Design of "KIBO" structure and verification

Takayuki Shimoda[1] and Masaru Wada[2]
Japan Aerospace Exploration Agency, Tsukuba, Ibaraki,3058505

and

Shigeru Imai[3]
Japan Manned Space Systems Corporation, Tsuchiura, Ibaraki, 300-0033

Japanese Experiment Module (JEM, which is so called "KIBO") was completed and assembled as a part of the International Space Station (ISS) on orbit in July, 2009. The JEM is a payload of Space Shuttle at lift off and also it is a part of ISS on orbit. JEM structure is required to be compatible with Space Shuttle Flight and ISS. This paper shows the activities to evaluate and validate the structural compatibility.

I. Introduction

THE JEM (See Figure 1) was completed and assembled as a part of ISS on orbit in July, 2009. The JEM was launched by three Space Shuttle flights separately. The first flight (Flight 1J/A) of Experiment Logistics Module-Pressurized Section (ELM-PS) was conducted in March 2008. Continuously the second flight (Flight 1J) of Pressurized Module (PM) with Remote Manipulator System (RMS) was conducted in June 2008. The last flight (Flight 2J/A) after the successful two flights of Exposed Facility (EF) and Experiment Logistics Module-Exposed Section (ELM-ES) was conducted in July 2009.

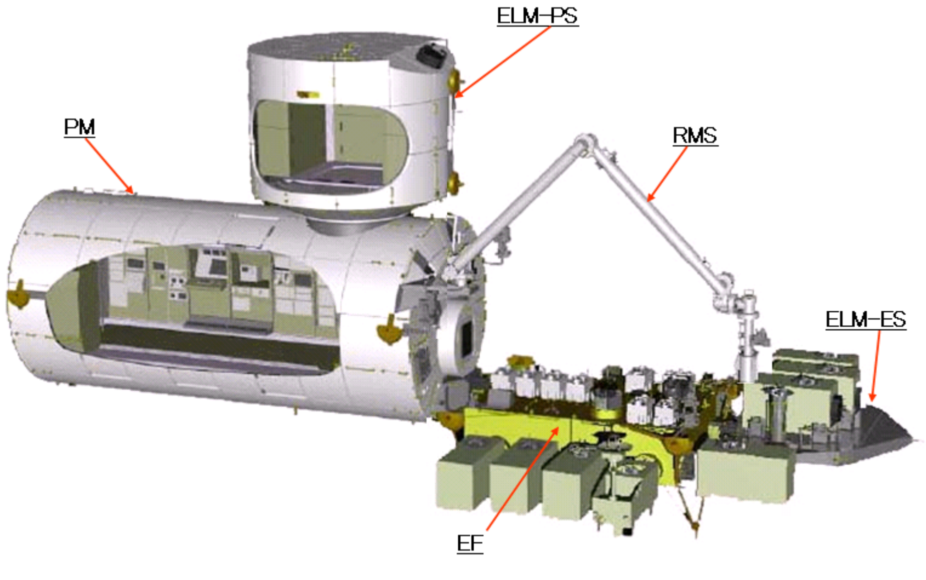

Figure 1. JEM Outline

[1] Associate senior engineer, JEM Mission Operations and Integration Center, shimoda.takayuki@jaxa.jp
[2] Associate senior engineer, Safety and Mission Assurance Department, wada.masaru@jaxa.jp
[3] Associate senior engineer, Manned Space Systems Department, simai@jamss.co.jp

JEM Structure is required as a payload of Space Shuttle to meet the structural compatibility requirement for launch/contingency landing phase. The most severe load for each JEM element carried by Space Shuttle is an ignition impact or acoustic vibration of solid rocket booster at lift off. These loads will be calculated with Structural Math Model composed of Space Shuttle model and JEM element model as a payload. The analysis is conducted using Space Shuttle forcing functions. The Structural Math Model for the analysis is required to correlate with modal survey test under 50Hz frequency where there is a possibility to couple with vibration modes of Space Shuttle. Also JEM structure is required as an element of ISS to meet the structural requirement.

This paper presents the verification of JEM structural analysis for compatibility with Space Shuttle and ISS. The verification requirements, validation results, and technical challenges are introduced.

II. Structural Compatibility with Space Shuttle

Structural compatibilities are required and described in the Interface Control Document (ICD) for Space Shuttle Payload. As major requirements, following points could be listed and explained hereafter:

- Weight and Center of Gravity (C.G.)
- Stiffness and structural damping
- Strength
- Dynamic clearance

Compatibility of these requirements needs to be verified on test-basis, and the difference should be reinforced by analysis between test configuration and flight configuration. Verification result is subject for several reviews and needs to be approved by NASA for flight certification.

A. Requirement of Weight and Center of Gravity (C.G.)

Weight and C.G. of payload is one of the most important factors for Space Shuttle flight. These data determine the required amount of propellant and ballast to achieve an appropriate ascent performance and flight control stability in descent. It is also essential for remote manipulator to handle payload accurately and safely on orbit. NASA figures out overall Space Shuttle weight and C.G. to evaluate its ascent performance margin (APM) and flight control stability (especially for descent phase) with payload-provided data. Since NASA needs to conduct these evaluations with the predicted mass properties and/or mathematical models as pre-launch assessment, NASA is supposed to perform final weight and C.G. measurement of each payload with flight configuration in L-2 months and compares with pre-estimated numbers to verify that the flight performance analysis is effective. The allowable error is respectively, 200 lb (weight) and 1 inch (C.G.) RSS in three axes between predicted numbers and actual ones, and if this requirement is not met, pre-launch assessments need to be reinforced by additional assessment for its validity.

B. Requirement of Stiffness and Structural Damping

Stiffness and structural damping are the driving factors for flight stability and control. These characteristics are under strict control by structural requirement since these also affect payload (and subsequently Space Shuttle overall) dynamic response (mode and amplitude).

Space Shuttle payload is required to verify the flight-conditioned constrained stiffness above 5.1 Hz and structural damping above 1% (less than or equal to10Hz) / 2% (greater than 10Hz) of critical damping for lift-off and 1% of critical damping for landing. Also, all the major payload modes up to 50 Hz are required to be correlated to meet the requirement shown in Table 1. Stiffness requirement needs to be met to accurately estimate flight mode which affects flight stability and control as well as induced loads. Stiffness is also required to be linear based upon which structural analysis program is coded for its simplicity to accurately capture physical phenomenon. Structural damping requirement needs to be met to guarantee an induced load peak (amplitude) under which strength verification should be done in calculation.

These requirements need to be verified by modal survey test with flight model or flight-equivalent model, and if these requirements are not met, Payload developer and/or NASA need to perform additional analyses to judge that exceedance can be acceptable.

Table 1. Mathematical model correlation requirement

Model Verification Check	Correlation Requirement
Identify nonlinearities	Vary input excitation levels and reciprocity checks
Frequencies: comparison of analytical and test	Within 5 % for primary modes, within 10 % for secondary modes
Mass representation/Auto-orthogonality	Diagonals close to 1.0; off-diagonals less than 0.1
Mode shapes : comparison of analytical and test with cross-orthogonalities	Cross-orthogonality diagonals greater than 0.9; off-diagonals less than 0.1

C. Requirement of Strength

Strength is another key factor for flight safety. Strength can be verified by test and/or analysis with correlated model. There are two approaches recommended as strength verification such as applying 1.4 times of flight limit load to QT model with static correlation or applying 1.2 times of flight limit load to flight model or qualification model and verifying the strength for ultimate load by correlated model in analysis. Margin of safety needs to be applied 1.0 for limit load and 1.4 for ultimate load. Mathematical model error should be within 10% in displacement and within 20% in stress.

D. Requirement of Dynamic Clearance

Contact of payload with Orbiter is recognized as potential risk in flight safety because it might cause catastrophic accident. Since ISS modules were designed before Shuttle/Payload Interface Control Document had established conservative clearance requirement, NASA has been recently spent quite time to assess dynamic clearance assessment for safe flight.

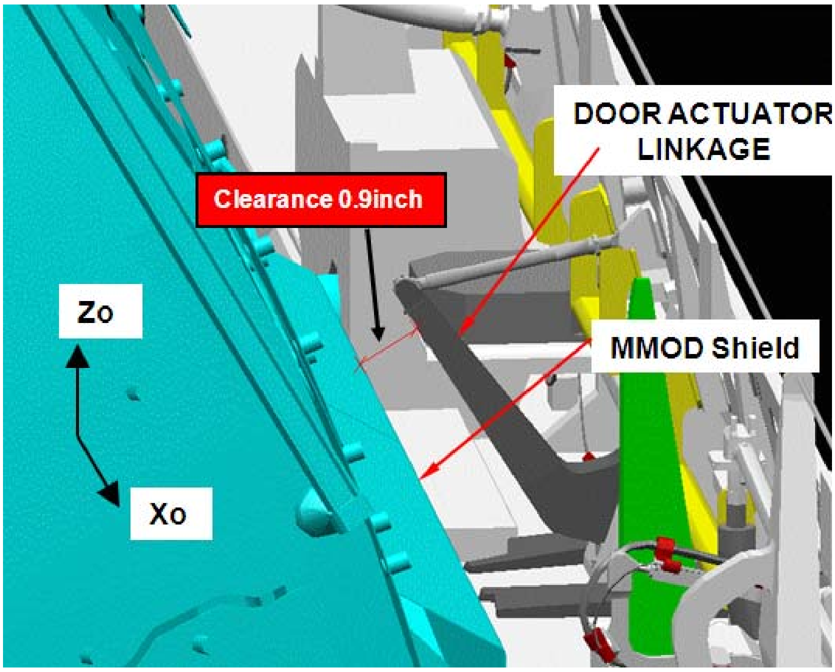

Figure 2. A sample of Dynamic Clearance of PM and Space Shuttle

III. Structural Compatibility with International Space Station

The JEM elements attached to ISS during on-orbit operation suffer many kinds of loads like an impact load at Russian vehicle docking, a load by acceleration at reboost, and a load by EVA activities of astronauts. These loads are calculated with Structural Math Model of whole ISS. Restraint condition of on-orbit structure analysis is different from that of flight phase analysis. In other words, the connection structure of the elements should be focused and the structural characteristics should be identified.

IV. Structural Compatibility Verification of JEM Elements

A. Verification of ELM-PS

The structure of ELM-PS is a pressure vessel to keep inside at an atmospheric pressure, and also it should resist external loads at launch and contingency landing phases of Space Shuttle flight and on-orbit load during being attached to ISS. ELM-PS has also debris bumpers against collision of space debris. ELM-PS has an integrated structure with AL2219. The structure as a pressure vessel was verified with STM for internal pressure. The flight model was verified with proof pressure and validated as healthy. The ELM-PS is supported by Space Shuttle latch mechanism inside the Space Shuttle at 5 trunnions, 2 primary trunnions and 2 secondary trunnions and a keel trunnion during flight configuration. The outline of ELM-PS structure is shown in Figure 3 and Table 2.

Figure 3. Outline of ELM-PS

Table 2. Outline of ELM-PS Structure

Main structure	Al-Isogrid panel Welded Cylindrical structure
Material	Cylinder: Al2219 Others: Al7075 Trunnion pin: INCONEL-718
Dimension	External diameter: 4.4m Internal diameter: 4.2m Length: 4.2m
Shuttle Interface	7 DOF support at 5 trunnion

The requirement of Structural Math Model eigenvalue frequency is larger than 25Hz for the racks installed in ELM-PS. However, that of PSSR is around 10Hz and this is natural because PSRR mostly consists of CTBs which are soft bags to carry components inside PSRR. The eigenvalue frequency around 10Hz can be resonant with Space Shuttle and high response of PSRR that can affect ELM-PS response can be thought in calculation. This phenomenon should reduce margin of safety in VLA beside of the real phenomena. We have conducted sensitive analysis to validate the effect of low frequency by white noise first, and conducted DCLA in succession with time history forcing function of Space Shuttle. As a result of that, we concluded that a normal way of VLA can be adapted to 1J/A VLA analysis. VLA result could verify the compatibility of ELM-PS to Space Shuttle. As a result of the final VLA, no issue was identified and our consideration was proved reasonable for ELM-PS modeling.

Modal survey of JEM ELM-PS in launch configuration was conducted and the math model was improved. The correlated model in launch configuration has been used for on-orbit loads analysis because modal survey test of the module in on-orbit configuration has not been performed. In order to validate the model for on-orbit loads analysis, fidelity of some parts has been additionally confirmed.

B. Verification of PM

The structure of PM is also a pressure vessel to keep inside at an atmospheric pressure like ELM-PS, and also it should resist external loads at launch and contingency landing phases of Space Shuttle flight and on-orbit load during being attached to ISS. The PM has also debris bumpers against collision of space debris. Experimental payloads and main subsystems are installed in racks with common dimension and installed to PM. PM has an integrated structure with AL2219. The structure as a pressure vessel was verified with STM for internal pressure. The flight models were verified with proof pressure and validated as healthy. The PM is supported by Space Shuttle latch mechanism at 5 trunnions, 2 primary trunnions and 2 secondary trunnions and a keel trunnion, during flight configuration. The outline of PM structure is shown in Figure 4 and Table 3.

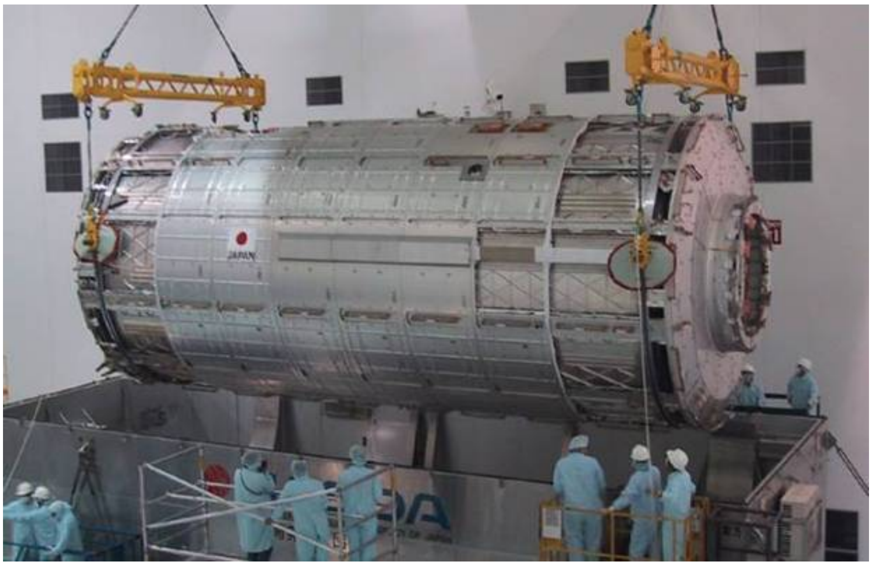

Figure 4. Outline of PM

Table 3. Outline of PM Structure

Main structure	Al-Isogrid panel Welded Cylindrical structure
Material	Cylinder: Al2219 Others: Al7075 Trunnion pin: INCONEL-718
Dimension	External diameter: 4.4m Internal diameter: 4.2m Length: 11.2m
Shuttle Interface	7 DOF support at 5 trunnion

-Negative structural margin

Due to the update of Space Shuttle mathematical model and forcing functions, it was found that positive M.S. can not be maintained at JEM-PM keel trunnion fitting (Figure 5). Keel trunnion pin is designed to restrain +/- Y motion of JEM-PM, and slides along X direction by sliding mechanism of trunnion latch of Orbiter. Since there is a certain amount of friction in sliding motion, JEM PM keel pin is subject to bending moment, and had negative M.S. at fitting structure.

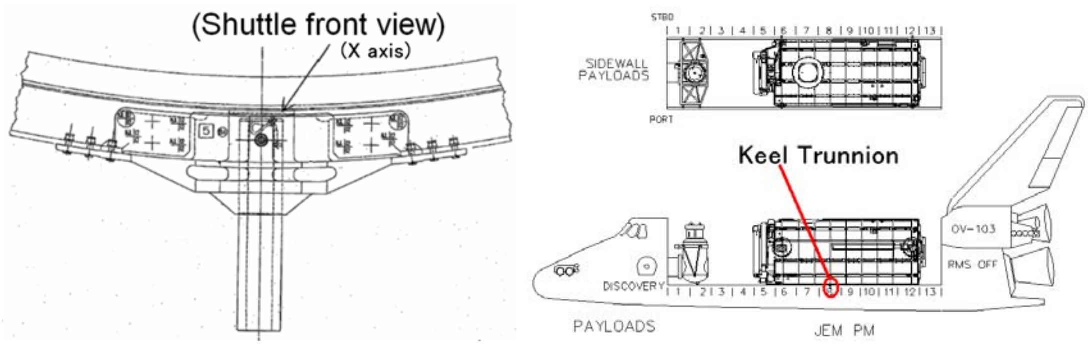

Figure 5. Keel trunnion of PM

During the discussion with NASA, it was also found that this fitting was modified in flight hardware to increase strength after completing mathematical model.

Therefore, first, bending stiffness was introduced from the original math model and we performed hammering test of keel pin to identify the bending stiffness of this fitting, then reflected this result into strength mathematical model. Physical properties are checked and boundary conditions between the fitting and main structure are also modified. Since it was still negative margin, JAXA performed non-linear analysis and judged if strain is under the limit (3% strain). Applied load was conservatively set by considering several factors, such as friction uncertainty and analytical error. Analysis shows 0.8% strain (Figure 6) and strength verification was approved.

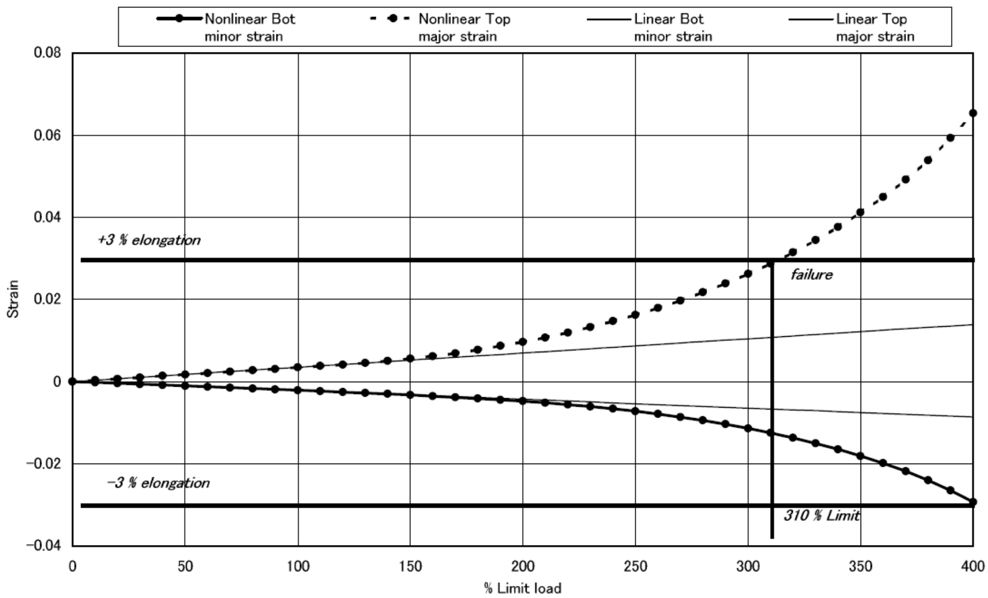

Figure 6. Result of non-linear analysis for keel trunnion

-Close clearance Interference

The dynamic interference of SRMS elbow camera was found in 2001 and had been left as open issue for long time (Figure 7). Predicted interference is 4.6 inch and some design change was definitely required. Once in 2003, with the status of low APM, NASA determined to offload SRMS itself from Flight 1J which can resolve the interference issue too. However, the Space Shuttle “Columbia” accident had this arm returned with the reason that SRMS is indispensable for Orbiter’s tiles (known as TPS (Thermal Protection System)) inspection and flight crew also expressed the necessity of its elbow camera for situational awareness in robotics operation.

The following countermeasures have been taken;

1) Removal handrail from JEM-PM (Figure 8)

2) Design change of wedge bracket of camera pan/tilt unit

3) More accurate assessment of multi-components dynamics by motion simulation solver.

4) Critical clearance points are measured their coordinate with tolerance less than 0.05” by 3D measurement, both for Orbiter side and JEM PM side.

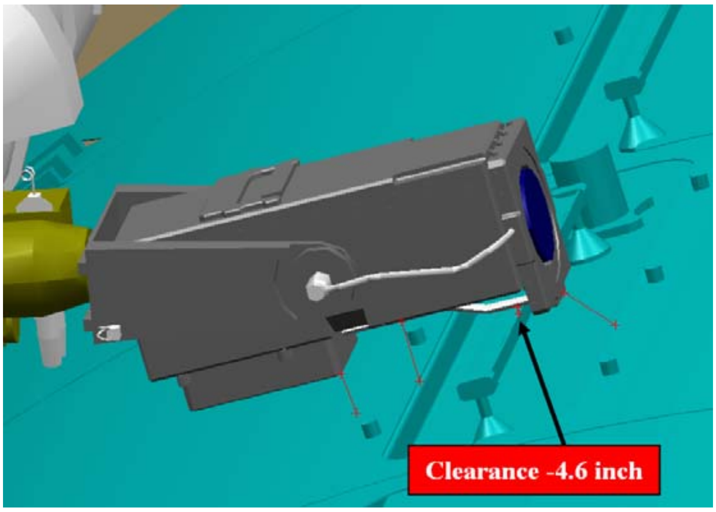

Figure 7. Interference of SRMS elbow camera to handrail

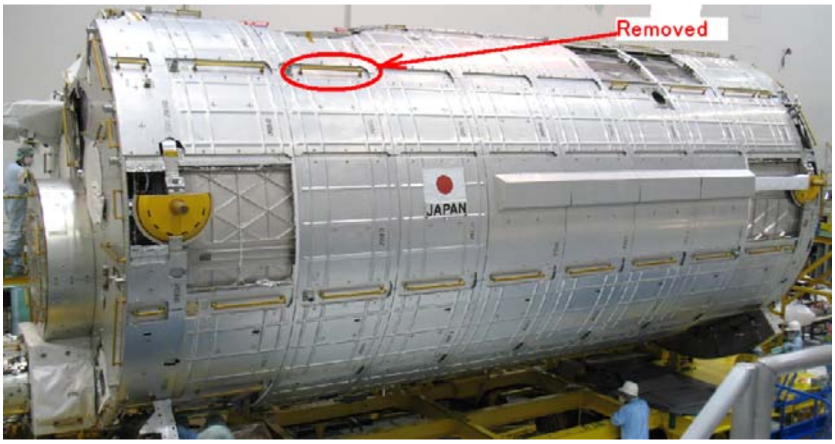

Figure 8. Removal handrail from JEM-PM

At L-1 month with these actions implemented, NASA figured out 0.2 inch in liftoff and 0.1 inch in abort landing” as the dynamic clearance. Since L-1 moth is the timing that all the mathematical models correlation has been completed and flight configuration has been completely fixed, the clearance requirement is “no negative number”, and this configuration has been finally approved for flight.

Modal survey of JEM-PM in launch configuration was conducted and the math model was improved. As Flight 1J cargo model, this model has been also approved with JEM-RMS installed. The correlated model of JEM-PM in launch configuration has been used for on-orbit loads analysis because modal survey test of the module in on-orbit configuration has not been performed. In order to validate the model for on-orbit loads analysis, fidelity of some parts has been additionally confirmed.

C. Verification of JEM-RMS

The main arm is the YPPPYR type arm with six degree of freedoms which consists of a boom, an elbow mechanism, an elbow electronics, an end effecter, and an elbow camera. The sub arm is the RPPPYR type arm with six degree of freedoms which consists of a boom, an electronics, an elbow, a camera, and end effecter. The outline of JEMRMS structure is shown in Figure 9 and Table 4.

Modal test of JEM-RMS in launch configuration was conducted and the detailed model was correlated with the test result. In this correlation, it was confirmed that stiffness of the joints (J1 and J2) which are dominant factors of the JEM-RMS mode in on-orbit configuration were sufficiently correlated.

For on-orbit analysis, JAXA decided to provide NASA with the stick beam model and correlated stick beam model with the detailed model. Based on a request from NASA to provide articulatable model, stick beam model correlated with the detailed model was re-defined to be articulatable and provided to NASA.

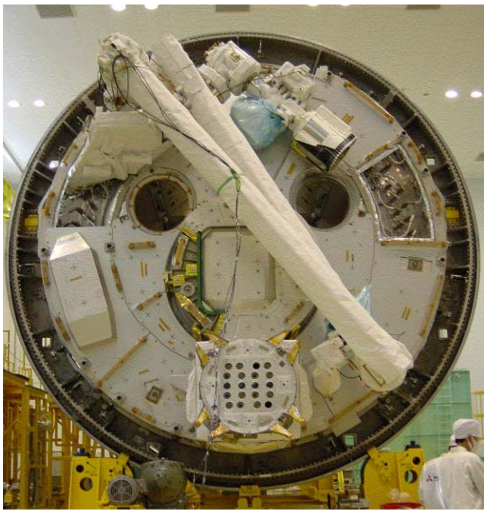

Figure 9. Main Arm installed to PM (Flight Configuration)

Table 4. Outline of JEMRMS Structure

Main structure	Arm with 6 DOF Joints
Material	Arm: CFRP tube structure
Dimension	Main Arm length: 9.9m Sub Arm length: 1.9m
Shuttle Interface	Supported at 4 points by PM

D. Verification of EF

Figure 10 and Table 5 show the outline of EF. Main structure of EF is panel/Frame structure made of Al7075 alloy. The EF is supported by Space Shuttle latch mechanism at 5 trunnions during flight configuration. The EF will be connected to PM on orbit by EFBM. EFBM passive on EF and EFBM active on PM will be connected with 4 latch bolts.

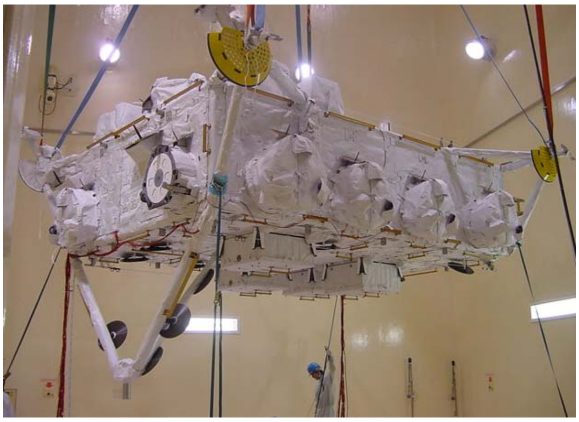

Figure 10. Outline of EF

Table 5. Outline of EF Structure

Main structure	Al-Panel/Frame structure
Material	Panel/Frame: Al7075 Trunnion pin: INCONEL-718
Dimension	Width: 5.0m Height: 4.0m Length: 5.6m
Shuttle Interface	7 DOF support at 5 trunnion

Verification result of EF Structural Math Model for flight phase combined with Space Shuttle model is as below. The modal test of EF was conducted with EF main structure, which is supported at interface points by Space Shuttle, and dummy mass for second structure. The test configuration is shown at Figure 11. The acceleration sensors are placed to obtain the mode shape formerly analyzed and targeted to meet the correlation requirements shown in Table 6. The correlation of structure mathematics model was conducted based on the test result and it was verified that the requirement was satisfied as shown in Table 6.

The final verification load analysis was conducted by NASA with the correlated structure mathematics model and no issue was validated for shuttle flight. The EF will be launched in June 2009 with ELM-ES by Space Shuttle.

Figure 11. Modal test configuration of EF

Table 6. Correlation result of EF structure

	Test Results							
Analysis Results	Mode No.		1	2	3	4	5	6
		Freq. [Hz]	8.47	12.34	16.43	19.3	27.28	32.74
	1	8.18	0.99	-0.06	0.01	-0.04	0.01	0.07
	2	12.43	0.07	0.99	0.07	0.07	-0.03	0
	3	16.07	-0.01	-0.06	0.99	0	-0.01	-0.02
	4	19.84	-0.04	0.07	-0.01	-0.99	0.02	-0.09
	5	26.11	0.01	0.05	0.02	-0.01	-0.98	-0.03
	6	32.03	0.01	0	-0.01	-0.04	0.02	0.97

At the modal survey test of EF, stiffness around both Exposed Facility Berthing Mechanism (EFBM) support structure and Exposed Facility Unit (EFU) support structure were confirmed. As for EFBM support structure, frequency differences are within 5% for first two bending modes (mode #1 & #2) and about 15% for torsion mode (mode #3). As for EFU#1 support structure, frequency difference is about 1% for EF in-plane bending mode and about 9% for EF out-of-plane bending mode. Based on these results, correlation for EFU support structures at both forward and aft sides of EF were completed for on-orbit.

E. Verification of ELM-ES

Figure 12 and Table 7 show the outline of ELM-ES. Main structure of ELM-ES is grid-panel structure made of Al7075 alloy. The ELM-ES is supported by Space Shuttle latch mechanism at 5 trunnions during flight configuration. The ELM-ES will be connected to EF on orbit by EEU. EEU passive (PIU) on ELM-ES and EEU active (EFU) on EF will be connected with 3 latch arms. ELM-ES can accommodate 3 payloads via Payload Attachment Mechanism (PAM) for launch.

Figure 12. Outline of ELM-ES

Table 7. Outline of ELM-ES Structure

Main structure	Al-grid Panel structure
Material	Grid panel: Al7075 Trunnion pin: INCONEL-718
Dimension	Width: 4.9m Height: 2.2m Length: 4.2m
Shuttle Interface	7 DOF support at 5 trunnion

-Non-linear stiffness of structural latch mechanism

Structural Latch Mechanism (SLM) is one of the system component of ELM-ES that is manifested in STS-127 (Flight 2J/A) (Figure 13). The function of this mechanism is to structurally support EF-payloads on ELM-ES during flight. Figure 14 shows how to hold EF-payload trunnion.

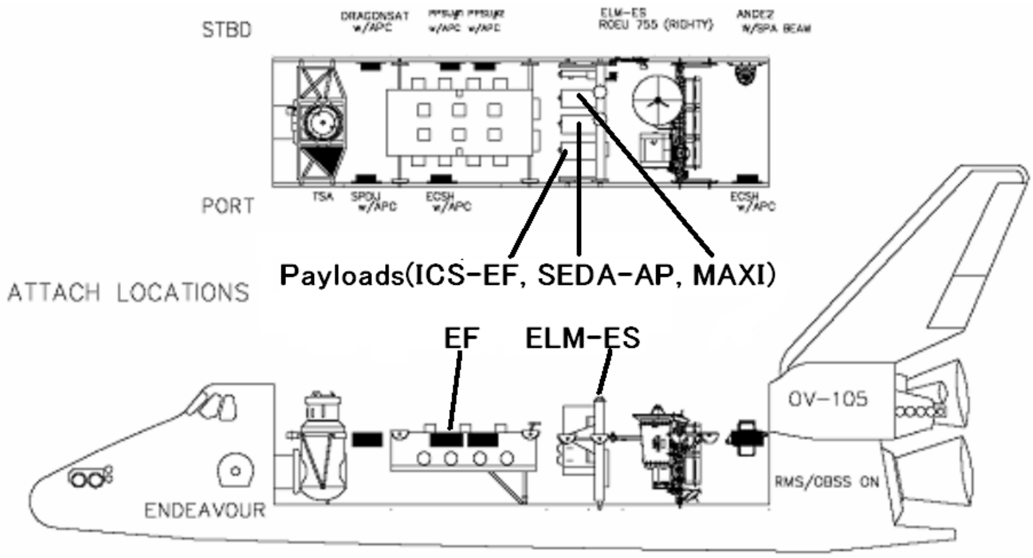

Figure 13. Flight 2J/A Cargo Manifest

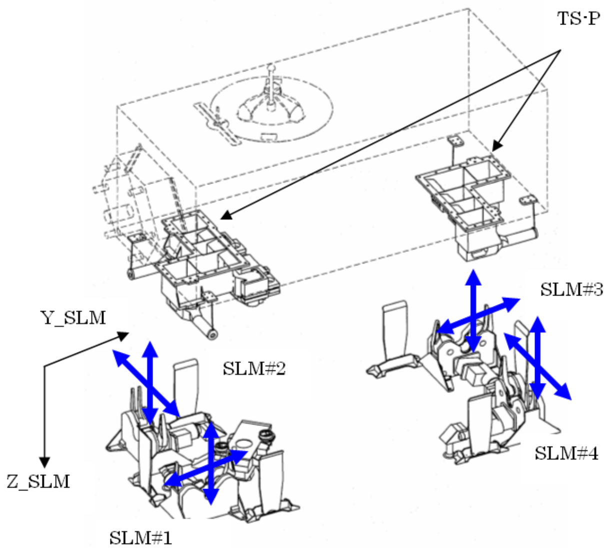

Figure 14. SLM configuration for supporting trunnion

The SLM should be preloaded enough to keep stiffness linear for flight-induced loads at EF-payload trunnion. The external load, however, is subject to change in development phase due to mathematical model and/or forcing functions update and also design change of EF-payload (ICS-EF, SEDA-AP, MAXI), and external load actually increased even after ELM-ES was completed. As a result of that an external load exceeded SLM holding capability. Since SLM stiffness can not guarantee its linearity any more, JAXA decided to increase diameter of trunnion to increase preload for two EF-payloads (SEDA-AP and MAXI). Only one EF-payload (ICS-EF) can not be subject of this design change due to schedule impact and hardware damage risk, and it was required to assure linearity in a different manner.

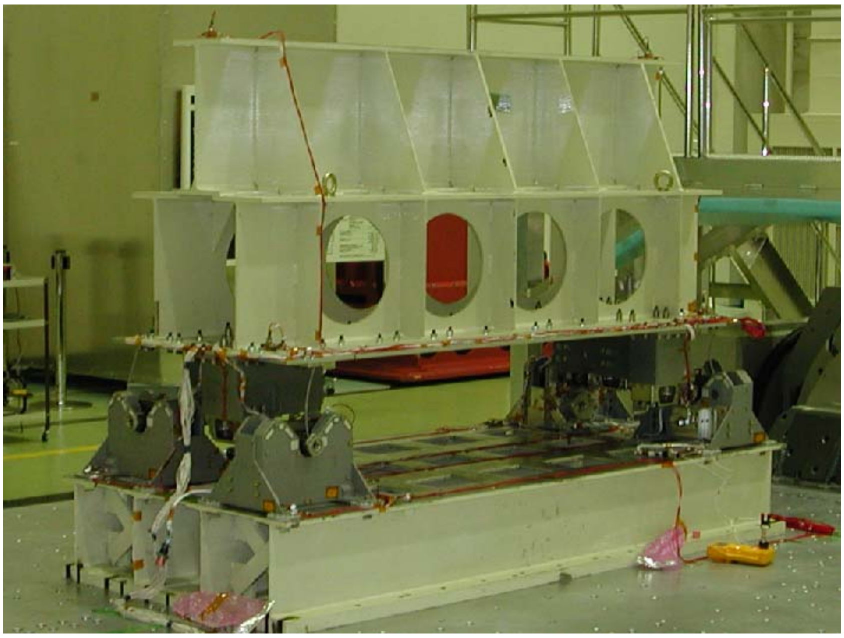

Figure 15. Vibration test for examining damping

In order to understand actual dynamics, JAXA performed vibration test with engineering model (Figure 15) and obtained effective damping factor. With this damping factor considered in NASTRAN, it was found that external load is decreased lower than preload and expected response is in linear range in stiffness (Figure 16). JAXA coordinated with NASA on how such unique damping factor should be set in VLA. As a result that we have concluded that there will be no issue with that.

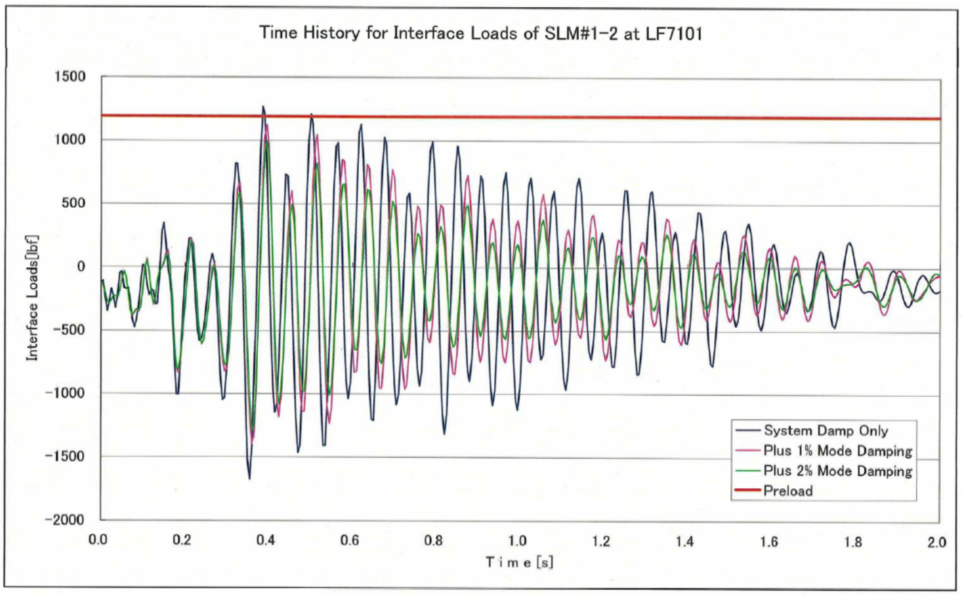

Figure 16. Comparison between preload and response

Modal survey test of ELM-ES simulating on-orbit configuration was performed and the structural math model was correlated to the test results. At the modal survey test, ELM-ES was air-supported and a mass dummy was attached to the Payload Interface Unit (PIU). Torsion modes of the ELM-ES structure, which will affect on ELM-ES / Payloads interface loads, were not selected as target modes because these interface loads are not critical for on-orbit but for launch phase. After the modal survey test, PIU stand was modified to be releasable by EVA crew. Therefore, correlation of the ELM-ES structural math model was performed by the following steps.

Stiffness of the PIU stand before the modification was reflected to ELM-ES structural math model based on the stiffness test results. ELM-ES structural math model was correlated with the modal survey test without changing characteristics of the PIU stand. Frequency differences between test and analysis are less than 0.2% and they meet the requirement (within 5%). Stiffness of the modified PIU stand was reflected to the modal survey test-correlated ELM-ES model based on the stiffness test results.

V. Conclusion

Structure verifications of the three flights have completed and the flights have been successfully conducted. On-orbit analysis results have been used without problem. They proved our activities of structure verification were properly accomplished.

The experience acquired by the development of JEM structure should contributes to our future activities on the development of Japanese manned space systems. The era of realizing Japanese original manned space system is around the corner.