

Design/analysis of the JWST ISIM bonded joints for survivability at cryogenic temperatures

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ABSTRACT

A major design and analysis challenge for the JWST ISIM structure is thermal survivability of metal/composite bonded joints below the cryogenic temperature of 30K (-405°F). Current bonded joint concepts include internal invar plug fittings, external saddle titanium/invar fittings and composite gusset/clip joints all bonded to M55J/954-6 and T300/954-6 hybrid composite tubes (75mm square).

Analytical experience and design work done on metal/composite bonded joints at temperatures below that of liquid nitrogen are limited and important analysis tools, material properties, and failure criteria for composites at cryogenic temperatures are sparse in the literature. Increasing this challenge is the difficulty in testing for these required tools and properties at cryogenic temperatures. To gain confidence in analyzing and designing the ISIM joints, a comprehensive joint development test program has been planned and is currently running. The test program is designed to produce required analytical tools and develop a composite failure criterion for bonded joint strengths at cryogenic temperatures. Finite element analysis is used to design simple test coupons that simulate anticipated stress states in the flight joints; subsequently the test results are used to correlate the analysis technique for the final design of the bonded joints.

In this work, we present an overview of the analysis and test methodology, current results, and working joint designs based on developed techniques and properties.

Keywords: Composite, Joint, Bond, Adhesive, Cryogenic, CTE, Finite Element Analysis (FEA)

1. BACKGROUND

The James Webb Space Telescope (JWST) is a deployable telescope designed to study the origin and evolution of galaxies, stars, and planetary systems. The telescope is developed by an international collaboration of American, Canadian, and European space agencies with NASA Goddard Space Flight Center as the mission lead. Launch is currently scheduled for 2011 on an Ariane-5 expendable launch vehicle. To accommodate the very cold temperatures required for optimizing infrared observations, the observatory will be placed in the Sun-Earth L2 orbit (second Lagrange point for the Sun-Earth system), $1.5E10^6$ km from the Earth. Further temperature reduction of critical instruments down to an operating temperature of ~30K will be accomplished by means of a deployable sunshield. The observatory is comprised of three primary elements, the Optical Telescope Element (OTE), the spacecraft, and the Integrated Science Instrument Module (ISIM) element. The sunshield separates the observatory into a sun facing side and a cold anti-sun side, which includes the OTE and ISIM.

The ISIM is a distributed system consisting of three science instruments and a fine guidance sensor. It provides structure, environment, and data handling for the instruments and fine guidance sensor. The ISIM structure to which the instruments and sensor are supported by is a composite truss structure with biased composite tubes, quasi-isotropic (QI) composite gussets, metallic clips, and metallic internal and external joint fittings (Figure 1). The primary technique of attaching all components of the structure is through adhesive bonding.

Primary load environments for the structure include launch loads and on-orbit thermal loads. For the design and analysis of the bonded joints, the most challenging requirement is thermal survivability from room temperature

(assembly and cure temperature for the joints) to the operating temperature of 30K and survival temperature of 22K. The truss tubes and the joint components must be strong and stiff for surviving launch loads and meeting fundamental frequency requirements. Conversely, the tubes and joints must be compliant at cryogenic temperatures to mitigate temperature stresses due to CTE mismatches and the large temperature excursion from assembly to operation. For a robust structure and joint designs, positive strength margins with a factor of safety (FS) of 1.5 is required to be shown analytically for all joints under all load environments.

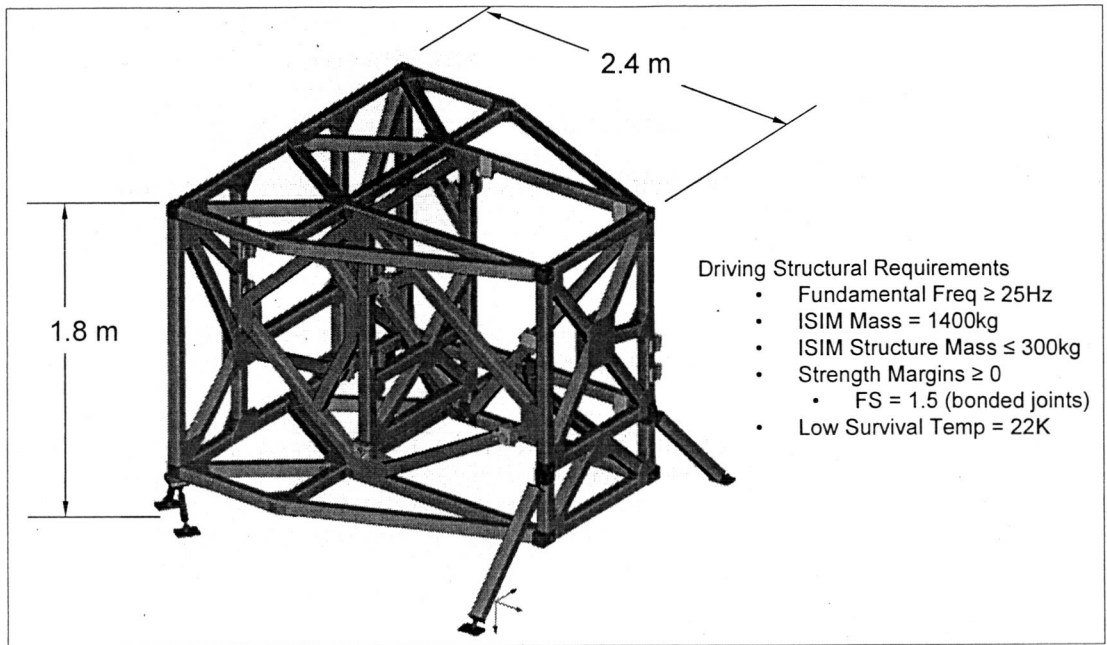


Figure 1 – The ISIM structure

2. DESCRIPTION OF BONDED JOINTS

The ISIM structure can be considered as an assembled and bonded structure made up of basic building blocks of composite tubes and joint elements. The four basic joint elements are metallic plug fittings, metallic saddle joints for instrument interfaces, gussets, and shear clips. Each joint element possesses unique design and analysis challenges for both cryogenic survivability and structural integrity under launch and handling loads of the ISIM structure.

To meet multiple stringent requirements including mass, stiffness, thermal distortion, and cryogenic survivability, the composite tubes are designed with a hybrid lay-up composed of M55J/954-6 and T300/954-6 unidirectional pre-impregnated tapes. The tube is engineered for thermo-elastic properties with $E_{axial} = 146\text{GPa}$, $E_{hoop} = 43\text{GPa}$, $CTE_{axial} = 0\text{ppm/K}$, and $CTE_{hoop} = 3.7\text{ppm/K}$ (stiffness properties are given for room temperature and thermal expansion properties are secant CTE from room temperature to 30K). Early in the design of the truss structure, the tubes were designed with a higher axial stiffness ($\sim 207\text{GPa}$) and higher hoop CTE ($\sim 10\text{ppm/K}$), however a solution could not be found for positive margins of the joints under cryogenic cool down loads. The current lay-up balances the need for high stiffness at room temperature and low total thermal strains during cryogenic cool down in both the axial and hoop directions. The T300/954-6 plies are stronger in the interlaminar directions and are placed in the outer layers of bonded interfaces, where interlaminar stresses are highest.

Because flat surfaces on the composite tubes facilitate gusset/clip joining of the members and simpler instrument joint interfaces, the truss members are designed as square tubes with a 75mm outside flat-to-flat dimension and a nominal wall thickness of 4.6mm. On the other hand, a square tubular section complicates the design of the joints for thermal

survivability. The relatively high CTE in the thickness direction for the composite causes a distortion of the cross section with the flats concaving toward the center of the tube. This distortion creates high temperature stresses for the joints, especially for shear clips bonded to orthogonal tubes. Great care was taken in the analysis and design of the clips in order to reduce the high stresses produced by this effect.

The basic plug joint is a critical joint element since it is located at highly loaded truss nodes of the ISIM structure, the ISIM to JWST interfaces. The plug joints are also located where multiple truss members come together from different angles and planes. The plug joints need to have enough strength to survive launch loads and yet be compliant to minimize temperature stresses and survive at cryogenic temperatures. Also, to make mechanical attachment possible at these interfaces, the plugs must be metallic. After a number of design concept iterations, which included different materials and configurations, an invar internal plug with fingered flexures bonded to the flat inner surfaces of the tube was designed (Figure 2). An additional T300/954-6 ply was added to the internal surface of the composite tube for stress relieving the weaker M55J/954-6 inner plies. The additional ply is oriented in the tube axial direction for picking up high transverse shear stresses that are created in that direction under both the thermal and mechanical loads.

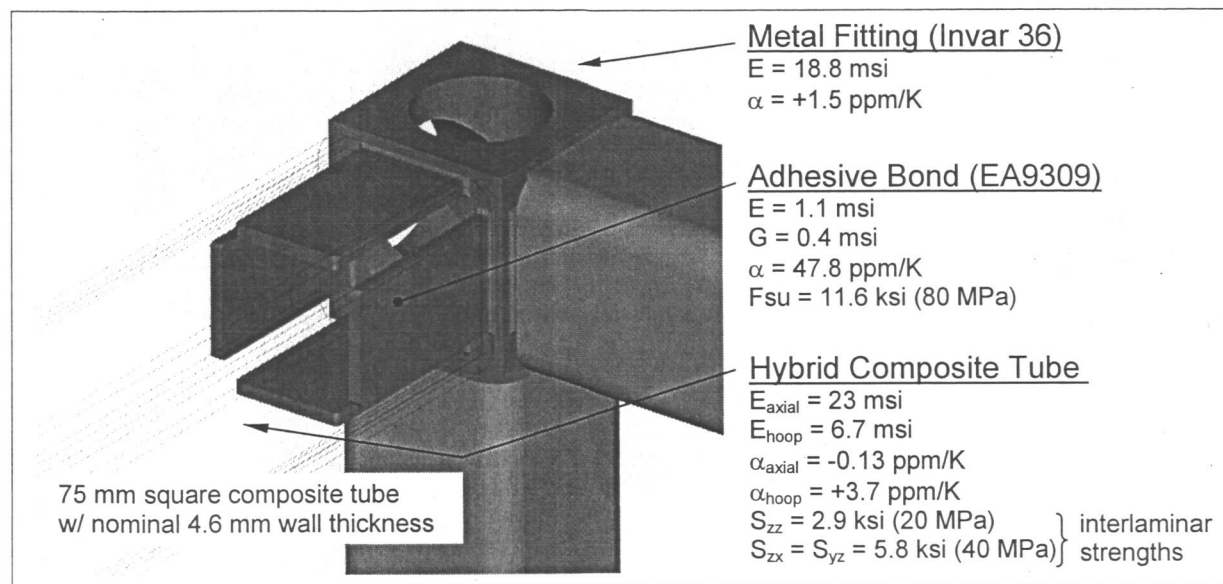


Figure 2 – Basic plug fitting

3. ANALYSIS METHODOLOGY

3.1 Initial considerations

Early in the program design stage, preliminary studies and a comprehensive literature search were conducted to determine the optimal analysis methodology for designing the ISIM joints that would meet all imposed requirements. Simplified analysis techniques including Hart-Smith closed form solutions for bonded joints and finite element analysis with plate and spring elements were investigated. The methods were chosen for their simplicity, ability to quickly gain insight on joint parameters (Hart-Smith), ease of modeling (plate/spring elements), and quick solution turn-around for initial trade studies. However, the methods were severely lacking in critical and fundamental areas that precluded them from obtaining final analytical solutions and designs for the ISIM flight joints. Important bonded joint aspects that are not included in these approaches are the relatively large CTE mismatch between the adhesive ($\sim 50 \text{ ppm/K}$) and the adherends ($\sim 0 \text{ ppm/K}$), the orthotropic material nature of the composite constituents, and the interaction of multi-axial stress components for strength of the composite adherends. Although these simplified approaches are deficient at capturing enough detail for final design and analysis of the joints, they still prove useful for insightful trade studies and

for basic understanding of bonded joints. A more rigorous analysis technique was needed that ensures accurate results and confidence in designs that would meet the harsh environments the ISIM structure will undergo.

The analytical methodology settled on for the final analysis and design of the ISIM joints includes finite element analysis using three-dimensional elements, in particular linear solutions with 8-noded brick elements. Although computationally intensive and time consuming for running solutions and modeling, the approach captures complicated geometries and boundary conditions. FEA using three-dimensional elements also allows for the inclusion of all joint constituents and properties, the three-dimensional nature of the composite material properties, and the extraction of all stress components for a more comprehensive approach in predicting failures under temperature and mechanical loads.

3.2 Finite element modeling

After several modeling and analysis iterations using the three-dimensional FEA approach, the best solution for the difficult challenge of analyzing a complicated flight joint was determined. A typical joint FEM includes 8-noded linear brick elements that sized to 2.5mm by 2.5mm in the bonded interface plane and varies in the out-of-plane direction according to the bonded constituent being modeled. The adhesive bond layer is modeled with only one element through the thickness and includes both stiffness and thermal expansion properties. The composite adherend has several elements modeled through the thickness with the first few plies at the bonded interface dimensioned according to ply thickness dimensions. The orthotropic nature of the composite is captured in the material properties of the composite using smeared properties of the laminate. Explicit properties of the individual lamina are not modeled except for the internal surfaces of the composite tube (the first ply of the tube inner surface is not part of the tube basic laminate and the directional properties of the ply alleviate certain stress components for positive strength margins). Figure 3.1 gives a description of the plug joint analytical model.

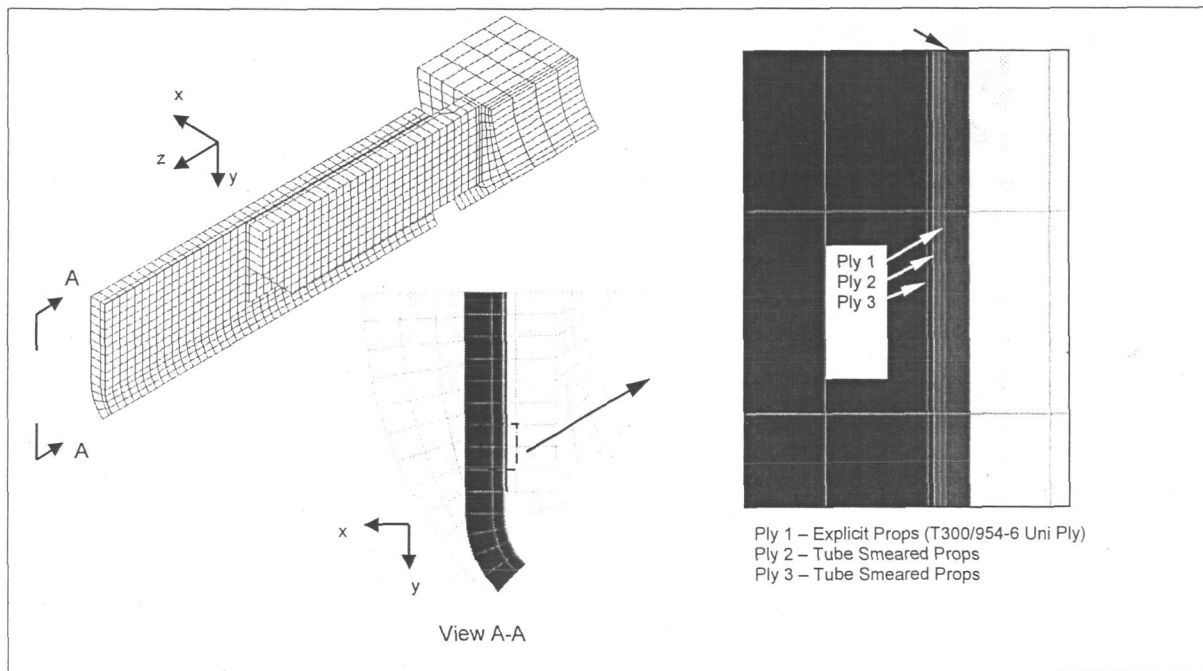


Figure 3.1 – Detailed analytical model of the ISIM basic plug joint

Thermal survivability of the joints was analyzed using secant CTE properties for each material. The secant CTE of a material from an initial temperature to the survival temperature is defined as

$$\alpha_{\text{sec.ant}} = \frac{\epsilon_{\text{total}}}{T_f - T_o}$$

where ϵ_{total} is the total thermal strain that a given material experiences when unconstrained from an initial temperature T_o , to a final temperature T_f . The initial temperature for the analysis was assumed at 293K (the joints will be bonded and cured at room temperature). The final temperature was taken at the survival temperature of 22K, the total temperature load is -271K (= 22K - 293K). For material elastic constants, end state properties were conservatively used. Most materials increase in stiffness with decrease in temperature. The dependency of Young's modulus to temperature and the built up of stresses in the joints that occur with this increase was not considered. Using the higher end state elastic properties is conservative.

Preliminary analysis and engineering experience establishes that the adhesive fillet at the edge of a bond is a critical factor for joint strength, especially survivability under thermal loads. To simplify modeling of the joints, the fillets were not included. Although this is conservative for mechanical loads, the opposite is true for thermal loads. Finite element analysis performed on simple joints with and without fillets, show that fillets can increase interlaminar stresses in the composite adherend under thermal loads. Also, contrary to traditional thinking and experience, thicker adhesive bondlines can increase interlaminar stresses in the composite adherend for a bonded joint under thermal loads when the thermal expansion coefficients are similar between the adherends. The increase of stresses with bondline thickness under a thermal load appears to be effected by the high CTE differential between the adhesive and the adherends. In order to account for adhesive fillets and bondline thickness, test coupons for correlation of the analysis were designed and fabricated with adhesive fillets and bondlines comparable to the flight joint designs (see section 4).

3.3 Strength margin calculation

Strength margins calculated for the joints consider various failure modes anticipated under mechanical and thermal loads. Laminate in-plane stress components (σ_x and σ_y) are analyzed separately with respect to their individual allowables. Any interaction between in-plane and interlaminar stresses are ignored for strength assessment at the bonded interfaces. Decoupling the in-plane and interlaminar stress components for strength margin calculation is justified by assuming that the primary stress components for failure at the bonded interfaces are the interlaminar components.

For the lamina interlaminar stress components (σ_{33} , τ_{13} and τ_{23}) a semi-empirical approach is used. A second ordered failure surface is assumed and can be expressed in the positive coordinate space (+x, +y, +z) as shown in Figure 3.2. F_{33} , F_{13} , and F_{23} are interlaminar strengths for a given ply in a given laminate.

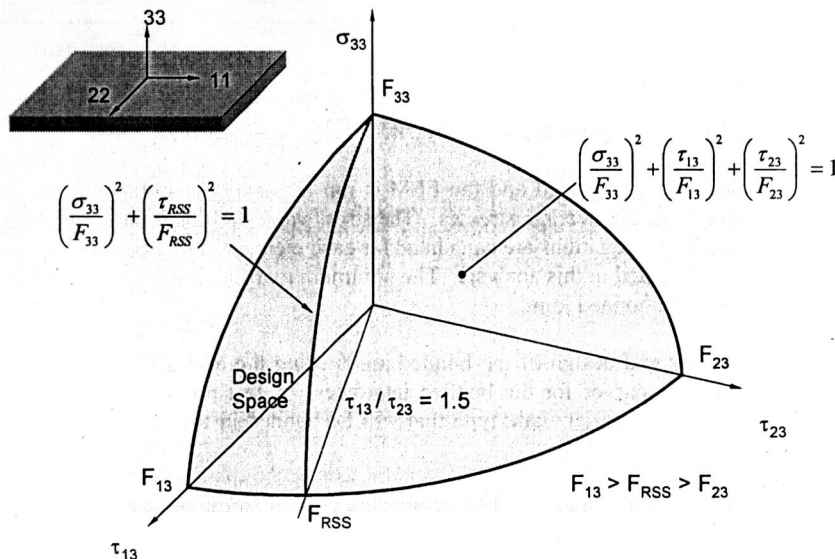


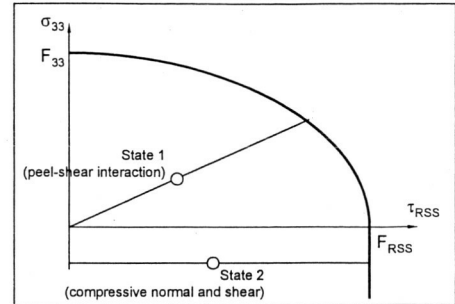
Figure 3.2 – Assumed three dimensional composite interlaminar failure surface

Preliminary analyses of the flight joints show that the τ_{13}/τ_{23} ratios at critical bond areas are greater than 1.5 and the design space is between the F_{33} - F_{13} curve and a F_{33} - F_{RSS} curve where F_{RSS} intersects the failure space at the τ_{13}/τ_{23} ratio of 1.5. Typically for composites, the fiber direction interlaminar shear strength (F_{13}) is greater than the transverse interlaminar shear strength (F_{23}); the failure surface expands away from the σ_{33} axis when sweeping from the τ_{23} axis to the τ_{13} axis. The F_{33} - F_{RSS} two dimensional curve is therefore a conservative failure criterion for interlaminar failure of the ISIM joints and simplifies margin calculation and testing. Also to make the analysis and testing more tractable, bonded areas with negative σ_{33} stresses (in compression) are assumed to fail in transverse shear only and a vertical line is assumed for the failure curve in the negative σ_{33} quadrant(s).

Assumed two dimensional interlaminar failure criterion

$$\tau_{RSS} = \sqrt{\tau_{13}^2 + \tau_{23}^2}$$

$$\frac{\sigma_{33}^2}{F_{33}^2} + \frac{\tau_{RSS}^2}{F_{RSS}^2} = 1$$



Margin equation for elements with $+\sigma_{33}$ stresses

$$MS = \frac{1}{FS \cdot \sqrt{\frac{\sigma_{33}^2}{F_{33}^2} + \frac{\tau_{RSS}^2}{F_{RSS}^2}}} - 1$$

Margin equation for elements with $-\sigma_{33}$ stresses

$$MS = \frac{F_{RSS}}{FS \cdot \tau_{RSS}} - 1$$

FS is the factor of safety imposed on margin calculations by JWST/ISIM requirements.

After thermal and mechanical loads are applied and the FEM is ran for analysis, interlaminar stress components are extracted for each element using element average stresses. The stress values are then imported into a spreadsheet and individual margins based on the above equations are calculated for each element. Only elements representing individual plies at the bonded interface are included in this analysis. The minimum margin of all elements analyzed is given as the margin for interlaminar failure of the bonded joint.

To have confidence in the analysis and design of the bonded joints using the above technique, testing is required for determining and/or verifying failure curves for the bonded interfaces. A test program was planned and is currently running to obtain failure curves for every laminate type that will be bonded in the ISIM structure for both room and cryogenic temperatures.

4. ANALYSIS/TEST CORRELATION

4.1 Analysis/test correlation procedure

Since the proposed analysis approach is semi-empirical, testing of candidate materials at bonded interfaces is critical. In order to simplify the test program, fabrication of coupons and post-test data analysis, simple coupons for each bonded

interface is being fabricated and tested at room temperature and at the cold survival temperature. Test coupons designed include flat wise tension (FWT) specimens, double strap joint (DSJ) specimens, and short beam shear specimens. The FWT and DSJ specimens are most relevant since test data from the coupons generate in-situ bond interface strengths. The bonded joints are designed so that they simulate expected stress states at critical bond interface locations predicted by preliminary analysis of the flight joints. Stress states produced by the various joint configurations include peel, interlaminar shear with peel stresses, and interlaminar shear with compressive normal stresses.

For a direct correlation of the test coupons and flight joints, finite element modeling techniques must be identical. Element in-plane and thickness dimensions, material thermo-elastic properties, method of element stress extraction (average vs. max corner), and fillet modeling must be the same for the flight and test joint models. The physical joints must also have corresponding geometries including fillet and adhesive bondline thickness dimensions. Because individual plies with explicit properties are generally not modeled and residual temperatures stresses internal to laminates are not captured in the analysis, every unique lay-up at bonded interfaces must be tested and correlated.

The basic steps to the analysis/test correlation flow include 1) design and modeling of a test joint, 2) fabrication and testing to failure of the test coupon, 3) applying the test loads (temperature and mechanical failure load) to the test analytical model, 4) extracting critical stresses in the analysis and assessing the failure surface of the bonded interface, 5) designing and analyzing the flight joint with respect to the test correlated failure surface. Figure 4.1 illustrates the procedure flow. As test data is made available, failure curves based on engineering judgment are updated. The updates may include a change in the F_{33} and/or F_{RSS} allowables and also a change in the equation form of the failure curve.

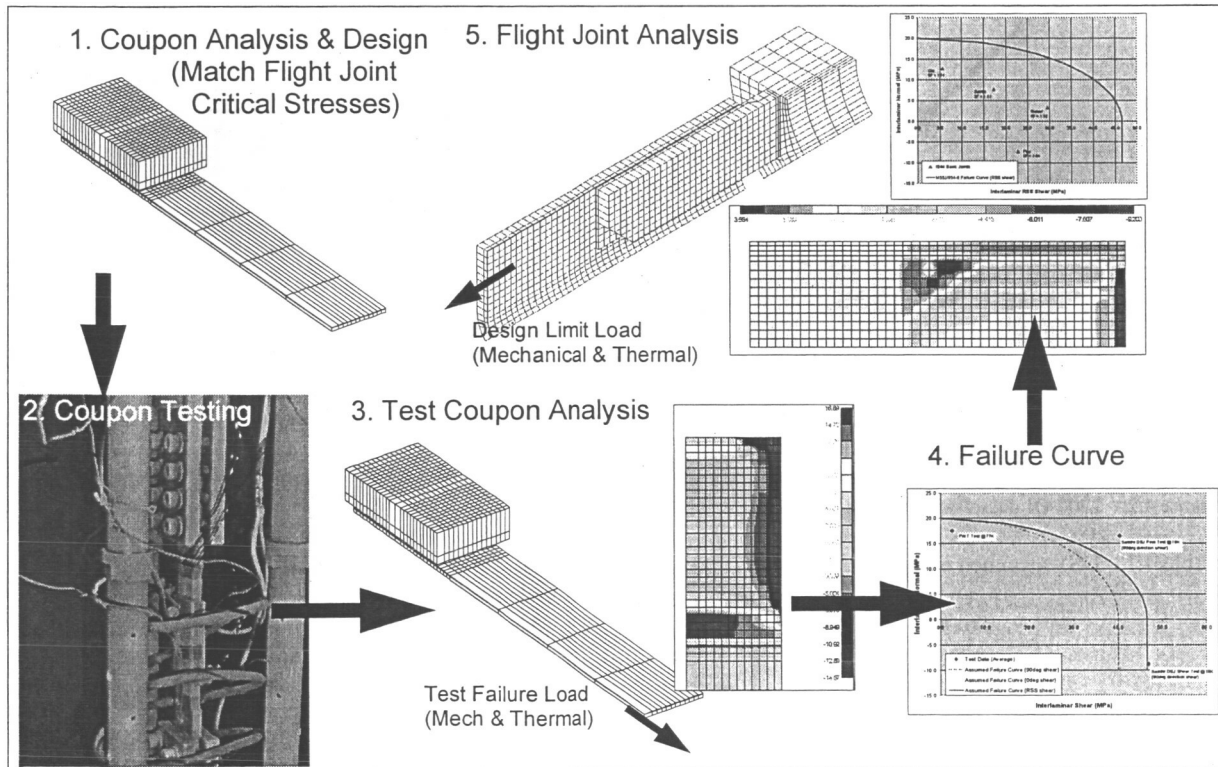


Figure 4.1 – Analysis/test correlation flow

4.2 Current test data results and correlation

Difficulty in fabrication, good surface preparation of metal adherends, and maintaining consistent adhesive bondlines have delayed testing and data recovery. However, a number of joint coupons, both FWT and DSJ configurations, have

been successfully tested and correlated for the gusset and tube surface bonded interfaces. In this paper we only present successful testing of the gusset bonded interface in order to demonstrate the analysis and testing methodology proposed. The test program is currently running and is anticipated for completion by the end of the year.

For the gusset T300-QI bonded interface, FWT specimens were pulled to failure at 77K (liquid nitrogen) and DSJ specimens (designed for shear dominated failure with compressive normal stresses) were pulled to failure at 19K. A statistical B-basis failure load was determined for each specimen type and the failure loads (mechanical B-basis failure load at temperature) were applied to the test coupon FEMs (Figure 3.2 for DSJ). Stress states at critical edge locations (Table 4.1) were extracted and plotted on a σ_{33} - τ_{RSS} plot along with an assumed failure curve at 30K. The assumed failure curve is based on engineering estimates for interlaminar allowables of $F_{33} = 30\text{MPa}$, $F_{23} = 55\text{MPa}$, and $F_{13} = 69\text{MPa}$ for the T300-QI laminate at 30K. Defining the failure curve at a τ_{13}/τ_{23} ratio of 1.5, the F_{RSS} allowable is calculated to be 63.6MPa. Figure 4.2 shows the assumed failure curve, test data stress states at failure, and stress states for a sampling of ISIM joints at critical bonded interface locations (minimum safety factors).

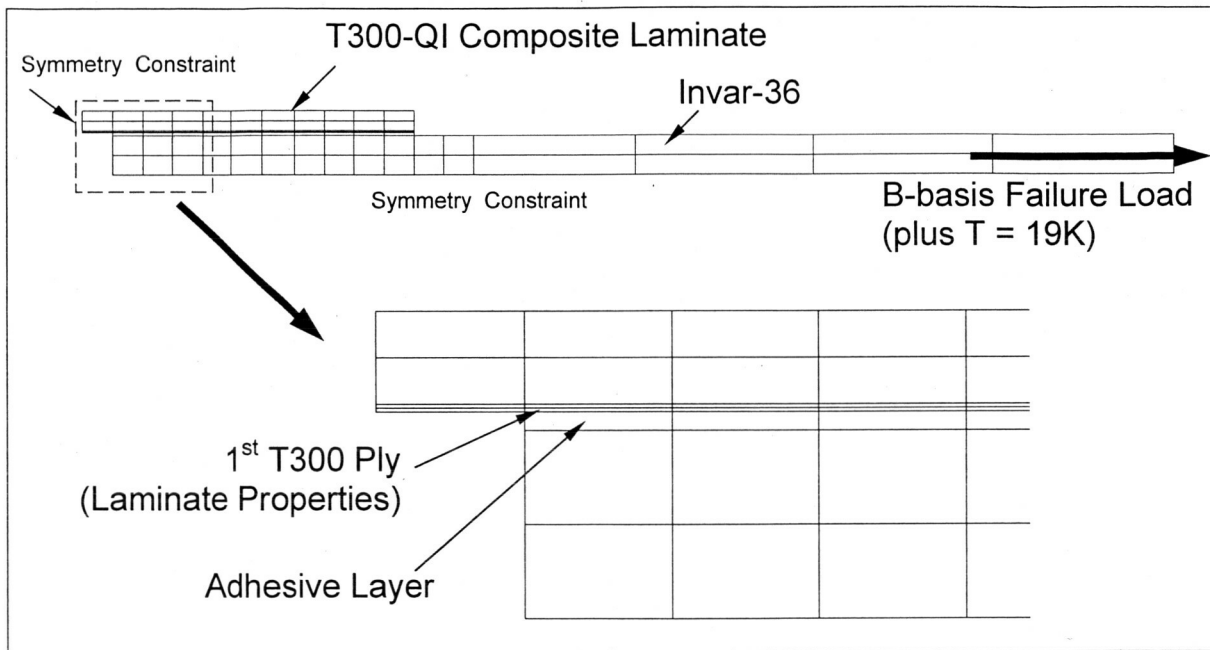


Figure 4.2 – T300-QI gusset bonded interface σ_{33} - τ_{RSS} plot

Table 4.1 – DSJ specimen element stresses (1st T300 ply elements with smallest safety factors)

Elm #	sigma-3	tau-13	tau-23	RSS Shear	SF
255	-7.2	62.2	17.6	64.6	0.98
277	-10.9	60.8	7.9	61.3	1.04
211	-11.5	60.8	-2.5	60.8	1.05
266	-13.4	59.1	2.5	59.2	1.08
212	-9.0	56.0	13.7	57.6	1.10
258	3.5	31.9	15.5	35.5	1.76
224	-2.1	33.4	6.2	33.9	1.87
280	1.3	30.6	8.0	31.6	2.00
223	0.5	30.8	-3.7	31.0	2.05

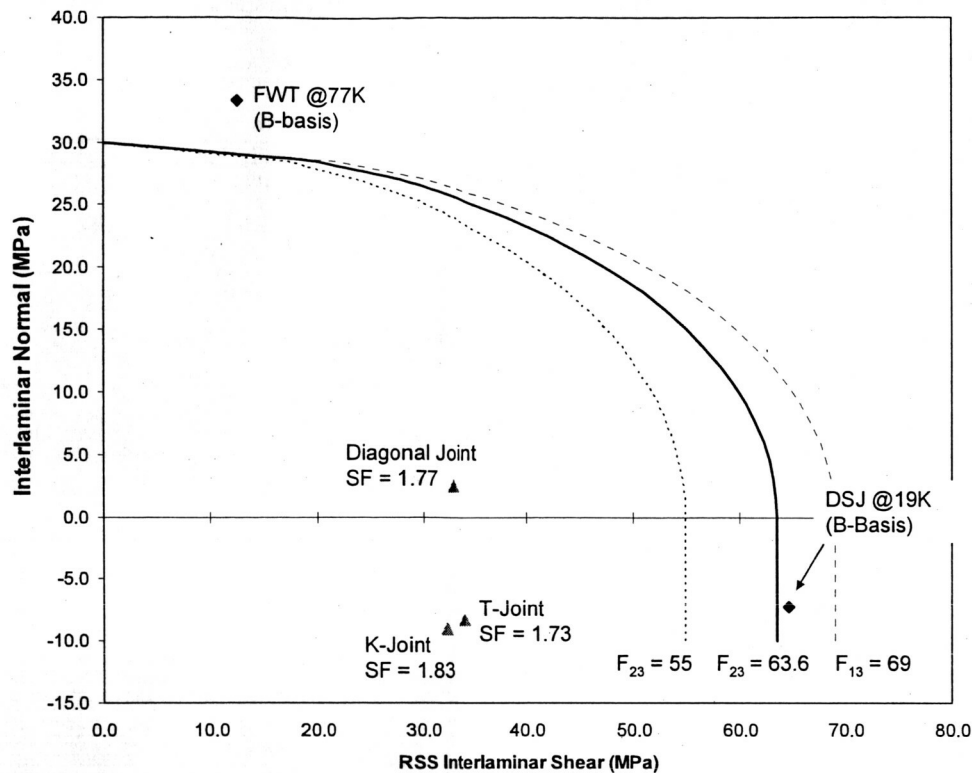


Figure 4.3 – T300-QI gusset bonded interface σ_{33} - τ_{RSS} plot

As can be readily seen in Figure 4.3, the test results fall reasonably well on the assumed failure curve for the gusset bonded interface. The FWT B-basis test data point is well above the current curve and the DSJ data point is just past the curve vertical for shear dominated stress states. Further testing that will include a DSJ coupon designed for a combined shear and peel stress state at cryogenic temperatures will complete the set of tested coupons for the gusset interface. The complete test set will guide in the final evaluation of a failure criterion for the particular bonded interface at cryogenic temperatures. Three similar test coupons will also be tested at room temperature for establishing a failure curve for launch load analysis.

A similar approach for all bonded interfaces anticipated in the ISIM structure will be conducted for establishing failure criteria for all bonded interface types (adherend materials and bond adhesive) for room temperature (launch) and 22K (cold survival temperature). The test correlated failure curves will then be used to guide design and analysis of the ISIM flight joints.

5. CONCLUSIONS

Analysis and design of composite bonded joints for thermal survivability at cryogenic temperatures is a major challenge for the JWST/ISIM structure as well as other structures of the observatory and space programs in the industry. The approach for analysis and testing outlined in this paper is semi-empirical and simple to apply. A test program that consists of test coupons that are easy to model for FEA, fabricate, test, and analyze are employed for establishing failure criteria of bonded interfaces for various joints. The test correlated analysis is then applied to design flight joints in the structure for confidence in joint integrity. The ISIM joint development test program is currently running and is scheduled for completion by the end of the year. A successful program for the ISIM bonded joint analysis and design

will help future programs at the Goddard Space Flight Center for similar structures and environments as well as other industries and applications.

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REFERENCES

F.E. Penado and Richard K. Dropek, *Engineered Materials Handbook*, Volume 3, p 477-500, year?

L.J. Hart-Smith, Adhesive-Bonded Double-Lap Joints, NASA CR-112235, Jan 1973

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