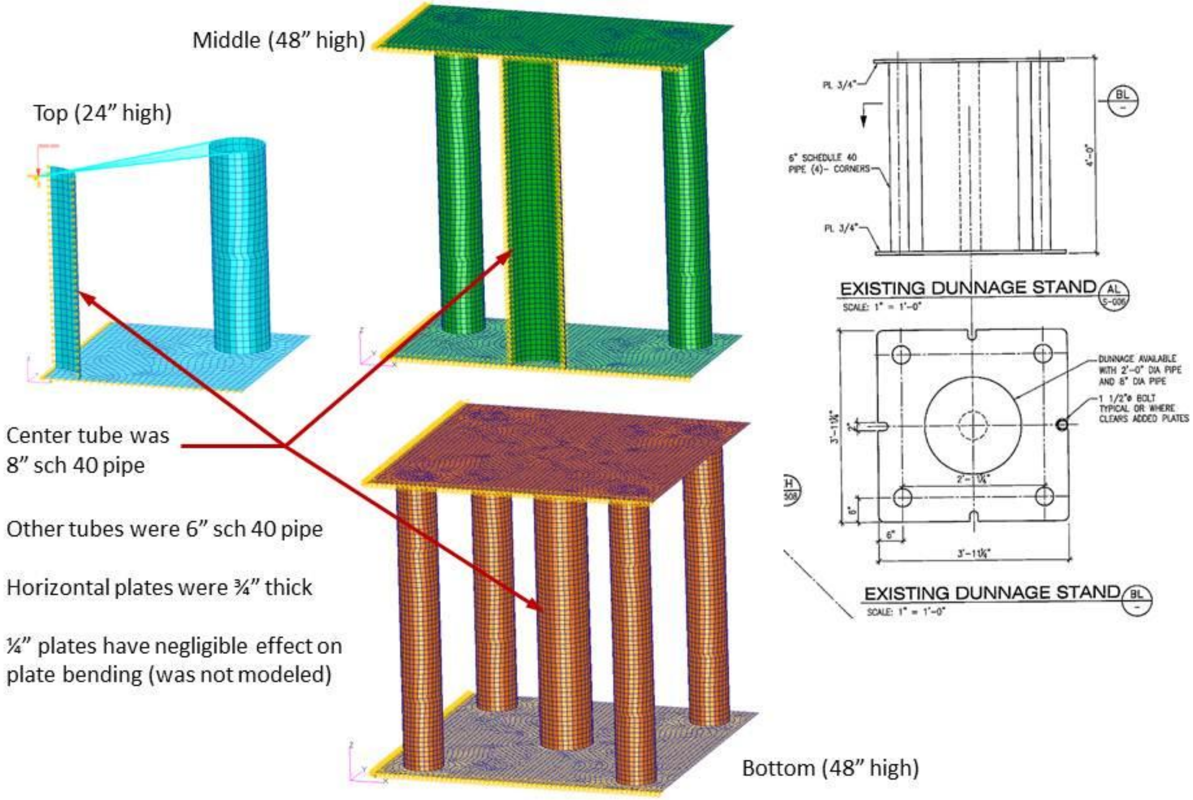
Staggered stacking of Dunnage results in all vertical load being transmitted via flat plates.
Dunnage plates are ¾", and load per aft side is about 55 kips + Support Frame weight & wind (~57 kips for 112 kips total per 90% submittal).



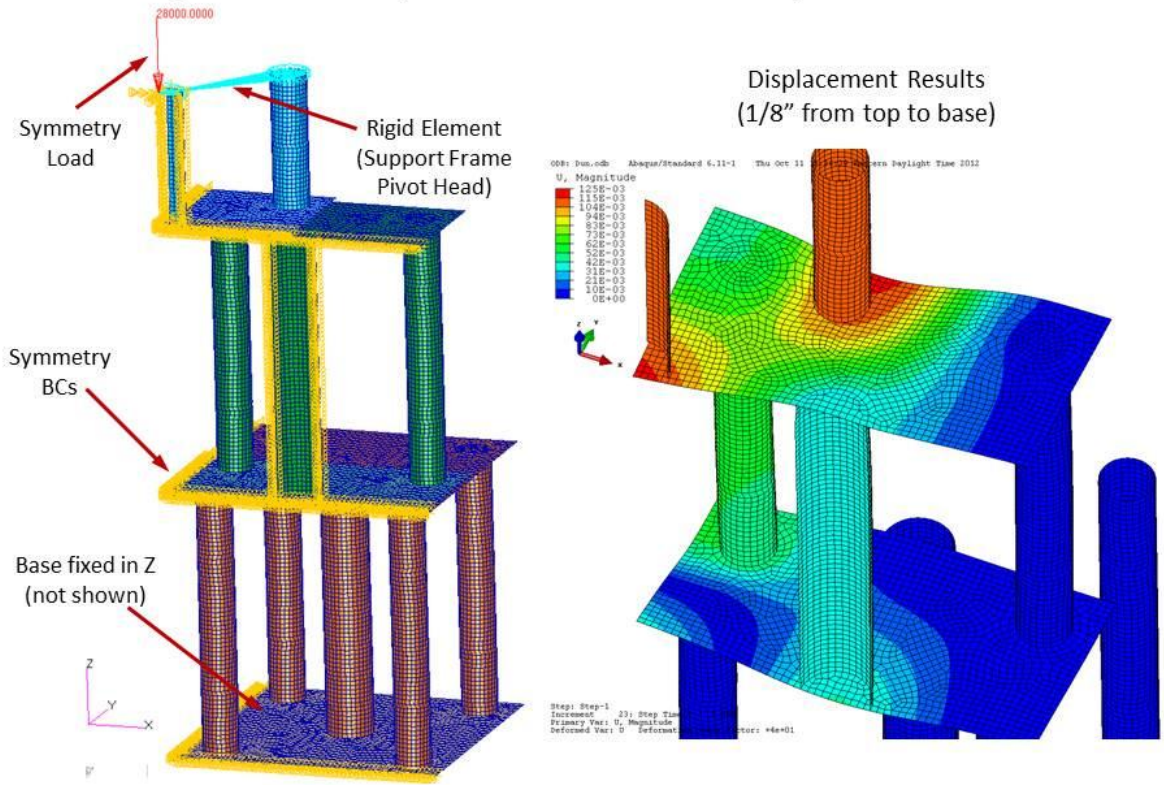
Dunnage FEA (Aft Starboard) with Staggered Stacking



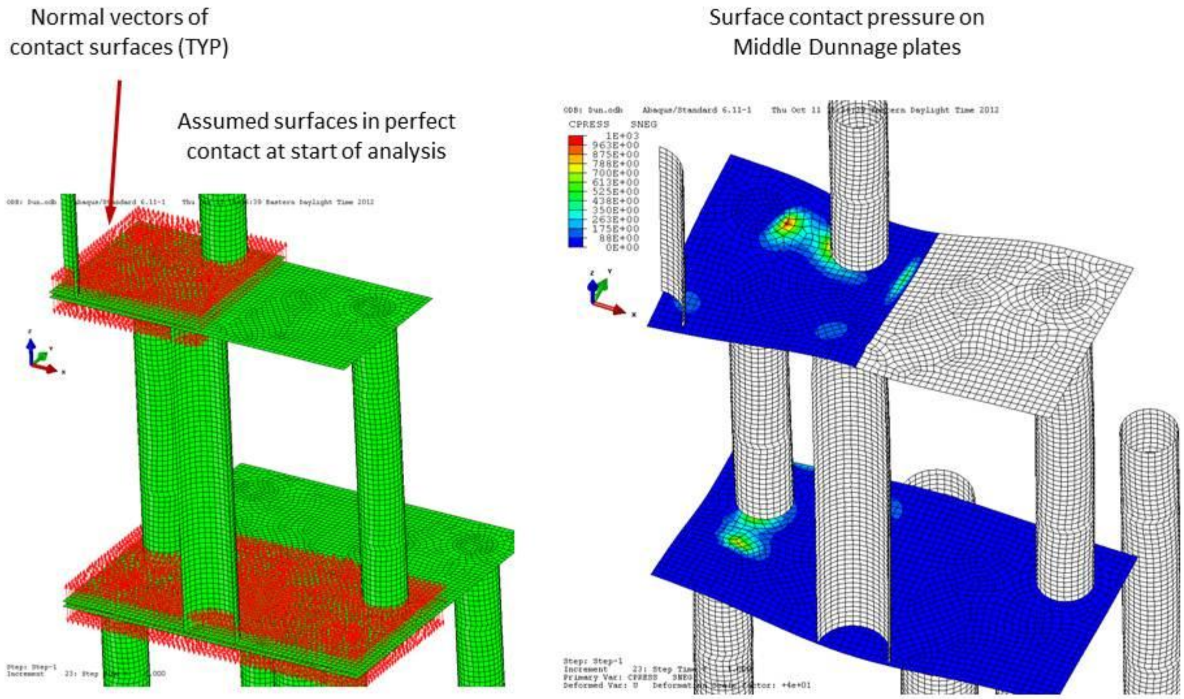
¼ Symmetry Dunnage FEMs



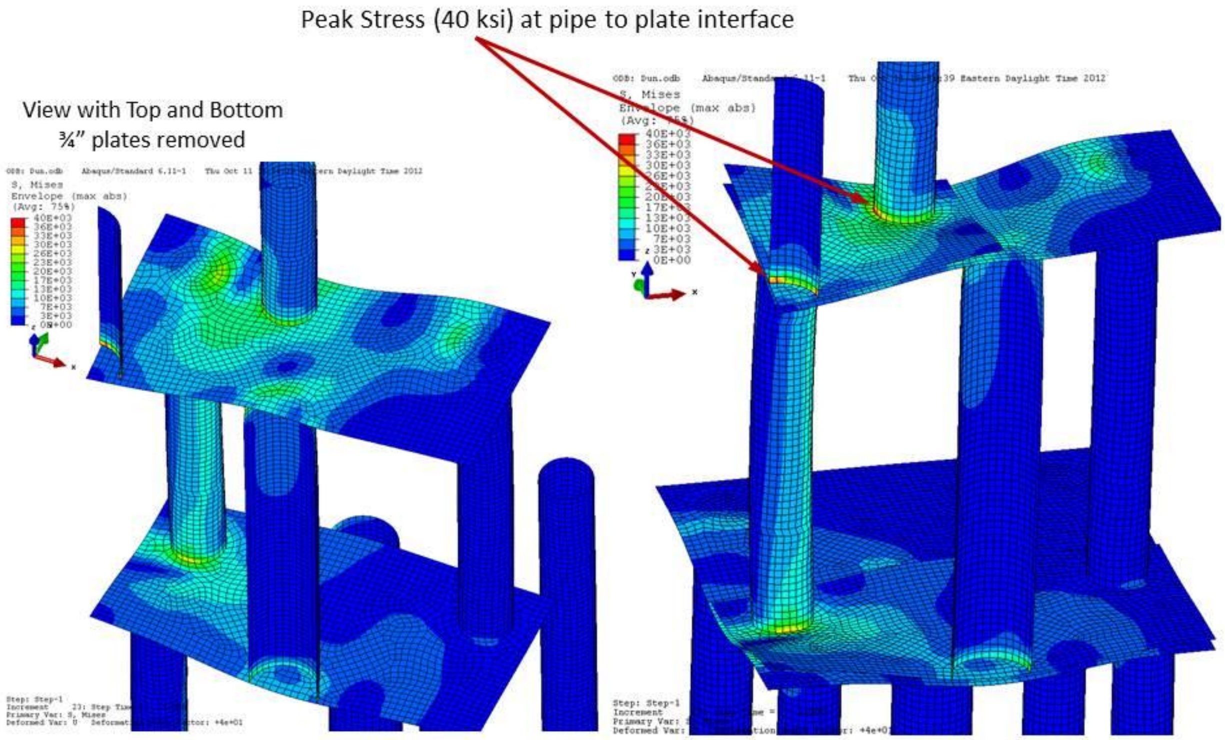
¼ Symmetry FEM and Displacements



Contact Surfaces and Pressure

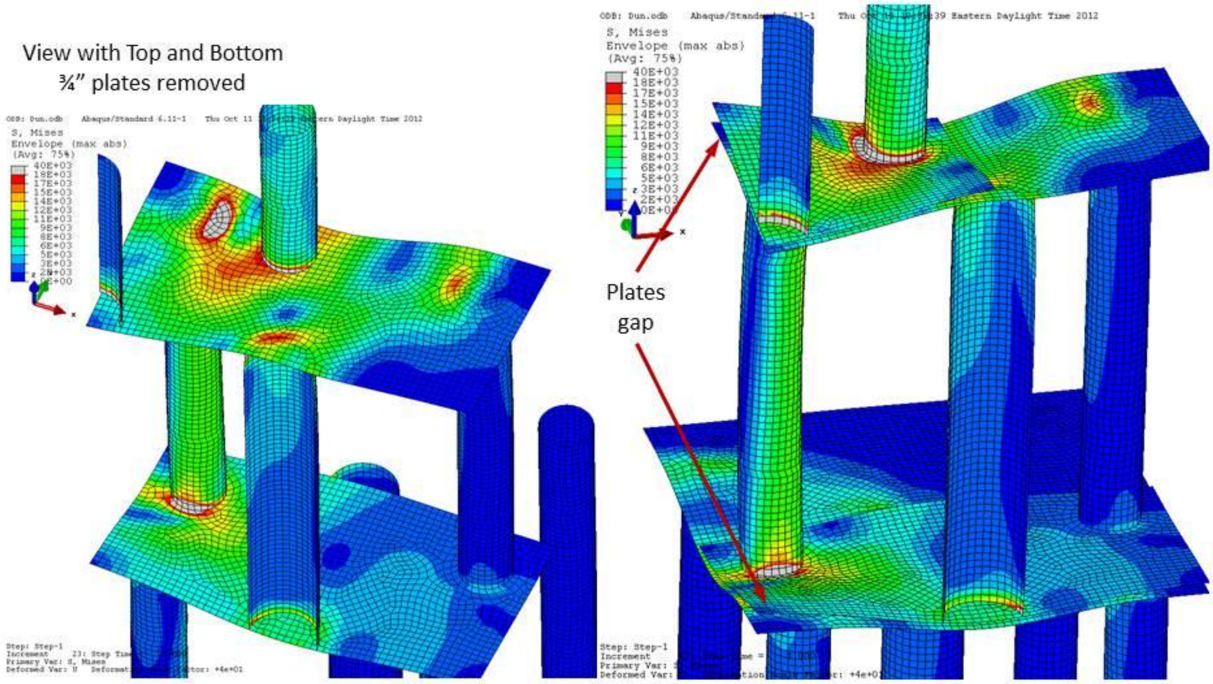


Stress Results



Stress Results

Stress plot using A36 material, FS of 2 on Yield or an 18 ksi stress limit.
Most of plate material has capacity (not gray)



Stress Results Summary

- Desirable to have FS of 3 on yield for buckling
- Plate is probably stronger than A36
- Peak stresses at base of pipes
- Center of short length pipes have low to moderate stress
  - Not likely to buckle due to localized end effects
- Geometry will vary, not likely to significantly affect results
- Not the way I would design it, but it will likely work

Appendix L. PLBD Support-C.pdf

OV-104 PLBD Support

Display at KSC-VC

May 2012

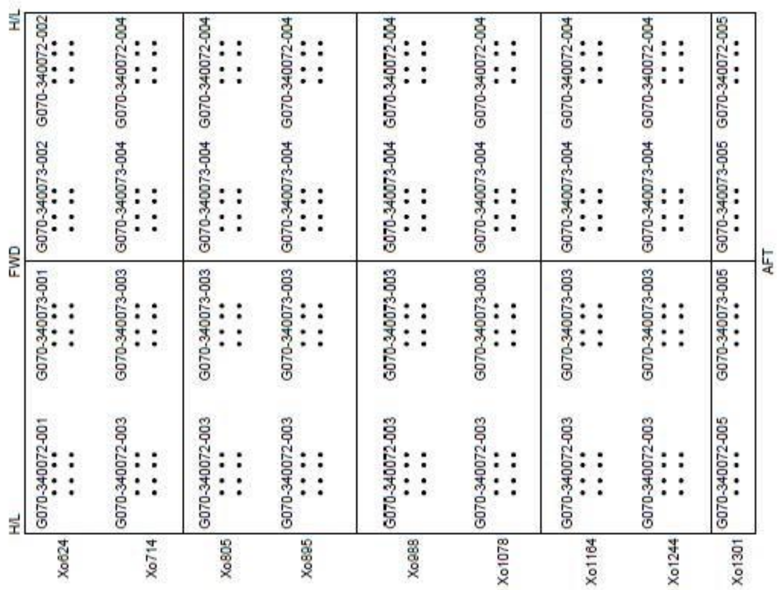
1

OV-104 PLBD Support

- Objective – Support PLBD mass and maintain shape integrity
- Composite Payload Bay Doors are not self-supporting in gravity environment
- Construction is multi-ply GR/Ep honeycomb panel over GR/Ep framework
- Door assembly divided into four primary segments and one aft closeout segment
    - door segments jointed with shear transfer pins and a sliding seal system
- Doors are opened and supported using H70-0529 GSE Strongbacks
    - Strongbacks support entire door weight (negligible amount at hinges)
    - counterbalanced to simulate zero gravity using weight and cable system
    - last known values from RTOMI V9023.303/304 (OV-104, OPF-2, July 2011)
        - LH Fwd: 1201 lb, LH Aft: 1715 lb, RH Fwd: 1285 lb, RH Aft: 1768 lb
- Use these approximate values for preliminary design
    - Boeing mass prop. engineer to provide accurate weight and CG

2

OV-104 PLBD Support



GSE Strongback Attach – 18 locations per side

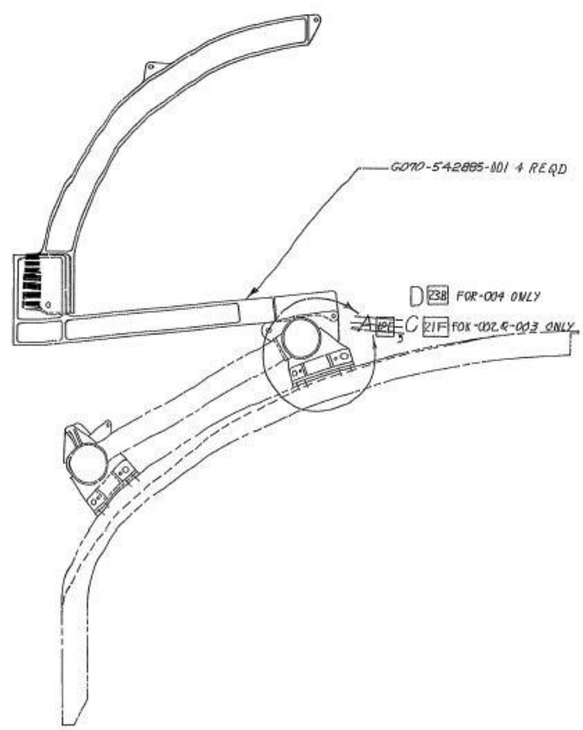
3

OV-104 PLBD Support

GSE Strongback Attach

4

OV-104 PLBD Support



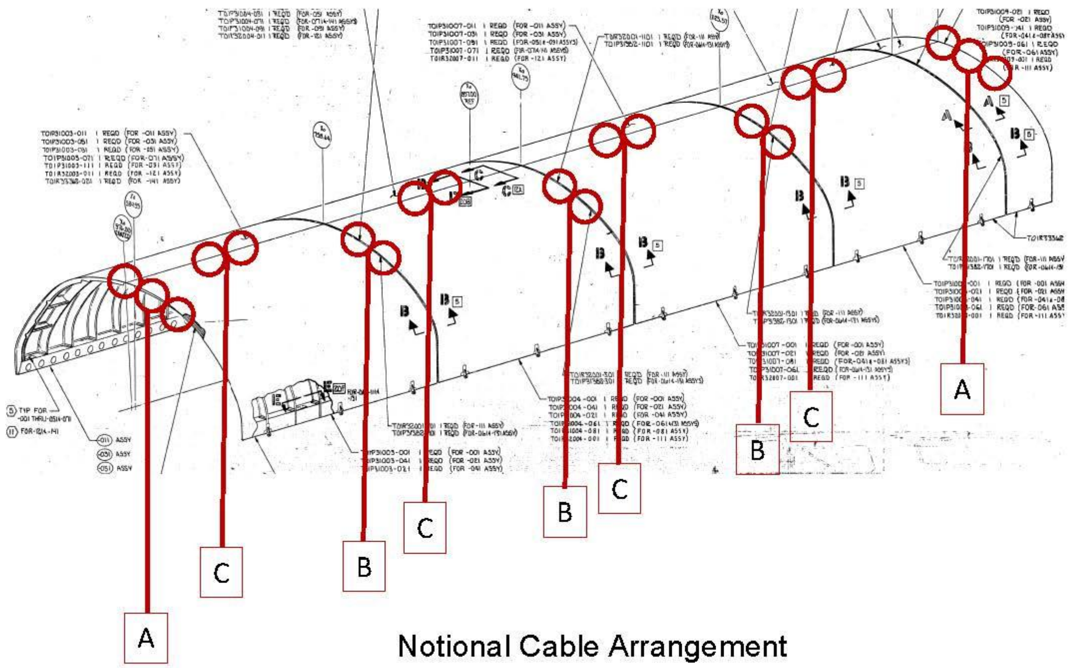
5

OV-104 PLBD Support

- Consider PLBD support to be a critical lift operation, Ref NASA-STD 9719.19
    - Requires minimum Design Load Safety Factor of 5 for wire rope slings
    - Requires proofload test factor of 2.0 for wire rope slings
- National Air and Space Museum spacecraft curatorial staff recommendation
    - Use non-oiled 7x19 316 stainless wire rope
- Minimize loading into hinge fittings until capability is confirmed
    - Stress analysis review required
- Recommend 3 cable types, 9 cables per side minimum, 3/16" diameter (3400# Ult)
- Final size, attach locations, and quantity TBD by Design Center stress analysis
    - cable "A" (2 per side) connects to PLBD latch mech. at Xo 576 & Xo 1307
    - cable "B" (3 per side) joins Yo 40 & Yo 68 shear tubes at Xo 758, Xo 941, and Xo 1125
    - cable "C" (4 per side) connects to centerline latch mech., joining two rollers per door
- Opportunity – Install cables/fittings in OPF prior to closing doors
    - connect to PLBD, then coil and stow extra length. Position to avoid interference with latching mech.
    - minimizes onsite PLBD work using manlifts

6

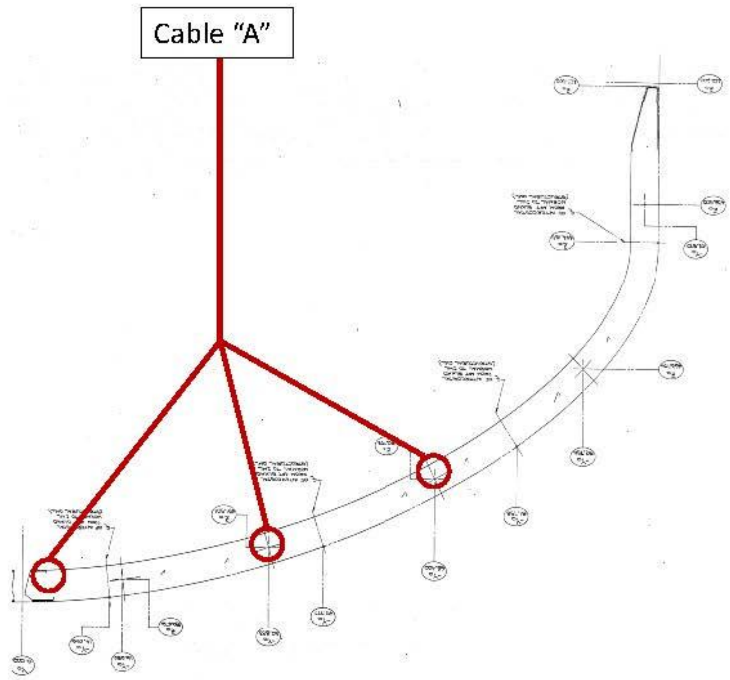
OV-104 PLBD Support



Notional Cable Arrangement

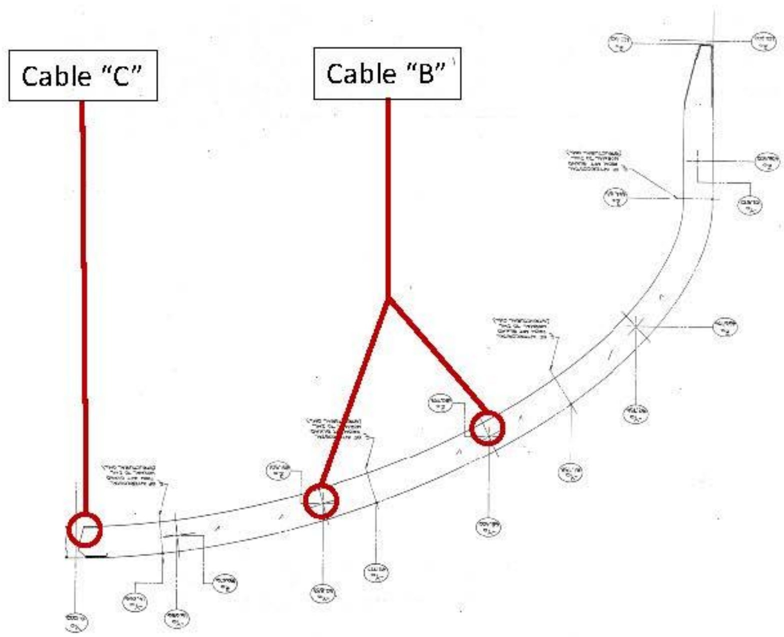
7

OV-104 PLBD Support



8

OV-104 PLBD Support



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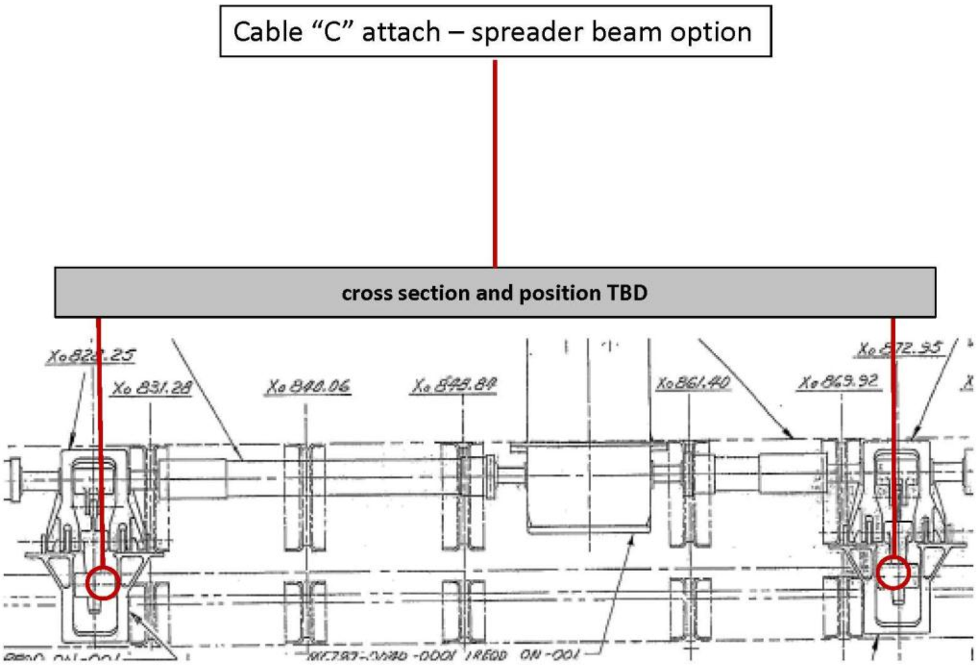
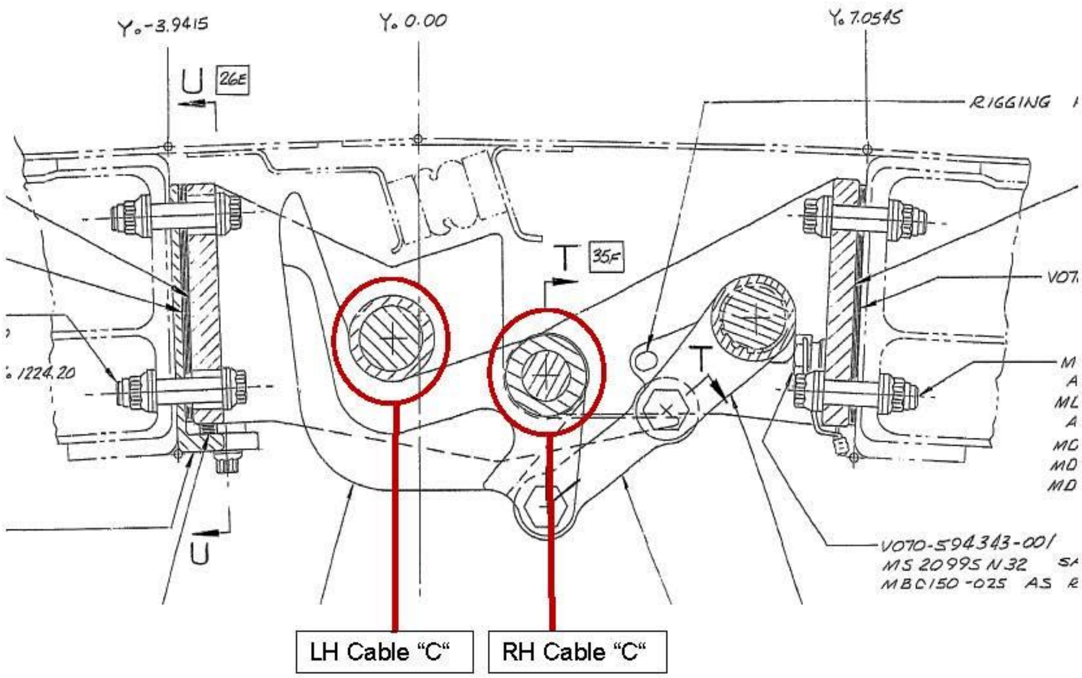
OV-104 PLBD Support



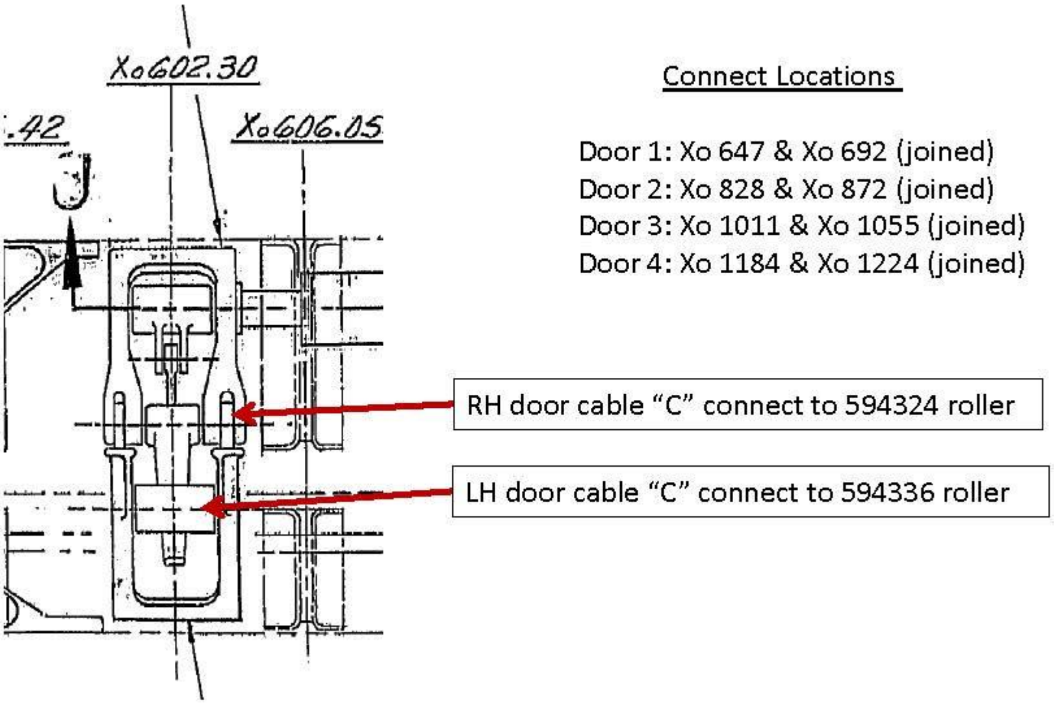
10

OV-104 PLBD Support



11

OV-104 PLBD Support



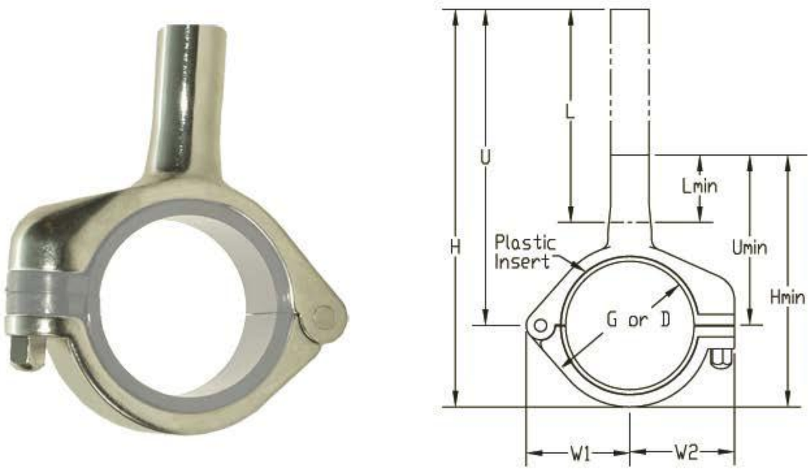
Connect Locations

Door 1: Xo 647 & Xo 692 (joined)
Door 2: Xo 828 & Xo 872 (joined)
Door 3: Xo 1011 & Xo 1055 (joined)
Door 4: Xo 1184 & Xo 1224 (joined)

12

OV-104 PLBD Support

COTS attach fitting option



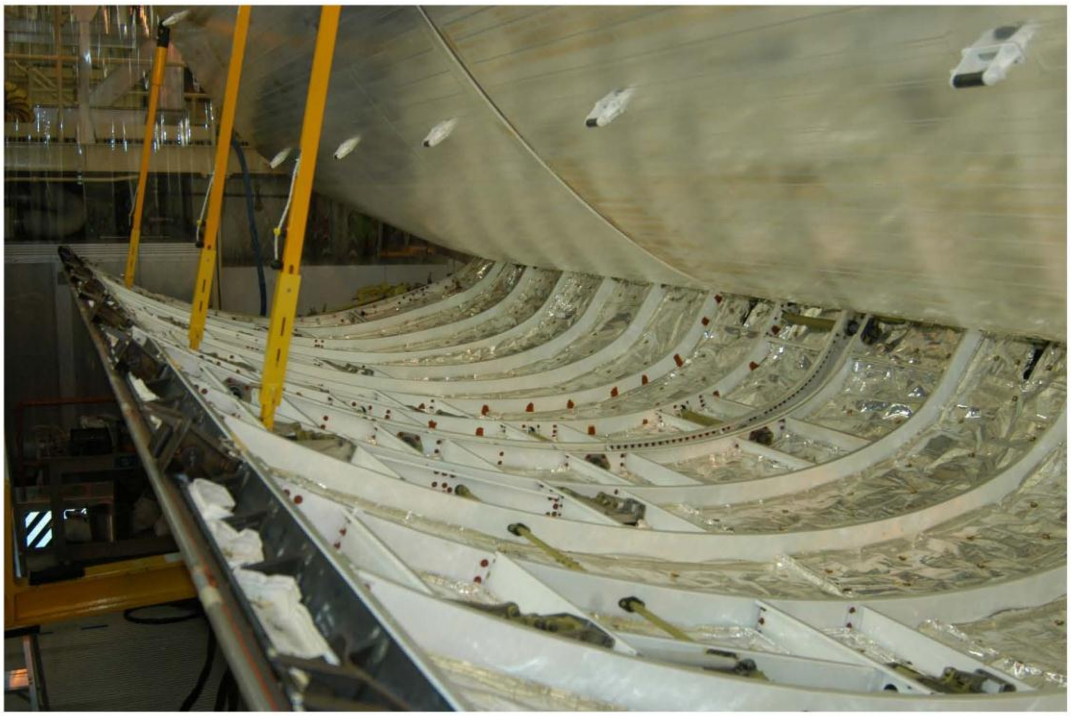
13

OV-104 PLBD Support

BACKUP

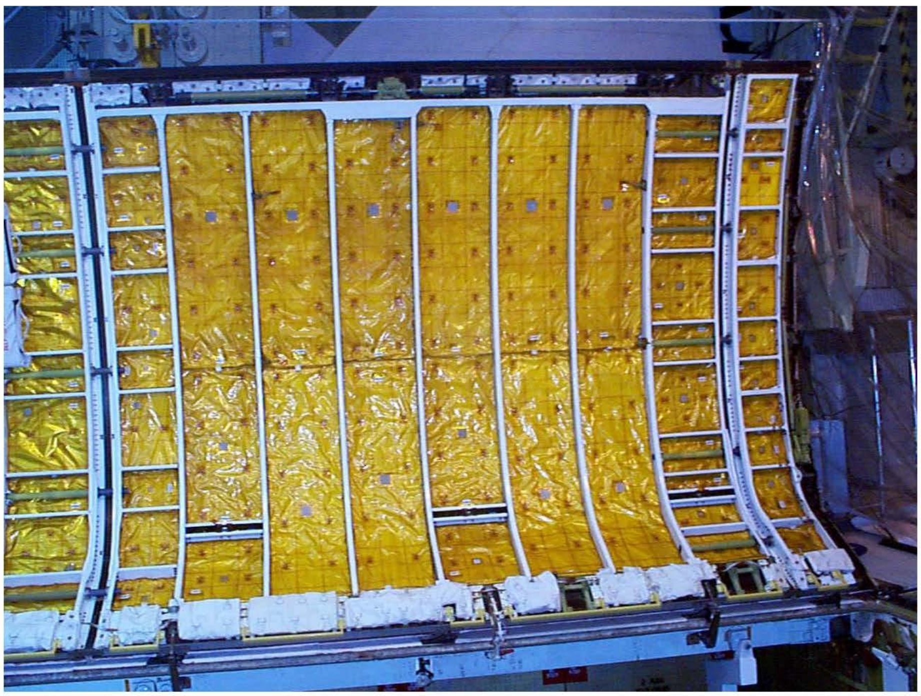
14

OV-104 PLBD Support



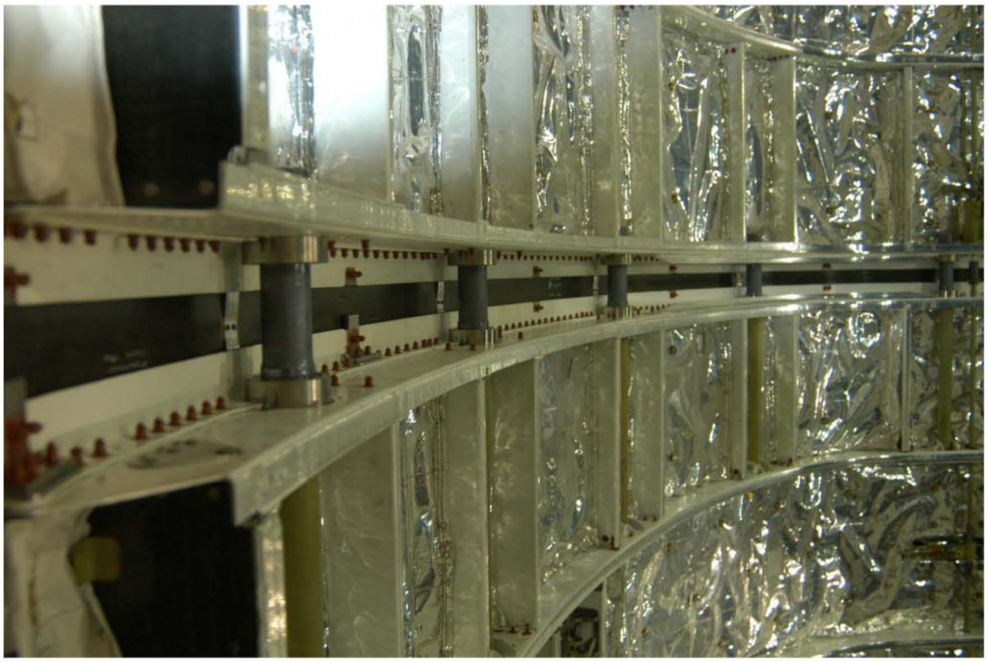
15

OV-104 PLBD Support



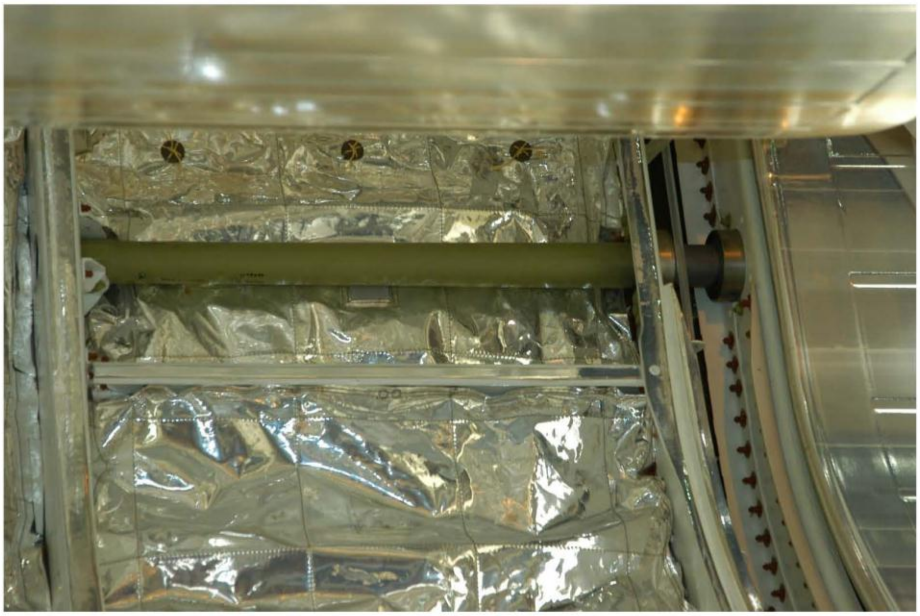
16

OV-104 PLBD Support



17

OV-104 PLBD Support



18

OV-104 PLBD Support

19

OV-104 PLBD Support

port centerline latch fitting

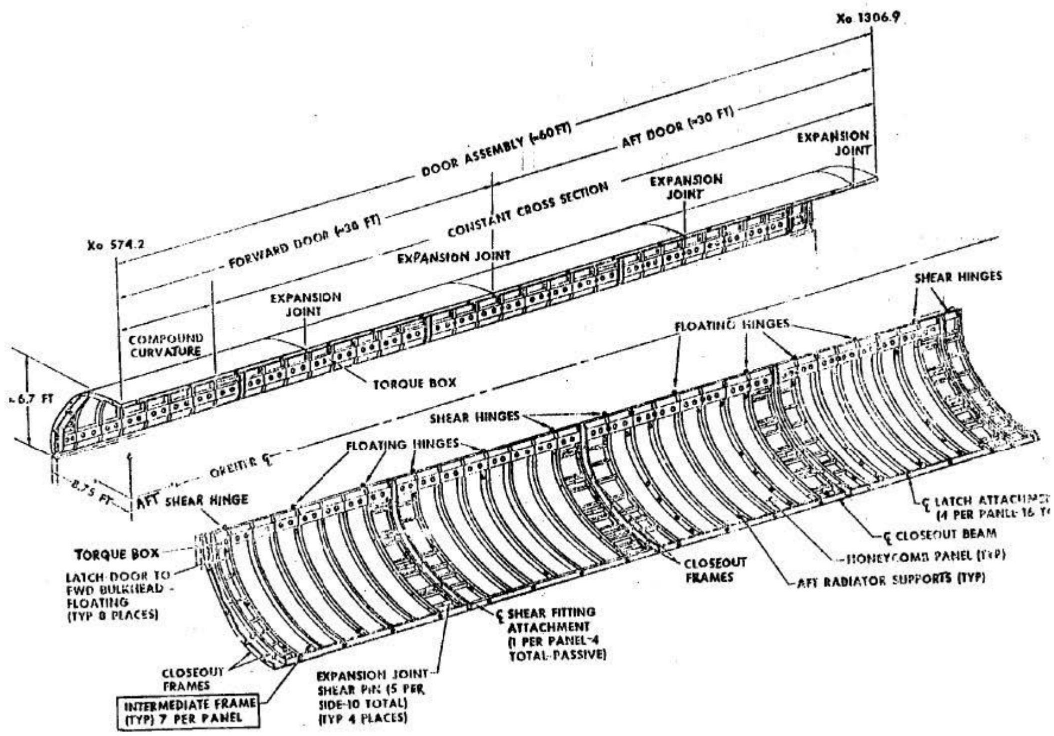
20

OV-104 PLBD Support

starboard centerline latch fitting

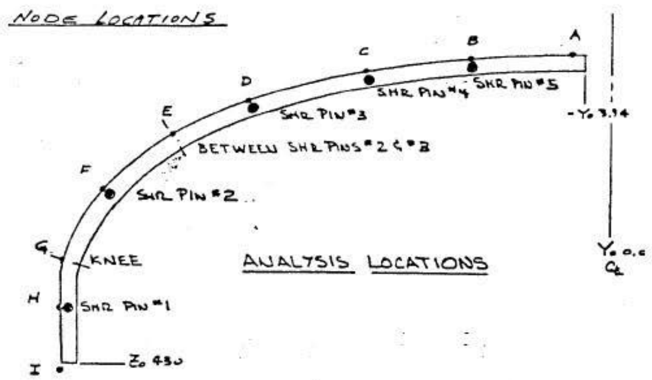
21

OV-104 PLBD Support



22

OV-104 PLBD Support

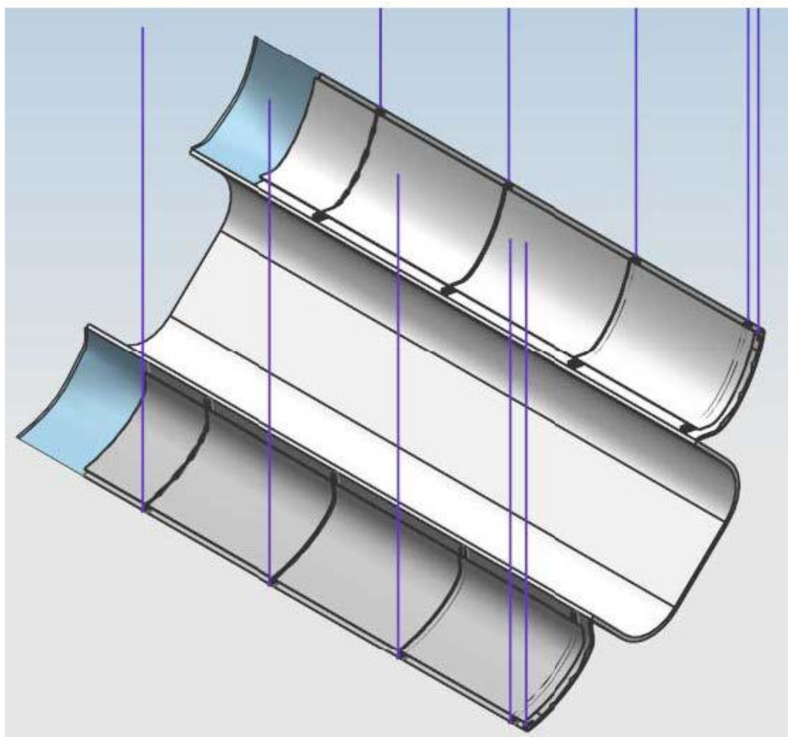


NODE	Y_o	Z_o	RADIUS
A	5.560	499.874	131.974
B	17.000	498.887	150.588
C	41.500	493.837	170.428
D	69.500	482.960	135.683
E	82.603	475.264	101.951
F	94.488	465.500	60.703
G	104.129	450.620	22.937
H	105.000	438.500	∞
I	105.000	429.500	∞
J	105.000	420.000	∞

23

Appendix M. G-Ops Support.pdf

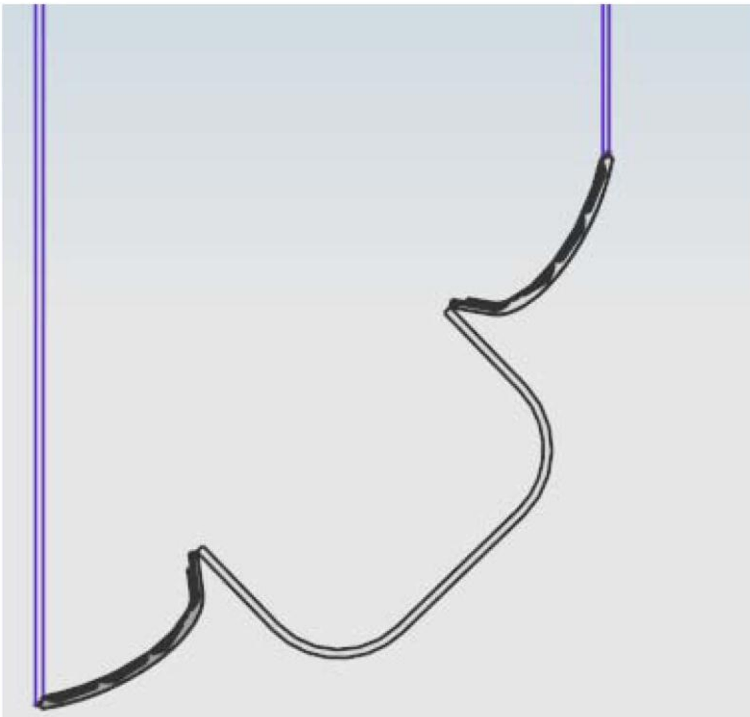
OV-104 Payload Bay Door Securing



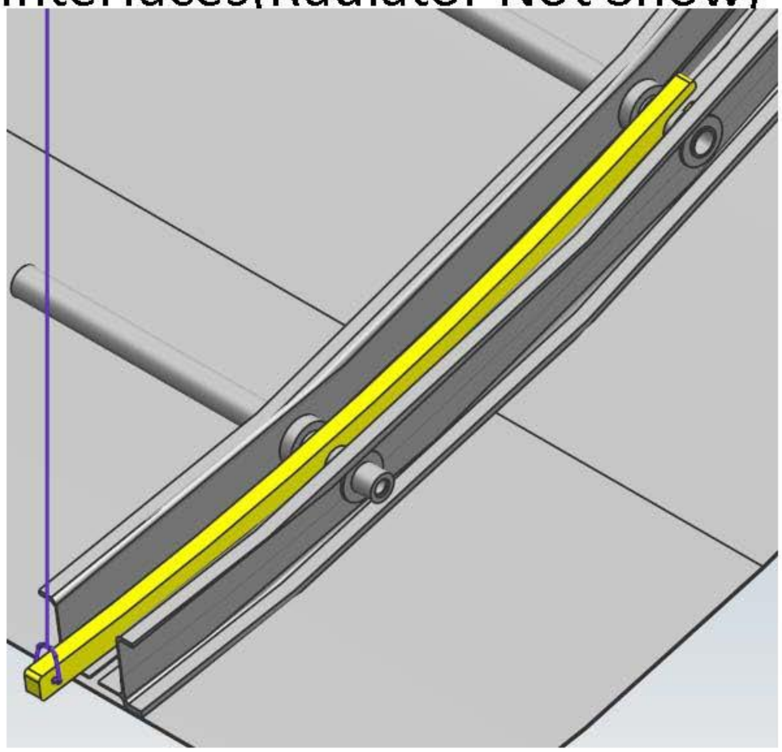
Assumption

- Minimal cables
- Doors 140 Degrees
- Vehicle 44 Degrees
- Doors Opened after Vehicle positioned
- Trolley Hoist and Strongback used for door opening

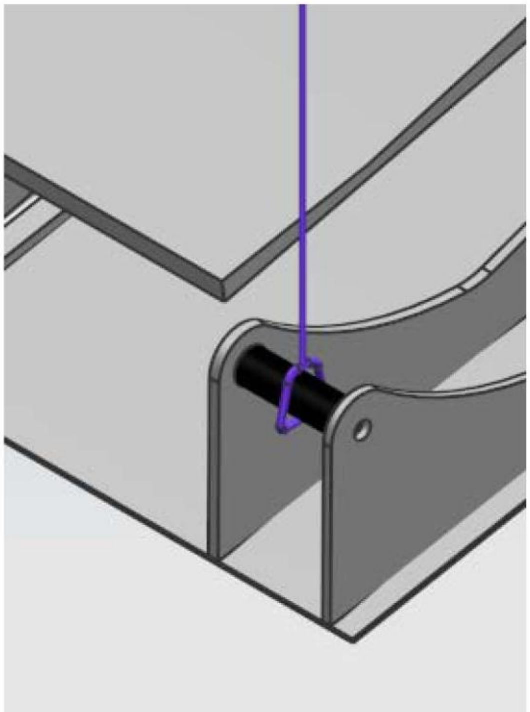
Rear View of Payload Bay Doors In Hang Position



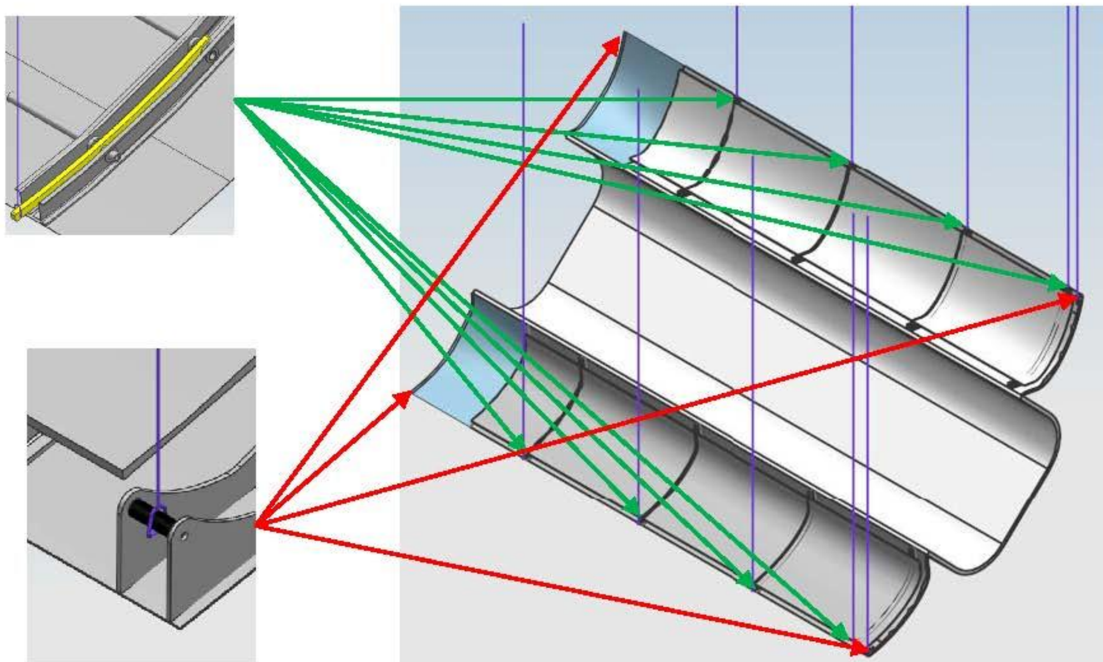
Attach Point Design For Door Panel Interfaces(Radiator Not Show)



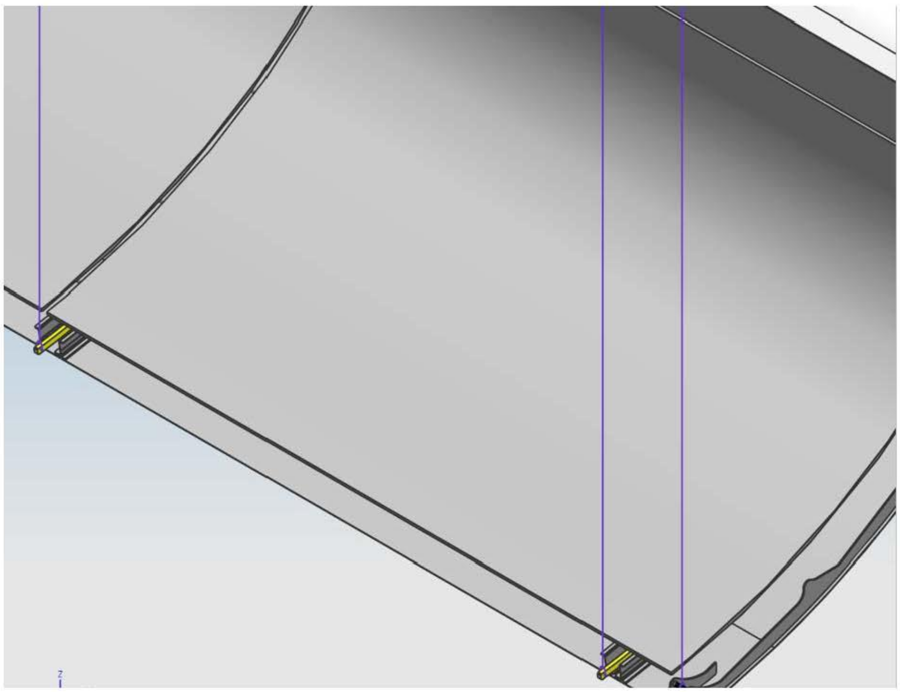
Attach Point Interfaces for Fore and Aft Ends of Door



Attach Type and Location



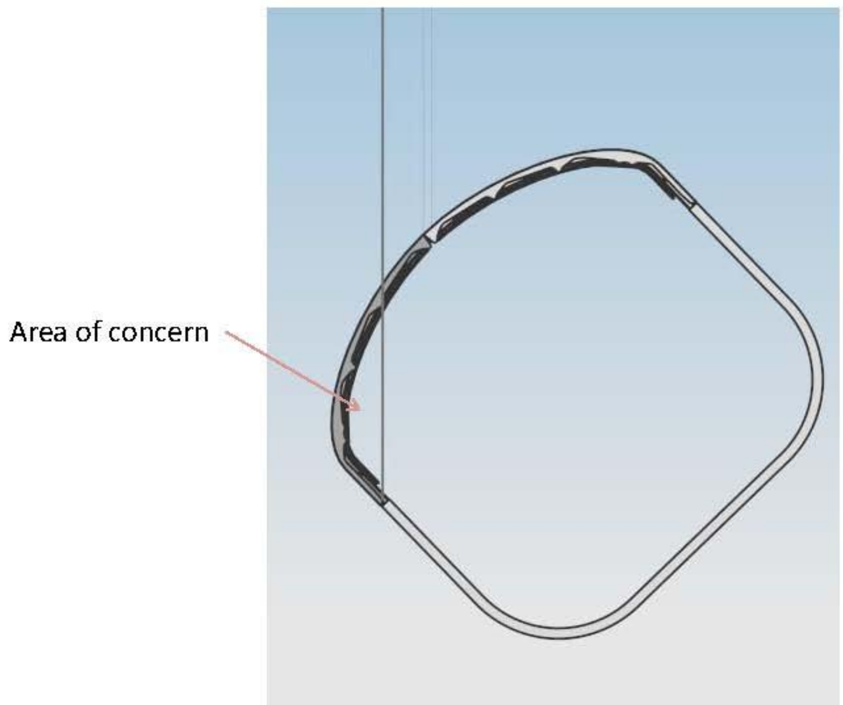
Attach With Radiators in Position



Concerns/Data Required

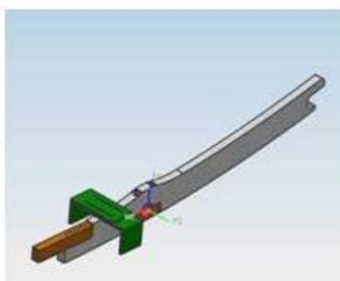
- Upper side wall deflection/stiffness
- Door mass/ center of mass
  - Left door opening when unlatched
  - Cable loading/design
- Do the panels need mid span support
  - If any left door only

Center of Mass for Lower Door



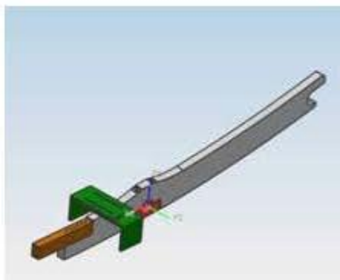
Appendix N. Mathcad - OV-104_Door_Support_Analysis_3.pdf

OV-104 DOOR SUPPORT ARM ANALYSIS



DATE: 2012, JULY 12

1.0 Support Arm Analysis



Weights based on counterweight values for 104s last door cycles.
RH door: 3569, LH door 3458. Conservatively used 3600 lbs

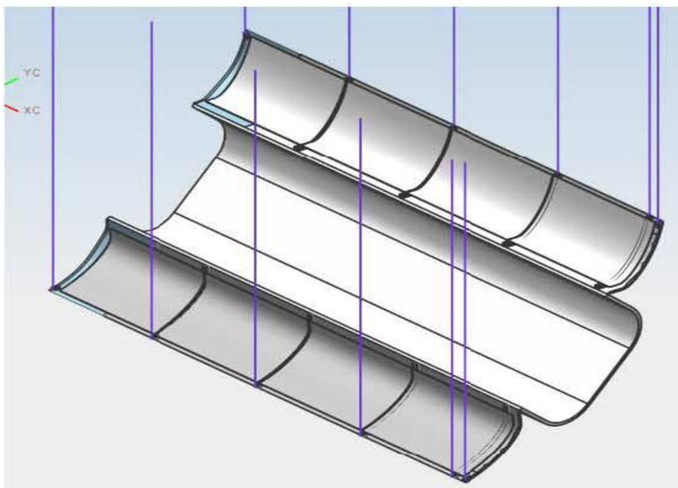
Strongback assy weights are 1400 lbs per side. Only upper tube will be used.
Assume 2/3 of strongback weight removed. Final counterweight value used should be approximately 2600 lbs.

Assume aft-most support is only used to support door 5 interface. No 'load' used to support door assys.

$$\frac{2666}{4} = 666.50$$

$F := 667 \cdot lbf$ Estimated load applied at each extension rod (in any direction)

$SF := 2$ Required Safety Factor for design



The forward-most and aft-most of the attachpoints will be hooked to the door roller assys. The inner four will use this support.

1.1 Extension Beam Analysis

bolt calculation 6 .25-28 bolts installed asume the bolt carries all the load

$Z := 1357\,lbf$ Load from free body diagram

$A_{ts} := 0.036 \cdot in^2$

$\sigma_{max2} := \frac{Z}{2 \cdot A_{ts}} = 18.85\,ksi$

Material: Cold worked 300 series stainless steel per ASTM F593

$Fy := 65 \cdot ksi$ $Fu := 100 \cdot ksi$ (size 1/4" thru 5/8")

$\boxed{Sf_{ys2} := \frac{Fy}{\sigma_{max2}} = 3.45}$ $\boxed{Sf_{us} := \frac{Fu}{\sigma_{max2}} = 5.31}$

Bending Calculation

$W := F = 667.00\,lbf$ (Load)

$H := 1.5 \cdot in$

$B := 1 \cdot in$

$L := 3.50 \cdot in$

$S := \frac{B \cdot H^2}{12} = 0.19 \cdot in^3$ (Section Modulus)

Stress at Support

$\sigma_{max} := \frac{(W \cdot L)}{S} = 12.45 \cdot ksi$

Material: 4340

$F_y := 60 \cdot ksi$ $F_u := 108 \cdot ksi$

$\boxed{Sf_{ys} := \frac{F_y}{\sigma_{max}} = 4.82}$ $\boxed{Sf_{us} := \frac{F_u}{\sigma_{max}} = 8.67}$

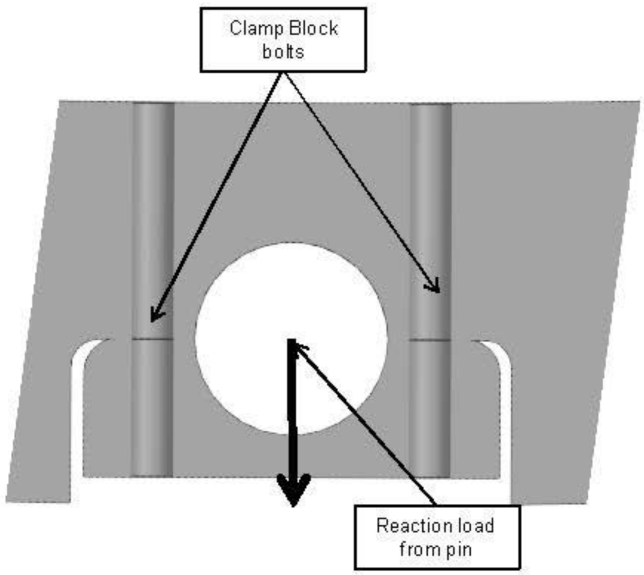
Tension Calculation

$$A_{beam} := .75 \cdot in \cdot 1.5 \cdot in$$

$$\boxed{Sf_{y} := \frac{F_y \cdot A_{beam}}{W} = 101.20}$$

$$\boxed{Sf_{u} := \frac{F_u \cdot A_{beam}}{W} = 182.16}$$

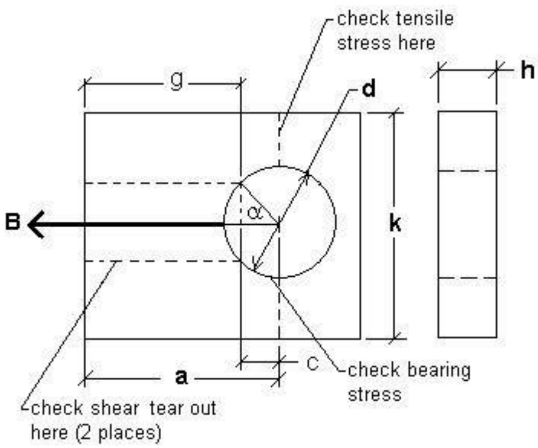
1.2 Clamp Block Analysis



Lug Analysis

Notes

Calculations based on *Analysis and Design of Flight Vehicle Structures* by E. F. Bruhn.



Input

$a := 1.25 \cdot in$

$d := 1.625 \cdot in$

$h := 1.00 \cdot in$

$k := 2.50 \cdot in$ Distance between clamping bolt hole centers

$\alpha := 40 \cdot deg$

$B := 1200 \cdot lbf$ Conservative value obtained from free body diagram

Calculations

Shear Tear out

$c := \frac{d}{2} \cdot \cos(\alpha)$ $\qquad$ $g := a - c$

$A_s := 2 \cdot g \cdot h = 1.26\,in^2$ (shear area)

$\boxed{f_s := \frac{B}{A_s} = 0.96\,ksi}$ (shear stress)

Material: 4340

$F_y := 60 \cdot ksi$ $\qquad$ $F_u := 108 \cdot ksi$

$\boxed{Sf_{ys} := \frac{F_y}{\sqrt{3} \cdot f_s} = 36.23}$ $\qquad$ $\boxed{Sf_{us} := \frac{F_u}{\sqrt{3} \cdot f_s} = 65.22}$ (safety factor, per von Mises criteria)

Bearing stress

$A_{br} := d \cdot h = 1.63\,in^2$ (bearing stress)

$\boxed{f_{br} := \frac{B}{A_{br}} = 0.74\,ksi}$

Note: If bearing properties are not available KSC-STD-Z-0004 permits use of the following formulas:

$F_{bry} := 1.4 \cdot F_y$ $\qquad$ $F_{bru} := 1.4 \cdot F_u$ (for hole edge distance < 2 x dia)

$\boxed{Sf_{yb} := \frac{F_{bry}}{f_{br}} = 113.75}$ $\qquad$ $\boxed{Sf_{ub} := \frac{F_{bru}}{f_{br}} = 204.75}$ (safety factor)

Clamping Bolt Analysis

$F := B = 1200.00\ \text{lbf}$

Fastener Thread: 3/8-16 UNC-2A

$A_t := .0775 \cdot in^2$

$\sigma_{max} := \dfrac{F}{2 \cdot A_t} = 7.74\ \text{ksi}$

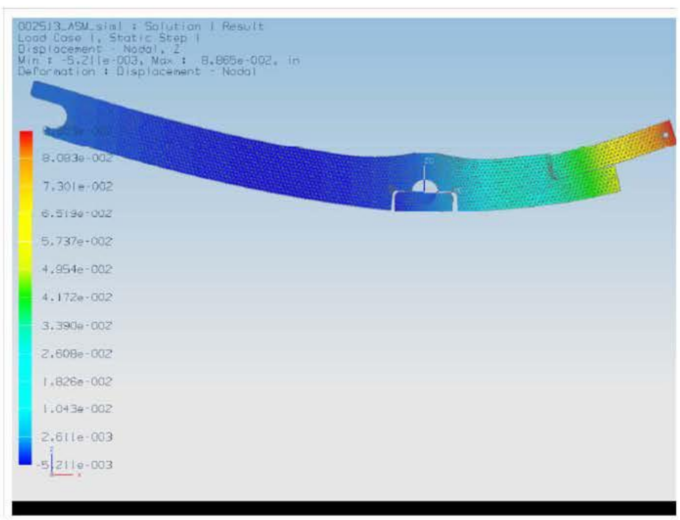
Material: Cold worked 300 series stainless steel per ASTM F593

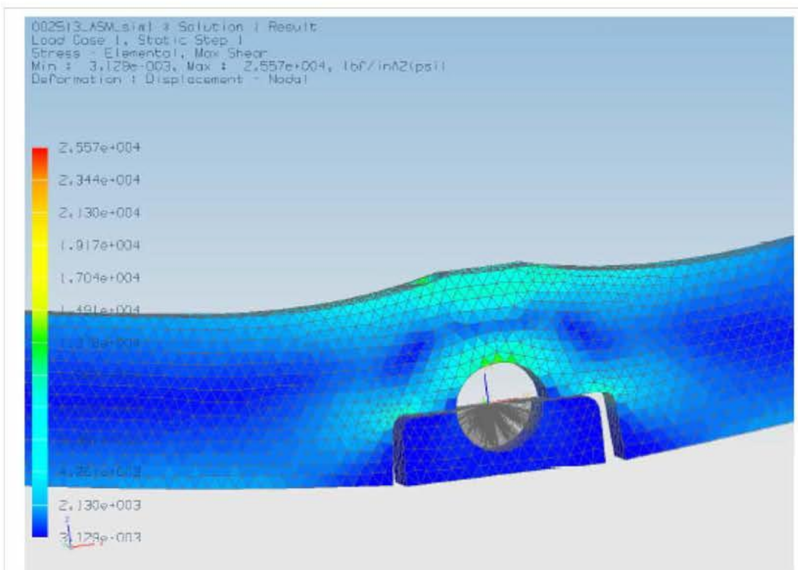
$Fy := 65 \cdot ksi$ $\quad Fu := 100 \cdot ksi$ $\quad$ (size 1/4" thru 5/8")

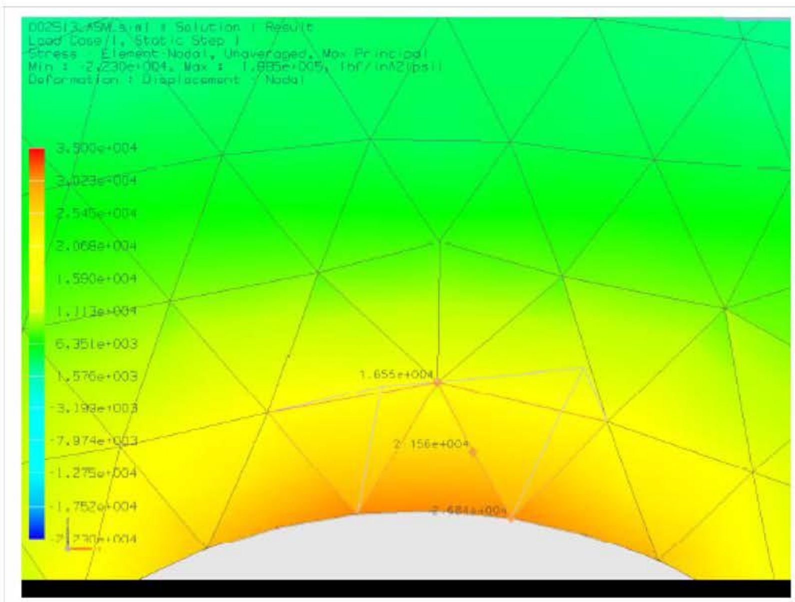
$\boxed{Sf_{yu} := \dfrac{F_y}{\sigma_{max}} = 7.75}$ $\quad$ $\boxed{Sf_{us} := \dfrac{F_u}{\sigma_{max}} = 13.95}$

1.3 Support Beam Analysis

A worst case bending load of this support beam was analyzed using a conservative 667 lbf load applied at such an angle that the worst case bending stress would be obtained at the weakest point of the structure -- the thin area of the beam located at the vehicle pin pivot point in the center of the beam.




002513_ASM_sim1 : Solution 1 Result
Load Case 1, Static Step 1
Stress - Elemental, Max Shear
Min : 3.128e-003, Max : 2.557e+004, lbf/in^2(psi)
Deformation : Displacement - Nodal
2.557e+004
2.344e+004
2.130e+004
1.917e+004
1.704e+004
2.130e+003



Maximum principal stress at inside of pivot hole from update FEM

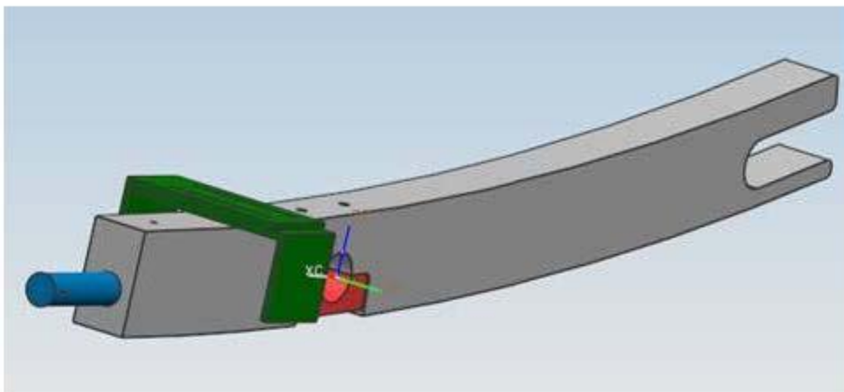
$\sigma_{max} := 26.84 \cdot ksi$

Material: AISI SAE 4340

$F_y := 60 \cdot ksi$

$$sf := \frac{F_y}{\sigma_{max}} = 2.24$$

For final install, tabs will be installed and shimmed at outer edge of door supports to keep the door joints from fanning out at the centerline of the doors. Recommend beam and angles be fabricated from 6061 T6 aluminum and primed and painted. Recommend block and round be fabricated from 300 series stainless steel.



Appendix O. PLBD Comments.pptx (K. Roscoe's assessment of PLBD analysis)

PLBD Comments

9/18/2012

1

Requirements

Per PLBD Support-C.pdf, provided via attachment of email from T. Kott, JSC to T. Roberts KSC on 6/1/2012, and subsequently by C. Larsen, on 6/18/2012

- Consider PLBD support to be a **critical lift operation**, Ref NASA-STD 9719.19 Requires minimum Design Load **Safety Factor of 5** for wire rope slings
  - Requires proofload test factor of 2.0 for wire rope slings

Per Mathcad - OV-104_Door_Support_Analysis_3.pdf, provided via attachment of email from S. Minute, KSC to I. Raju on 9/12/2012

- SF := 2 Required Safety Factor for design

The FS of 5 should be maintained until the load can be distributed into the structure. This doesn't happen until the load is into the PLBD shear tubes. A single failure of a membrane loaded member (pin or bolt) that would result in loss of a critical lift should have FS of 5.

2

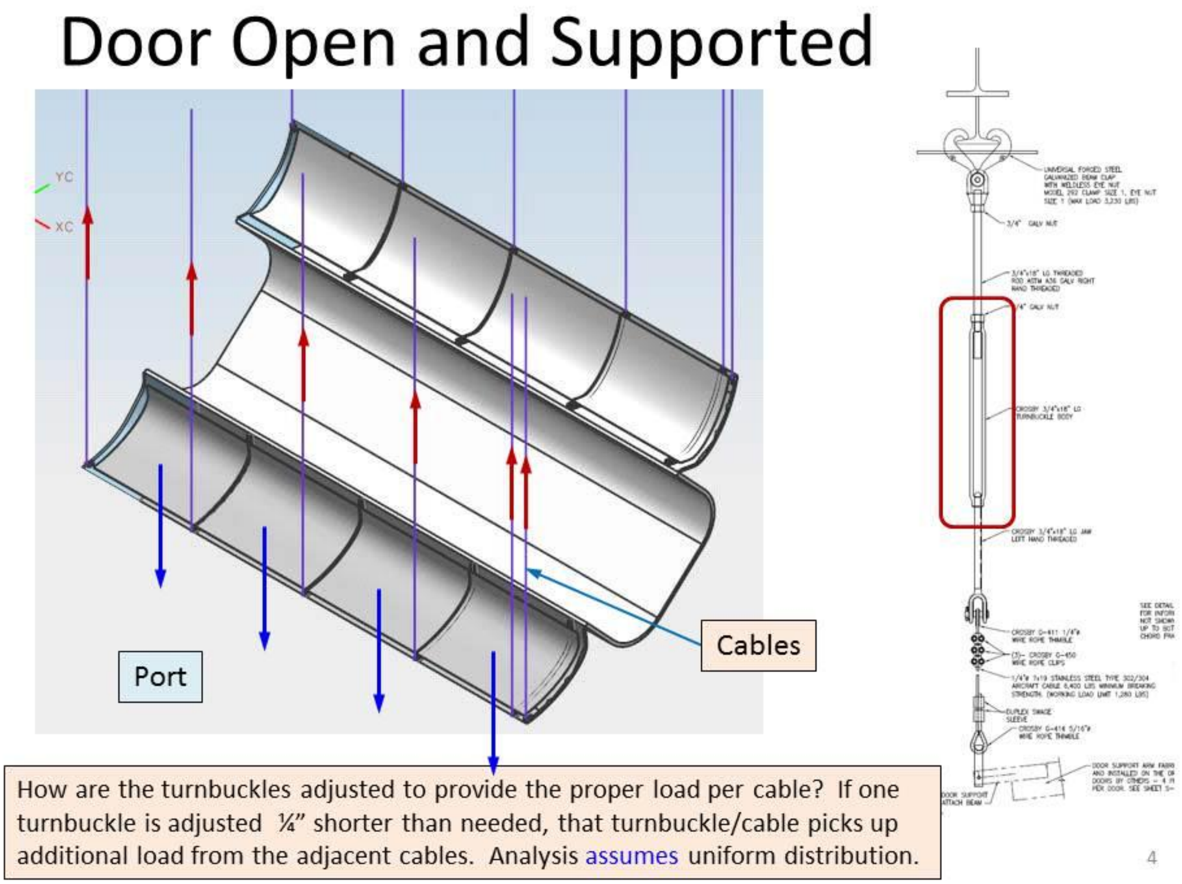
Total Supported Load

Assumes total per side is 3,600 lbs when using two GSE tubes. 2/3rds of GSE weight (1,400 lbs) is lost when using the 1 tube GSE? Source?

Supported by GSE to open position.
Worst case is PLBD open, suspended from cables and prior to removing GSE

Per Mathcad - OV-104_Door_Support_Analysis_3.pdf
Weights based on counterweight values for 104s last door cycles. RH door: 3569, LH door 3458. Conservatively used 3600 lbs
Strongback assy weights are 1400 lbs per side. Only upper tube will be used.
Assume 2/3 of strongback weight removed.

3



Door Open and Supported
YC
XC
Port
Cables
How are the turnbuckles adjusted to provide the proper load per cable? If one turnbuckle is adjusted ¼" shorter than needed, that turnbuckle/cable picks up additional load from the adjacent cables. Analysis assumes uniform distribution.
4

Attach Beam

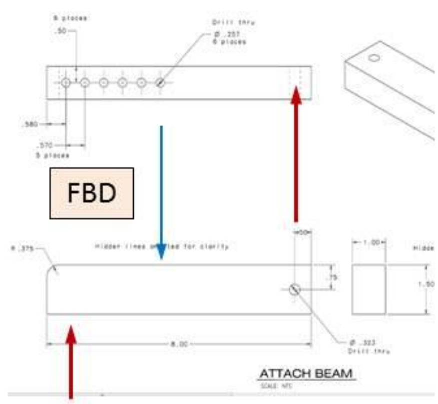
Assuming uniform cable loading: F = 667 lbs

Load per side w/ GSE	3,600
GSE 2 Tube Wt	1,400
Total Door Wt at cable	2,200
Ratio 1 to 2 Tube GSE	33.3%
GSE 1 Tube Wt	467
Wt on Cable	2,667
Num of Support Cables	4
Wt per support cable	667
Distribution factor	1.00
Wt per Attach Beam	667

Assumes load normal to AB (worst case)

Overall length	8		
pivot end	0.58		
pin end	0.5		
Cable lever arm	6.92		= 8 - 0.58 - 0.5
number of spacings	5		
spacing	0.57		
Bolt lever arm	2.9		= 5 * 0.57
Force ratio	2.39		
Bolt force	1,591		
	1/4"	3/8"	
Bolt tensile area	0.0364	0.0775	
Bolt tensile stress	43,735	20,529	
Bolt ultimate stress	100,000	100,000	
Bolt FS, ult	2.29	4.87	

Using other bolts may get to FS of 5, but they have diminishing lever arms.



Note: Sketch is NTS

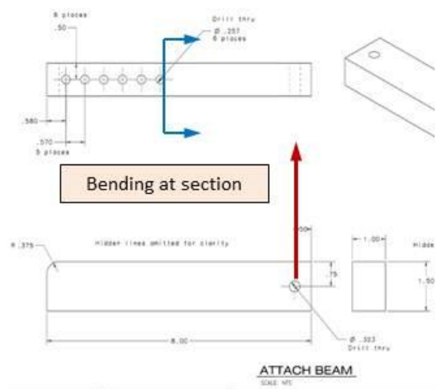
5

Attach Beam

Assuming uniform cable loading: F = 667 lbs

Attach Beam Bending			
Thru Bolt	1/4"	3/8"	
Height	1.5	1.5	
Width	1	1	
Hole thru	0.257	0.382	
Net width	0.743	0.618	
Section modulus	0.279	0.232	$= bh^2/6$
Lever	4.02	4.02	= 6.92 - 2.9
Moment	2,680	2,680	
Bending stress	9,619	11,564	
AB ultimate stress	108,000	108,001	
AB FS, ult	11.23	9.34	

Lots of bending capacity, not a lot of bolt capacity. Consider using 3/8" bolt at end.

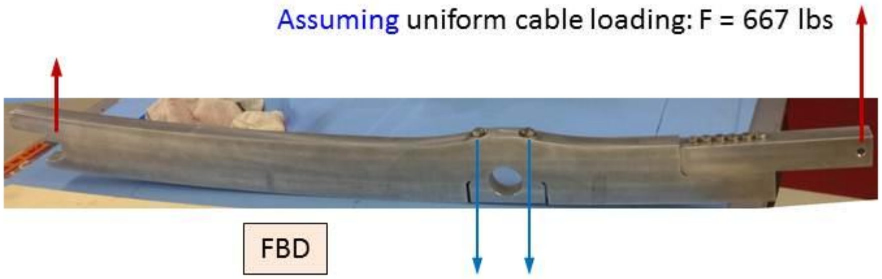


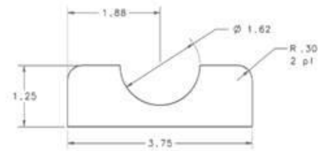
Note: Sketch is NTS

6

Support Beam

Assuming uniform cable loading: F = 667 lbs

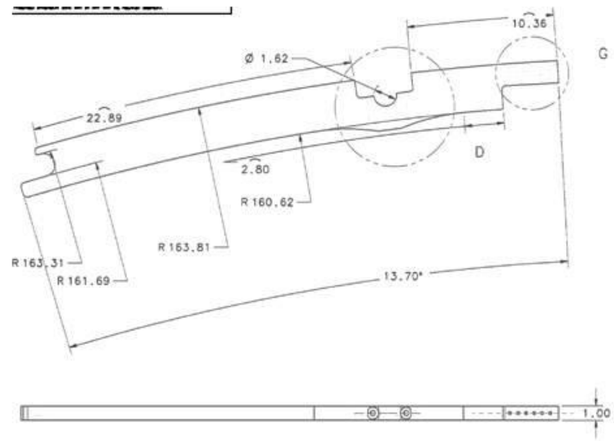




FBD

Geometry

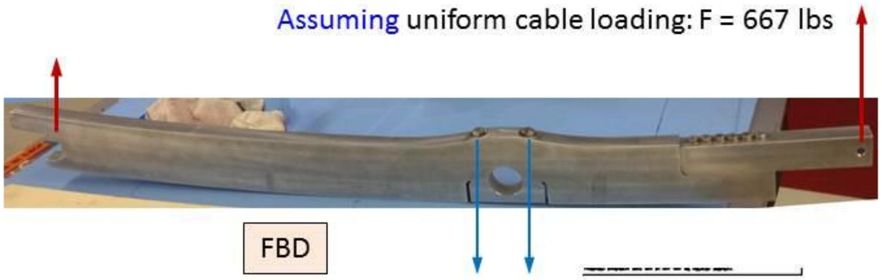
Shear Tube to shear tube distance	
Radius at bottom of hole	161.69
Shear tube radius	0.81
Radius at shear tube ctr	162.5
Arc length to Block edge	22.89
Distance to block edge	22.87
Block edge to tube ctr	1.875
Tube to tube distance	24.75
Edge to SB edge	10.36
Approx Tubt to SB edge	12.235
Tube to 1/4" bolt	11.665
Tube to cable	15.69
Cable to 1st 3/8" bolt	15.00

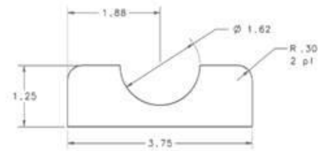


7

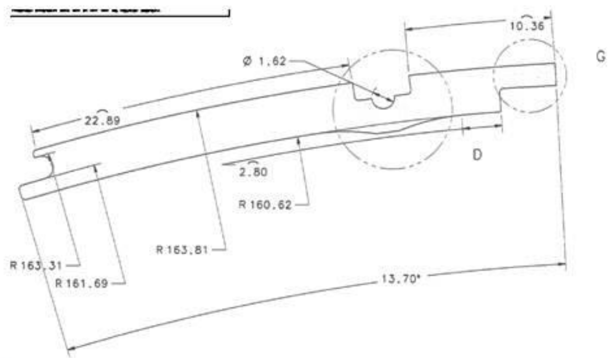
Support Beam

Assuming uniform cable loading: F = 667 lbs



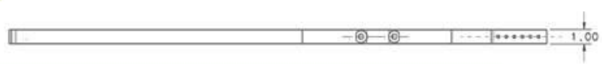


FBD



SB Bending

	At: 3/8" hole	Shear Tube	
Approx Depth	2.144	1.572	Scaled
Width	1	1	
Hole thru	0.386	0	
Net width	0.614	1	
Section modulus	0.470	0.412	$= bh^2/6$
Moment approx	9,997	10,457	
Bending stress	21,258	25,388	
AB Yield stress	60,000	60,000	
AB FS, Yld	2.82	2.36	Ultimate?

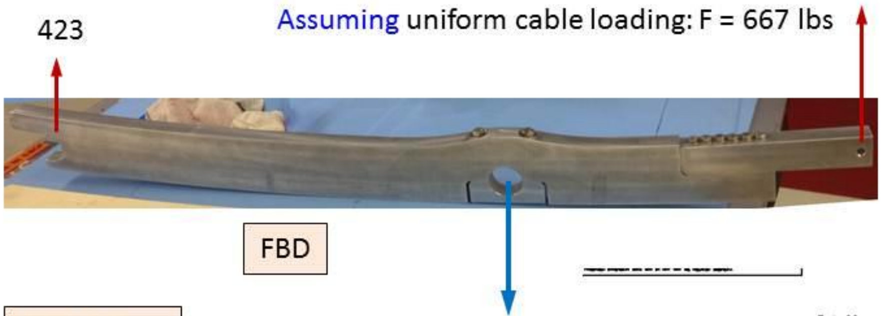


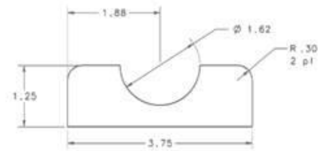
Same as in Mathcad doc. Ultimate? Note: Not concerned about stress concentrations (Kt). They are for fatigue and slight yielding, neither are a concern. FEA will pick up some Kt.

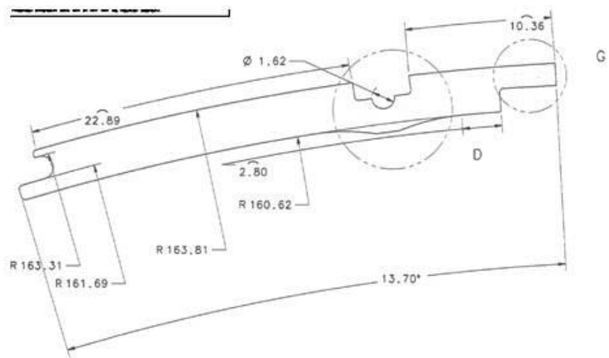
8

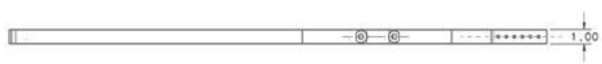
Support Beam

Assuming uniform cable loading: F = 667 lbs









3/8" Bolt

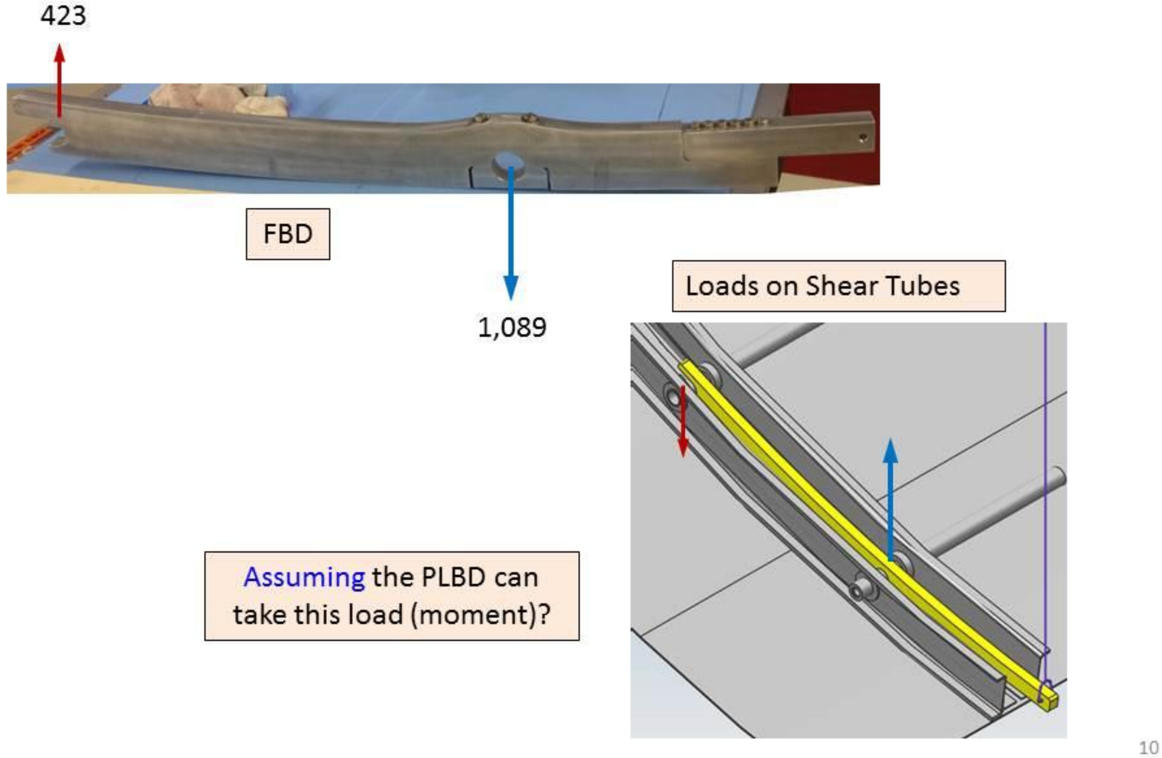
Reaction Loads

Cable lever arm	40.43	
Shear Tube lever arm	24.75	
Force ratio	1.63	
ST force middle	1,089	
ST force end	423	
3/8" bolt Force	545	~ 1/2 ST force middle
Bolt tensile area	0.0775	
Bolt tensile stress	14,056	
Bolt ultimate stress	100,000	
Bolt FS, ult	7.11	> 5

Approx same as in Mathcad doc when scaled (force ratio, load).

9

Support Beam



Summary

- The cables are in an indeterminate system
  - Analysis did not account for possibility of extra load
  - Cable tensioning procedure?
  - MS is dependent on Cable tensioning
- Recommend modifying 1 bolt from a ¼” to a 3/8”. Modifications:
  - Drill 1 hole bigger
  - Drill and tap 1 hole bigger
  - Acquire an extra 3/8” bolt

11

Appendix P. PLBD Attach Beam calcs.xlsx (K. Roscoe's analysis)

PLBD Calcs

Load per side w/ GSE	3,600		
GSE 2 Tube Wt	1,400		
Total Door Wt at cable	2,200		
Ratio 1 to 2 Tube GSE	33.3%		
GSE 1 Tube Wt	467		
Wt on Cable	2,667		
Num of Support Cables	4		
Wt per support cable	667		
Distribution factor	1.00		
Wt per Attach Beam	667		
Overall length	8		
pivot end	0.58		
pin end	0.5		
Cable lever arm	6.92		= 8 - 0.58 - 0.5
number of spacings	5		
spacing	0.57		
Bolt lever arm	2.9		= 5 * 0.57
Force ratio	2.39		
Bolt force	1,591		
	1/4"	3/8"	
Bolt tensile area	0.0364	0.0775	
Bolt tensile stress	43,735	20,529	
Bolt ultimate stress	100,000	100,000	
Bolt FS, ult	2.29	4.87	

Attach Beam Bending		
Thru Bolt	1/4"	3/8"

Height	1.5	1.5	
Width	1	1	
Hole thru	0.257	0.382	
Net width	0.743	0.618	
Section modulus	0.279	0.232	= $bh^2/6$
Lever	4.02	4.02	= 6.92 - 2.9
Moment	2,680	2,680	
Bending stress	9,619	11,564	
AB ultimate stress	108,000	108,001	
AB FS, ult	11.23	9.34	

Lots of bending capacity, not a lot of bolt capacity:
Consider using larger bolt

Shear Tube to shear tube distance	
Radius at bottom of hole	161.69
Shear tube radius	0.81
Radius at shear tube ctr	162.5
Arc length to Block edge	22.89
Distance to block edge	22.87
Block edge to tube ctr	1.875
Tube to tube distance	24.75
Edge to SB edge	10.36
Approx Tubt to SB edge	12.235
Tube to 1/4" bolt	11.665
Tube to cable	15.69
Cable to 1st 3/8" bolt	15.00

At:	3/8" hole	Shear Tube	
Approx Depth	2.144	1.572	Scaled
Width	1	1	
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Net width	0.614	1	
Section modulus	0.470	0.412	= $bh^2/6$

Moment approx	9,997	10,457	
Bending stress	21,258	25,388	
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Reaction Loads

Cable lever arm	40.43	
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Bolt ultimate stress	100,000	
Bolt FS, ult	7.11	> 5

Appendix Q. AttachBeamBolts.xlsx (K. Roscoe's analysis)

bolt	load	Strength	area	factor
1	-810	180,000	0.0364	n/a
2	-440	180,000	0.0364	n/a
3	-70	180,000	0.0364	n/a
4	290	180,000	0.0364	22.5931
5	660	180,000	0.0364	9.927273
6	1020	180,000	0.0364	6.423529

Load	lb	667
Load Arm	in	6.92

FEA

Bolt force	1,003
Stress	27,555
Strength	180,000
FS	6.5

Current Bolts

At	in2	0.0364		
Ftu	psi	100,000		
Fty	psi	60,000		
Bolt		1	2	3
Strength	psi	100,000	60,000	60,000
Capacity	lbs	3640	2184	2184
L	in	2.9	2.33	1.76
Moment	in-lb	10,556	5,089	3,844
Total moment	in-lb	19,489		
Applied mom	in-lb	4,616		
FS	-	4.2		

High Strength Bolts

At	in2	0.0364		
Ftu	psi	180,000		
Fty	psi	120,000		
Bolt		1	2	3
Strength	psi	180,000	120,000	120,000
Capacity	lbs	6552	4368	4368
L	in	2.9	2.33	1.76
Moment	in-lb	19,001	10,177	7,688
Total moment	in-lb	36,866		
Applied mom	in-lb	4,616		
FS	-	8.0		

Appendix R. Email from C. Larsen to Minute, et. al. on September 5, 2012: Re: Atlantis Support Structure – Orbiter allowable loads

From: Larsen, Curtis E. (JSC-C104)
Sent: Wednesday, September 05, 2012 12:43 PM
To: Minute, Stephen A. (KSC-C105); Raju, Ivatury S. (LARC-C104); ROSCOE, KEVIN (LARC-D206); Elliott, Kenny B. (LARC-D210); 'David Hamilton' (dave@lifethoughts.com)
Subject: RE: Atlantis Support Structure - Orbiter allowable loads
Importance: High

Folks –
I have gone back to Shuttle documentation and tabulated below the ET to Orbiter limit loads allowed during ascent flight. These allowable loads are higher than those in the ferry flight ICD for the obvious reason of the more severe flight environment. Thus they reflect the true Orbiter interface load capability and should give us additional comfort in accepting the loads to be imposed by the static display support structure. My reference for these loads is: Lockheed Martin report no. 826-2470, Jan. 2001, “SLWT Structural Load Indicators and Capabilities”.
All loads are in kips (1000 lbs), in Orbiter coordinate system.
Interface AO-1: Fx = 10.8/-8.5 Fy = 64.5/-70.9 Fz = 96.4/-127.8
Interface AO-2: Fx = 154.3/-705.3 Fy = 82.0/-107.8 Fz = 247.8/-326.0
Interface AO-3: Fx = 152.9/-699.8 Fy = 103.7/-70.7 Fz =243.1/-395.7
I hope this helps in our discussions.
Thanks,
Curt
Curtis E. Larsen, Ph.D., P.E.
NASA Technical Fellow for Loads & Dynamics
NASA Engineering and Safety Center (NESC)

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NASA (internal only) Loads and Dynamics Community of Practice:
https://nen.nasa.gov/web/lnd

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14. ABSTRACT
Mr. Christopher Miller with the Kennedy Space Center (KSC) NASA Safety & Mission Assurance (S&MA) office requested the NASA Engineering and Safety Center's (NESC) technical support on March 15, 2012, to review and make recommendations on the structural analysis being performed for the Orbiter Atlantis static display at the KSC Visitor Center. The principal focus of the assessment was to review the engineering firm's structural analysis for lifting and aligning the orbiter and its static display configuration.

15. SUBJECT TERMS
Safety & Mission Assurance; NASA Engineering and Safety Center; Transition and Retirement; Orbiter Atlantis; Static Display

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