Use of Shuttle Heritage Hardware in Space Launch System (SLS) Application-Structural Assessment

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Abstract

NASA is moving forward with the development of the next generation system of human spaceflight to meet the Nation's goals of human space exploration. To meet these goals, NASA is aggressively pursuing the development of an integrated architecture and capabilities for safe crewed and cargo missions beyond low-Earth orbit. Two important tenets critical to the achievement of NASA's strategic objectives are Affordability and Safety.

The Space Launch System (SLS) is a heavy-lift launch vehicle being designed/developed to meet these goals. The SLS Block 1 configuration (Figure 1) will be used for the first Exploration Mission (EM-1). It utilizes existing hardware from the Space Shuttle inventory, as much as possible, to save cost and expedite the schedule. SLS Block 1 Elements include the Core Stage, "Heritage" Boosters, Heritage Engines, and the Integrated Spacecraft and Payload Element (ISPE) consisting of the Launch Vehicle Stage Adapter (LVSA), the Multi-Purpose Crew Vehicle (MPCV) Stage Adapter (MSA), and an Interim Cryogenic Propulsion Stage (ICPS) for Earth orbit escape and beyond-Earth orbit in-space propulsive maneuvers.

When heritage hardware is used in a new application, it requires a systematic evaluation of its qualification. In addition, there are previously-documented Lessons Learned (Table -1) in this area cautioning the need of a rigorous evaluation in any new application. This paper will exemplify the systematic qualification/assessment efforts made to qualify the application of Heritage Solid Rocket Booster (SRB) hardware in SLS. This paper describes the testing and structural assessment performed to ensure the application is acceptable for intended use without having any adverse impact to Safety. It will further address elements such as Loads, Material Properties and Manufacturing, Testing, Analysis, Failure Criterion and Factor of Safety (FS) considerations made to reach the conclusion and recommendation.

Introduction

NASA is aggressively moving forward with development of the next generation human spaceflight system to meet the Nation's goals of human space exploration as expressed in the 2011 NASA Strategic Plan (Reference 1):

- Strategic Goal 1 – Extend and sustain human activities across the solar system.
- Strategic Goal 1.3 – Develop an integrated architecture and capabilities for safe crewed and cargo missions beyond low-Earth orbit.

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To meet this goal, with limited resources and an expedited schedule, affordability is a key driver. Hence, use of existing heritage hardware from Space Shuttle inventory is a major part of the SLS Program (SLSP).

The SLS is a heavy-lift launch vehicle being developed and designed to meet these goals and to provide affordable solutions to meet NASA's long-term exploration goals (Reference 2). The SLS Block 1 configuration is used for the first launch, EM-1.

SLS Block 1 Elements include the Core Stage, Heritage Boosters, Heritage Engines, ISPE LVSA, a Separation System, the MPCV MSA, and ICPS for Earth orbit escape and beyond-Earth orbit in-space propulsive maneuvers. Figure 1 illustrates the elements of the SLS Block 1 configuration.

NASA has a rich history in spaceflight and the development of various spacecraft for space exploration spanning over 50 years, beginning with the Mercury spacecraft, initiated in 1958 and completed in 1963, to Gemini and the Apollo programs, followed by the Space Shuttle Program and International Space Station.

The heritage or legacy of technical vulnerabilities, successes, and failures are well documented as technical reports and other reference materials, such as databases, technical requirements, and guidelines in the form of Standards and Specifications and System Engineering and Integration processes (Reference 4), as well as independent verification and validation processes.

Heritage Boosters (leftover inventory from the Space Shuttle Program) are integrated to the SLS Core Stage by forward structural attach points in the Booster Forward Skirts and aft attach points on the Booster aft segments. The Boosters also provide the main structural attach points to the mobile launcher and support the mass of the integrated vehicle prior to launch. However, these SLS Boosters utilize five segments instead of four (and do not have parachutes for recovery), as compared to the Space Shuttle Heritage Boosters. Also, for SLS missions, Boosters will be jettisoned and disposed of in the Atlantic Ocean once their propellant has been consumed, and will not be reused, as was the practice during the Space Shuttle Program.

The application of leftover Space Shuttle inventory SRB hardware in the SLS architecture introduces a challenge, as it is important to ensure that, in this new application, use of previously used Booster components meets all the structural and functional requirements. Initially, it was generally understood that the hardware application is very similar to Shuttle and, as such, heritage qualification may be sufficient with very little additional effort. However, as more knowledge was gained and loads were developed for this new architecture, it was subsequently noticed that the structural change (e.g., relocation of the aft attachment to a different location, along with five segments) will result in loads exceeding those experienced in the Space Shuttle Program at the forward thrust post region. In addition, these design loads exceeded the qualification loads used during the Space Shuttle Program, thus negating the heritage application.

Though there have been numerous successes in spaceflight, the failures remind NASA engineers and program managers that spaceflight and the design and development of spacecraft are, and will always remain, a high-risk technological undertaking; therefore, the use of heritage hardware in a new application requires special consideration, and understanding of the Lessons Learned becomes a very important criterion. Lessons Learned should be carefully assessed and addressed in the design space for the development, qualification, validation, and verification of next generation spacecraft hardware. Engineers and designers are very mindful of the pitfalls of using "heritage" as verification and validation for hardware and software as they seek to minimize the full range of needed independent verification and validation, especially when the heritage data may not be quite applicable. In general, heritage hardware should be used very cautiously in a new program, and only after a rigorous assessment of the applicability of similarity is validated and verified, since it is very rare that heritage hardware is either produced using identical procedures and/or used in identical applications.

In addition, Lessons Learned numbers 2, 3, 4, and 6 (Table 1) documented by Charles Gunn in Launch Space Magazine, January 1999, demonstrate the sensitivity and interdependency of complex spacecraft systems and their impact on the success or failure of a mission.

Work Description

Based upon these observations and Lessons Learned, it was determined that a new qualification plan needed to be instituted to ensure suitability of Space Shuttle Heritage Boosters in the SLS application. This paper delineates the steps taken to establish a rationale for qualification of this hardware for the SLS application addressing all of these identified salient Lessons Learned and interactions (Table 1) in detail. The following is a brief summary of all key parameters (Figure 2) addressing critical disciplines and an assessment made to justify the acceptance of Space Shuttle Heritage Boosters within the SLSP.

Loads

The primary purpose of the SRB Forward Skirt is to support the core vehicle prior to launch and act as the axial thrust take-out point from the Booster to the core vehicle during flight. Pre-launch loads consist of rollout, on-pad stay, and core engines thrust buildup. The critical load cases for the Forward Skirt consist of compression loads that occur during SRB Ignition up to Pre-staging, where the SRB is pyrotechnically released from the Core Stage.

The SRB thrust is greater than the Core Stage thrust during the initial flight profile. The difference in thrust, combined with the weight of the SRBs and Core Stage induce a state of compression at the interface. Due to the increase in mass of the Core Stage for the SLS vehicle compared to the Space Shuttle vehicle, primary interface loads during flight are approximately 40 percent higher compared to the loads used to qualify the Space Shuttle Boosters.

Luckily, the predominant load experienced at the Forward Skirt Booster-to-Core Stage interface post is statically determined and can be developed knowing the thrust profile of the Boosters along with the mass of the Boosters and vehicle acceleration at various stages of flight. In addition, the maximum load experienced occurs during ascent near the time of maximum vehicle acceleration. Since loads were deterministic and key parameters/variables are understood to a high degree of confidence level, three sigma axial loads can be developed using the following equation.

$$\text{Fwd Attach Load} = \text{Booster Thrust} - \text{Booster Mass} * \text{Vehicle Accel}_x$$

Due to the design of the interface, this axial load produces a large moment that is reacted over a relatively small fillet area that is machined into the thrust post forging. This moment produces high surface strains that require a detailed assessment to assure that the structural integrity for flight application meets NASA design and construction standards, per NASA-STD-5001, “Structural Design and Test Factors of Safety for Spaceflight Hardware,” (Reference 3).

Material Properties and Manufacturing

The SRB Forward Skirt structural assembly (Figure 5) is an all-welded, ring-stiffened, monocoque cylindrical shell, primarily manufactured from 2200 Series Aluminum alloy by McDonnell Douglas in two increments between 1975 and 1984. The Forward Skirt is located between the Nose Cap/Frustum and Forward Motor Case. The skin is machined to various thicknesses around the circumference of the shell, with the forward ring, thrust post fitting, and attach rings machined from special forgings. The thrust post fittings are machined down from larger forgings with stepped thicknesses. The fittings are welded into the Forward Skirt cylinder with full-length, full-penetration welds.

Testing

As stated earlier, the SLS design loads are much higher compared to loads experienced during Space Shuttle flights. The significantly higher loads changed the response of the thrust fitting hardware from elastic to highly plastic for SLS and positive margins of safety could not be shown with traditional agency methodologies. This drove the need for instituting a new test program to anchor analytical results to assure the acceptance of hardware in this new application.

Structural testing of the Heritage Forward Skirt was performed for the SLSP in 2014 (Figure 6). Two Forward Skirts were randomly chosen from inventory. The first test sequence included the worst case lift-off load conditions at 1.0 x limit load, followed by the most critical ascent conditions to 1.1 x limit load. The test article was then disassembled and inspected for permanent deformation and any other visual damage. The test article subsequently reassembled and tested to 1.4 x limit ascent load. The second test sequence consisted of six liftoff load cases taken to 1.0 x limit load, followed by the six liftoff cases taken to 1.4 x limit load. Two ascent load cases were then tested to 1.0 x limit load. Both tests concluded with taking the Forward Skirt to failure by ramping up to the 1.4 x limit ascent condition, holding the radial component constant, and increasing the compression load until load carrying capability was lost (Figure 7).

Extensive strain data were acquired from strain gauges and the use of ARAMIS (Reference 19) digital photogrammetry systems. Displacement data were acquired using string potentiometers, and acoustic emission detectors were employed to help determine crack initiation. A total of 421 strain gauges, deflection gauges, acoustic emission detectors, and instrumented pins were used during testing to monitor the structural status of the hardware. Pre-test analysis and Space Shuttle flight instrumentation results were used to determine instrument locations.

Both test articles failed well above the maximum predicted limit load for SLS, and pre-test analytical predictions due to crack initiation and growth across the fillet radius of the fitting. After the thrust post cracked, the gussets supporting the shelf buckled prior to the load removal. Axial, radial and tangential loads were applied during testing to simulate flight, including loading and unloading to account for Pad shutdown, etc.

Strain gauges and ARAMIS were located on the region of failure and compared well with each other (Figures 8 and 9). Due to loading events prior to testing to failure, there was residual strain in the fillet regions. Strain readings were post-processed to determine accuracy and verify total strain at failure. ARAMIS results were able to capture the peak strain where crack initiation occurred. The strain gauge was offset from this location by a couple of inches. Comparison between the ARAMIS major strain and the strain gauge readings at the critical radii are shown in Figure 9. The ARAMIS strain at failure (Figure 9) was consistent with the ultimate failure strain noted during lot acceptance for this material (thick forging).

In addition, post-test material samples were cut from the failed forgings to determine material-specific properties for fracture assessments and effective strains versus triaxility factors for use in Fracture mechanics to establish critical initial flaw size and safety factors.

Analysis

Structural acceptability of metal structures can be determined with linear-elastic or elastic-plastic finite element analysis. Linear-elastic analyses produce stresses that are compared to the material allowable ultimate strength. Elastic-plastic analysis produces strains that are compared to the allowable material elongation. The majority of Booster hardware used for the Space Shuttle Program was designed to utilize the linear-elastic approach. However, in SLS application, due to the large amounts of yielding predicted and noted during testing, this is no longer a valid approach and requires much more detailed elastic-plastic analysis.

Two independent models (Figures 12 and 13) were developed by two different groups, one using a combination of Nastran and ABAQUS Finite Element Programs (Reference 17) and one using ANSYS (Reference 18). Pre-test analysis predicted failure right at the ascent limit load in the inner bore region of the thrust post, directly below the compression loading. Test results showed the failure actually occurred in the fillet region at a much higher load, prompting an evaluation of alternate approaches to evaluate the capability.

A detailed, finite element submodel was constructed using ANSYS to correlate strain gauge and ARAMIS data in the test configuration. This test model included actuators and associated loading hardware to more accurately validate results.

The testing sequences were applied to the model in the order that they were applied in the actual testing. The principal stresses, von Mises stress, and total equivalent strain in the region of fracture initiation were developed (Figure 15) for every node, and a triaxiality factor was calculated. Both independent models did a good job in predicting the strains noted in the test.

Material Properties

To determine the flight configuration minimum FS, ascent temperature conditions, minimum stress-strain curves, and refurbishment conditions were taken into account using the material properties established using forgings representing flight hardware and near critical radii region, since material properties vary through thickness. In addition, testing was performed at "ambient" conditions, whereas, thermal analysis predicts that, for a hot day during flight, worst-case material radii temperature may exceed ambient temperature on the ground (Figure 14). Material properties were adjusted for temperature using standardized Metallic Materials Properties Development and Standardization (MMPDS, Reference 4) methodologies.

Factor of Safety and Failure Theory

Pre-test analyses evaluated the Forward Skirt hardware using the Constant Critical Strain Criteria methodology, where failure occurs at the same critical strain no matter what the stress state is. The FS using strain is determined by:

FS = e/EPTO

e = elongation strain from material testing

EPTO = total equivalent strain determined at 1.4 x limit load from an elastic-plastic analysis with the minimum required stress-strain curve.

However, research has shown that ductile failure of metallic structures consists of three phases:

1. Accumulation of damage caused by plastic strain
2. Initiation of fracture
3. Fracture propagation resulting in failure

Hence, a judicious approach was utilized and various damage initiation criteria were developed to quantify the damage associated with plastic strain and to predict the strain-to-crack initiation. Three triaxiality based damage initiation criteria were selected that had correlation data with aluminum material testing:

1. Johnson-Cook
2. Bao-Wierzbicki
3. Mohr-Coulomb

A comprehensive study of References 6-17 and a rigorous test program were undertaken to determine the appropriate failure criteria to evaluate the actual structural capability of the hardware. Test results were correlated with multiple Finite Element Models (FEM), and it was determined that the Bao-Wierzbcki equivalent strain-versus-triaxiality factor method more closely matched the test data. The test data and finite element analysis results were used to create a Bao-Wierzbicki indicator curve (Figure 15) that is used to predict failure of the thrust post. As shown below, the primary ascent load is applied to the model, and the total equivalent strain is plotted against the triaxiality factor. The load is increased until the analysis data intersects the derived indicator line. The amount of above limit load where this occurs is the FS.

Fracture Mechanics

Similar to how Strength properties were derived from forgings representing the flight hardware, a detailed test program (Figure 16) was established to develop the fracture toughness properties of the material representing (adjusting for ultimate strain) the forward post radii region. These material properties were used along with the expected fatigue spectrum to predict the critical initial flaw size for establishing the appropriate nondestructive inspection.

Images, Figures, and Tables

Lessons Learned

External, independent review teams judging the flight readiness of a vehicle should keep in mind the following key lessons gleaned from the past 20 years of space launches:

1. Propulsion systems are the primary cause of all launch failures. All propulsion test and checkout anomalies/failures demand special attention and review.
2. Hardware built out of normal sequence and hardware that has been reworked are major causes of failures. The processes, procedures, quality inspections, and particularly the re-test results demand special review.
3. There are no small, inconsequential changes in flight-critical components or subsystems. Systems engineering and every affected technical discipline must be involved in the assessment of all new systems and their changes. If a change is not recertified by test, the rationale must be thoroughly examined.
4. Test results that are "in-family," but near the edge of the acceptable envelope, should be thoroughly examined. Usually there is a subtle message. Always believe test data until they are conclusively proved wrong beyond all doubt.
5. All test anomalies/failures must be thoroughly understood and convincingly explained. All hardware that is potentially related to an unverified system anomaly/failure must be purged from the system before launch.
6. The flight environments and dynamic loads that set the qualification and acceptance test levels of each flight-critical component must be *rigorously* validated by a continuum of flight measurements and analyses.

Table 1

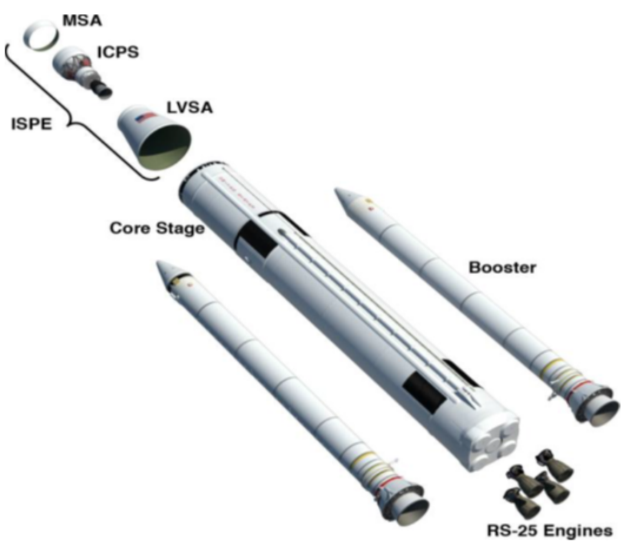


Figure-1 SLS Architecture

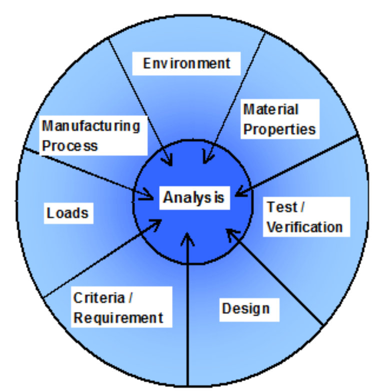
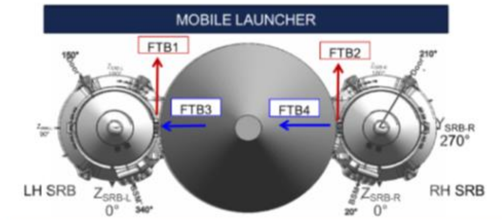


Figure-2 Key Parameters



Booster	Indicator	Direction	Description
Left	FTB1	Transverse	Toward the fwd skirt door is positive (+)
	FTB3	Radial	Radial inward is positive (+)
	FTB5	Axial	Compression is negative (-)
Right	FTB2	Transverse	Toward the fwd skirt door is positive (+)
	FTB4	Radial	Radial outward is positive (+)
	FTB6	Axial	Compression is negative (-)

Figure-3 Load locations and directions

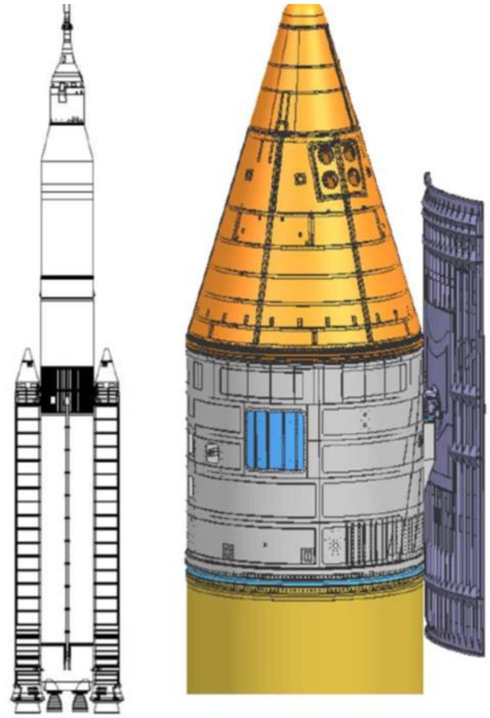


Figure-4: Forward Post Attach Point

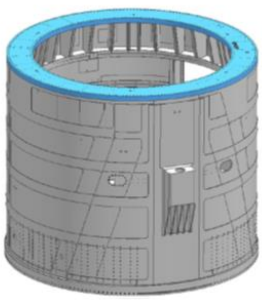


Figure-5: Forward Post

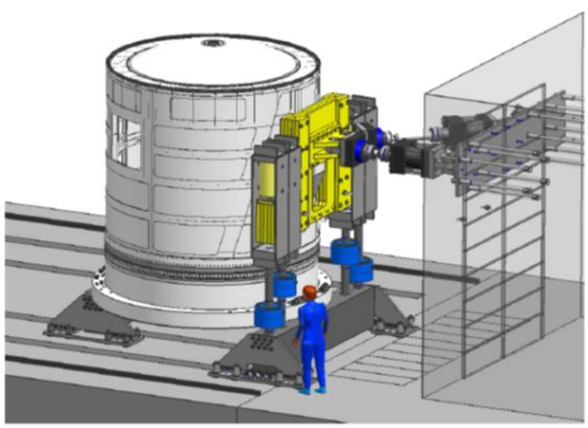


Figure-6 Test Configuration

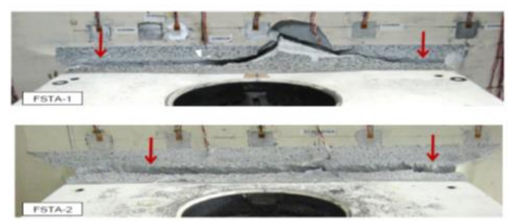


Figure-7 Initial failure location

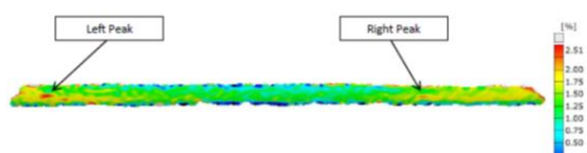


Figure-8 ARAMIS results at failure

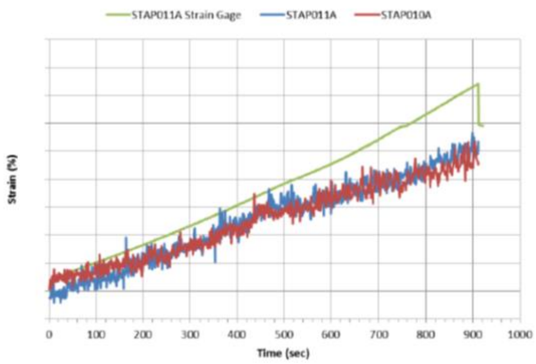


Figure-9 Measured Strains at critical failure location and analysis comparison

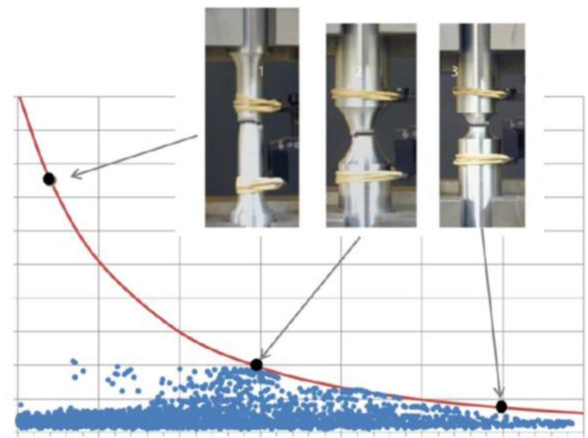


Figure-10: Development of Triaxiality factor
(total equivalent strain vs. Triaxiality factor)

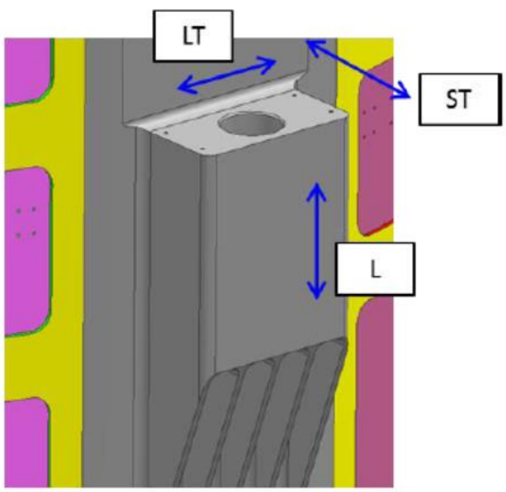


Figure- 11 Grain directions

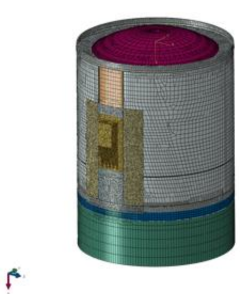


Figure-12 Global FEM Model

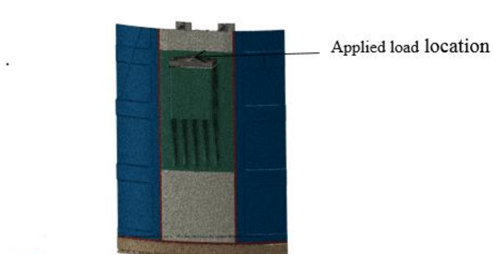


Figure-13 Sub model

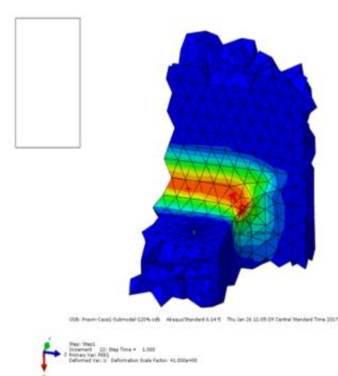


Figure-14 Peak strain location in radii

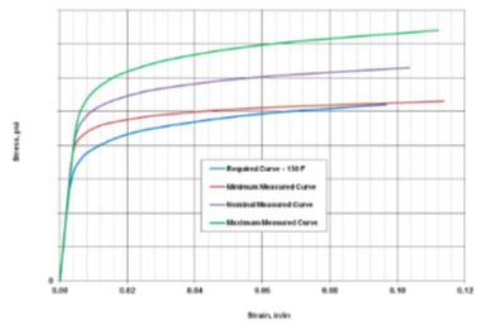


Figure-14 Stress-Strain Curves

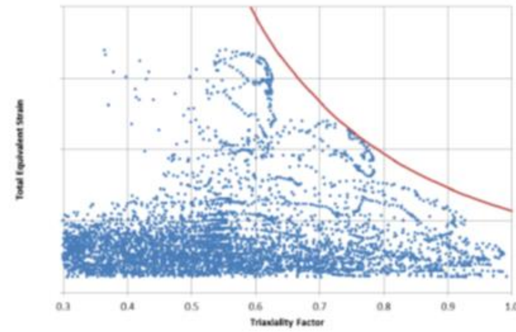


Figure-15 Triaxiality Factor versus Total Equivalent Strain at expected load

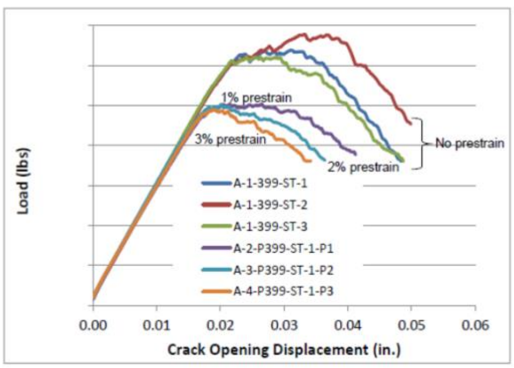


Figure-16 Crack Opening Displacement Testing for various pre-strains

Conclusion

A high degree of confidence in understanding of loads, material properties, failure phenomena anchored with analysis, and testing representing flight was instrumental in requalifying the "heritage hardware" in this new application. Key parameters that yielded this confidence include:

1. Well understood loads.

2. Detailed full-qualification testing of two units representing flight hardware.

3. Detailed FEM

   - Independent FEM/Analysis by NASA/MSFC.

   - Model correlated to test.

4. Failure criterion based upon triaxiality factor to account for "strain-to-crack" to guard, since material exhibits "brittle" behavior.

   -Modified to account for minimum "test-established" material properties/refurbish radii.

5. Hardware representing strength and fracture properties.

In addition, the SLSP has decided to add insulation in the critical radii region to provide additional protection against thermal-degraded properties (i.e., additional margin). The execution of a detailed test and qualification program and use of a more advanced analysis methodology, described herein, were directly responsible for expediting the schedule and saving the SLSP tens of millions of dollars that it would have cost to design, develop, and qualify a new Forward Skirt. This paper details the key drivers shown in Figure 2, addresses an approach for proper qualification of heritage hardware in new flight application, and meets NASA's two important tenets for Exploration Systems Development (ESD), Affordability and Safety.

Acknowledgments

We appreciate the work done by the team of engineers and technician at MSFC and Orbital Alliant Tech Systems in developing and executing the tests and analyses to help establish the Flight rationale for the Space Shuttle heritage hardware in SLS application. This paper takes advantage of the reports published to document the tests and analyses for developing the Flight rationale and was not possible otherwise; however, these references are not cited herein due to potential conflict with International Traffic in Arms Regulations.

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