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CRYOTANK SKIN/STRINGER BONDLINE ANALYSIS

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ABSTRACT

The need for light weight structure for advanced launch systems have presented great challenges and led to the usage of composites materials in variety of structural assemblies where joining of two or more components is imperative. Although joints can be mechanically bolted, adhesive bonding has always been a very desirable method for joining the composite components, particularly for the cryotank systems, to achieve maximum structural efficiency. This paper presents the analytical approach resulted from the conceptual development of the DC-Y composite cryotank, conducted under the NASA/Boeing NRA 8-12 Partnership, to support the continued progress of SSTO (Single-Stage-To-Orbit) concepts. One of the critical areas of design was identified as the bonded interface between the skin (tank wall) and stringer. The approach to analyze this critical area will be illustrated through the steps which were used to evaluate the structural integrity of the bondline. Detailed finite element models were developed and numerous coupon test data were also gathered as part of the approach. Future plan is to incorporate this approach as a building block in analyzing bondline for the cryotank systems of RLVs (Reusable Launch Vehicles)

Key Words: DC-Y, DC-XA, RLVs, SSTO, launch systems, composite, cryotank, bondline.

1. INTRODUCTION

The objective of the DC-Y composite cryotank study was to extend SSTO development. In particular, this study was intended to satisfy the Design Requirements/Traceability developed in the DC-XA Program, which was to demonstrate the mature technology in the application of composite cryotank structure to reusable launch vehicles. The most prominent new composite structure on the DC-XA vehicle shown in Figure 1, in term of size and technology advancement, is the unlined LH2 (liquid hydrogen) tank. Because of its size, the use of composite materials would provide a major weight benefit, particularly when it is scaled up for the subsequent RLV. Consequently, IM7/8552 toughened epoxy from Hercules, was selected as a composite material for DC-XA. Based on the producibility and its compatibility with liquid hydrogen, this same material has been chosen for DC-Y cryotank skin.

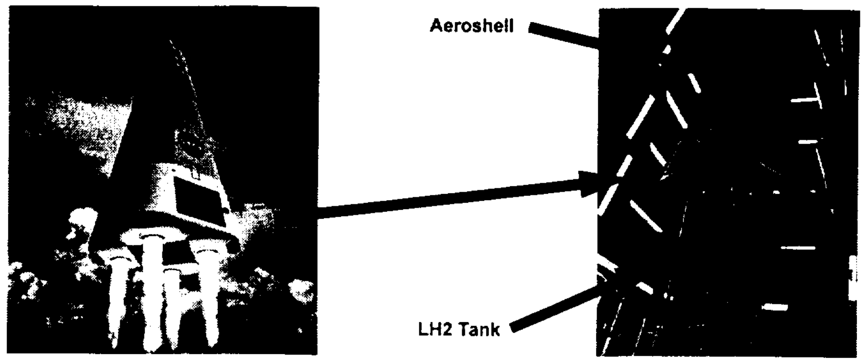

FIGURE 1. DC-XA Vehicle

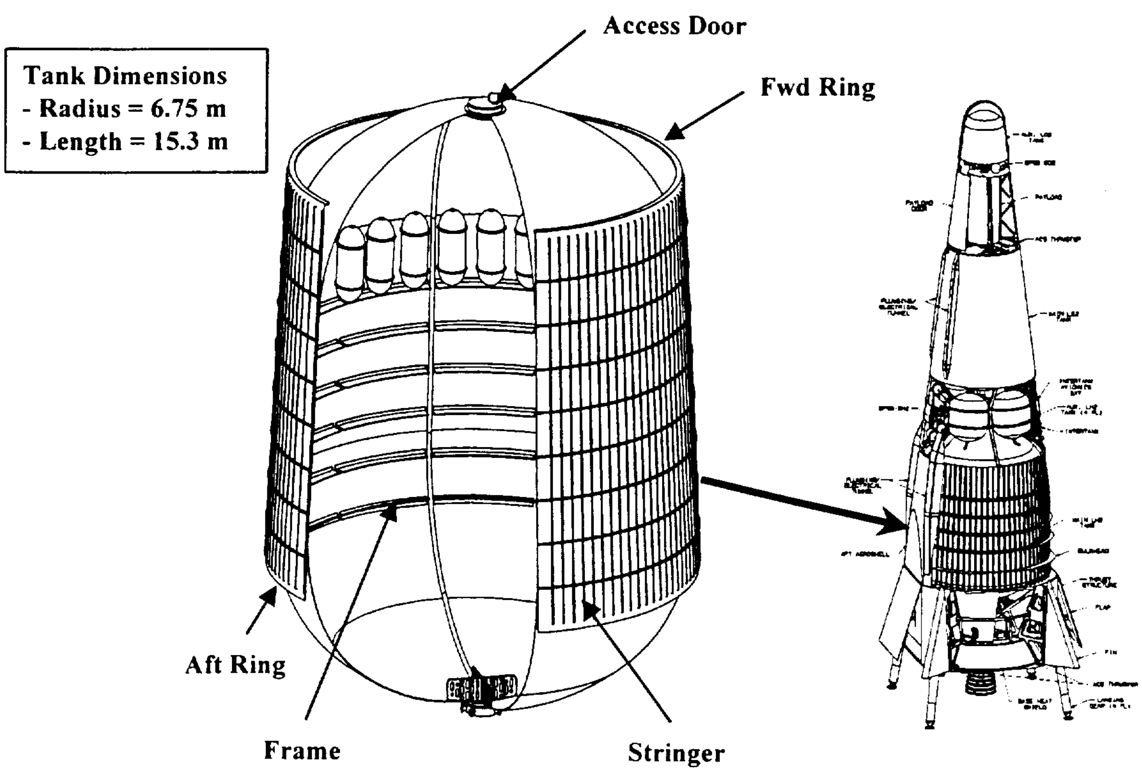

FIGURE 2. DC-Y Composite Liquid Hydrogen Tank

Because of high expected axial compressive line load, on the order of 1,750 N/mm, for the full-scale RLV, the conceptual design DC-Y utilizes the stiffened skin concept, i.e., stringer attaching to skin externally, to prevent premature buckling, as depicted in Figure 2. Also, in order to avoid having any type of holes in the composite skin which could leak hydrogen, the adhesive bonding approach for skin to stringer is chosen for the cryotank. As a result, this approach has created challenges for analysts in performing structural assessment of the bondline. For instance, the stringer pop-off on thin composite shell when subjected to various loading conditions such as internal pressure, mechanical and cryogenic temperature induced load always raises a concern to structural engineers. The behavior of the joints in composites is typically uncertain due to numerous design variables such as thickness of the laminate, composition of the fiber orientation, stacking sequence of layers, length and width of joint, three dimensional effects (e.g., interlaminar shear). The importance of bondline integrity has forced Boeing engineer spending significant amount of effort in developing plausible methods to predict failure. Hence, the content of this paper will be primarily focusing on this methodological development. For detailed analysis techniques, much information can be found in the papers listed in the reference section.

2. BACKGROUND

The most cited work in the analysis of adhesively bonded joints has been performed by Goland and Reissner in 1944. However, Goland and Reissner only investigated a single lap joint with an assumption that the adhesive bondline is thin such that its effects on the joint flexibility can be neglected. After more than half of a century, numerous authors has extended the work in the area of analysis of bonded joints based on Goland and Reissner's classical approach. Nevertheless, the subject of peel stress and interlaminar shear stresses in adhesively bonded joints of advanced fibrous composite structures has only recently gained prominence during the past decade.

In composite structure, three dimensional state of stresses is typically developed in the vicinity of discontinued (dropped) plies such as skin/stringer configuration. The out-of-plane stress present at the interface of skin and stringer, as depicted in Figure 3, may lead to delamination if not properly analyzed. One of the most common mode of failure for this type of configuration is the separation caused by interlaminar stresses at the interface. Because of the complexity, the analysis of adhesively bonded joint has always been a controversial subject. In many instances, engineers make assumption that the allowable stresses derived from test coupons alone are adequate for predicting bondline failure. The pitfall for this assumption is that they forget to recognize that there are tremendous differences between the behavior of adhesive bonds in test coupons and in structurally configured joints. Both peel and shear stress vary as a functions of joint geometry, beside the material construction and load direction.

The existence of peel stress, in addition to shear stress, in a adhesively bonded joint caused by in-plane load can be briefly described with of single lap joint configuration. The mechanics is quite simple, i.e., the peel stress or normal stress is resulted due to having induced moment caused by the eccentricity in the load path as illustrated in Figure 4. There are also cases where the joints will be subject to out-of-plane load. One of the examples is the skin/stringer joint subjected to internal pressure. In this case, the adhesive peel stress has a distribution governed by the classical beam-on-the-foundation equations. Also, the ratio of peak to average peel stress, as shown in Figure 5, is strongly influenced by the width to thickness ratio of the stringer

Even for a simple bonded joint, the precise analysis is quite complicated because of the interactions between each of the three potential failure mode: adherend yielding, adhesive peel, and adhesive shear. So far, most of the analysis approaches consider two-dimensional state-of-stress, thereby neglecting the influence of interlaminar shear and peel stress on the failure mechanism. In some situations, with conservatism, these approaches seem to be adequate for the design of bonded joints. Nonetheless, the composite joints, which consists of various variables, will need a development of analysis that accounts for a three-dimensional state-of-stress such that the failure prediction can be enhanced to avoid any costly redesign.

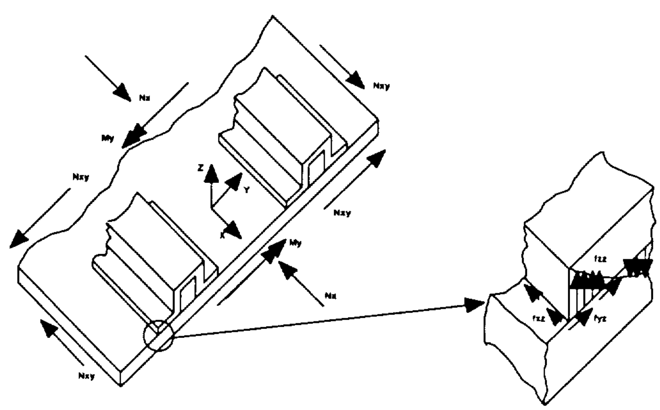

FIGURE 3. Interlaminar Stresses for Skin/Stringer Composite Structure

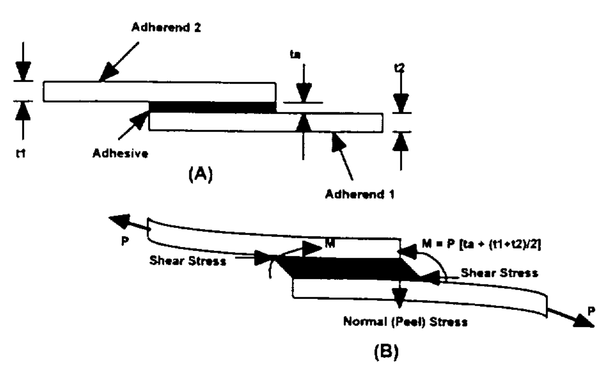

FIGURE 4. Bending, Shearing, and Elongation of a Single Lap Joint. (A) At Rest; (B) Under In-Plane Load

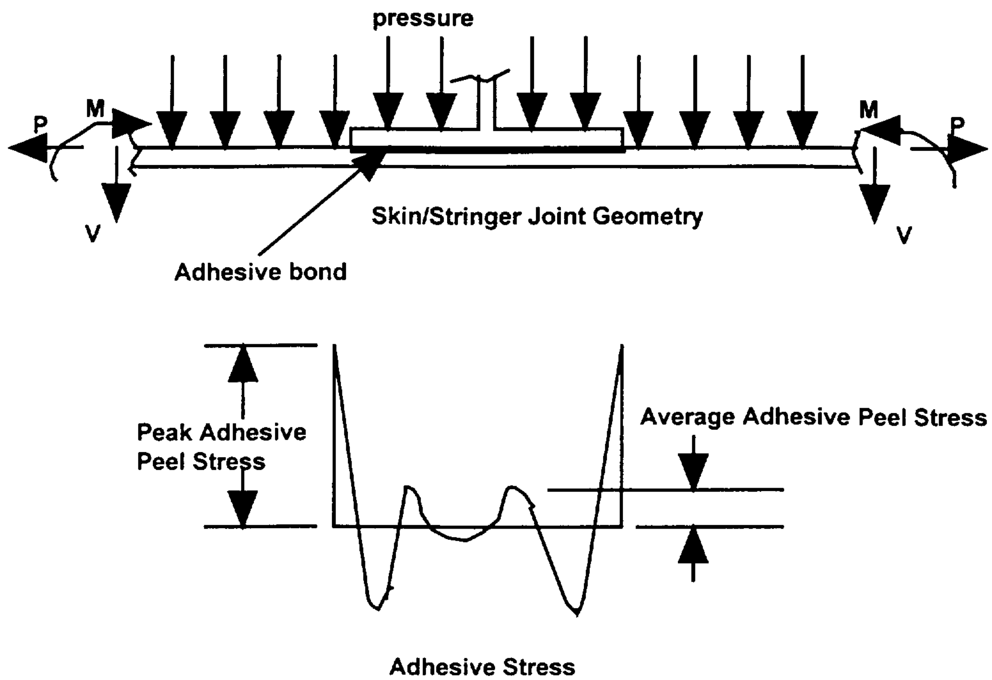

FIGURE 5. Typical Peel Stress Distribution Between Skin and Stringer

3. ANALYSIS APPROACH

Because of the complexity in joint design, particularly with composite materials, a pure analysis based on classical and numerical techniques will not be adequate to predict the bondline failure. This approach may work for composite joint with simple geometry and load condition, but may not effectively analyze joint such as skin to stringer in a cryotank system where it is subjected to various types of loading. This concern has prompted Boeing engineers to develop a plausible method for evaluating bondline integrity.

During the study of the DC-Y vehicle, a combination of experimental and finite element analysis work was used to assess the adhesive failure for the LH2 composite cryotank. The design features of this cryotank is depicted in Figure 6. The approach discussed here will be concentrating on the interface between the skin and stringer (Hat Shape) where the adhesive bondline is of primary interest. In this tank, the purpose of the stringers is to assure stability of the skin for compressive body bending load. Thus, it is essential to maintain the integrity of the adhesive which attach the stringer to the skin to prevent possible catastrophic failure.

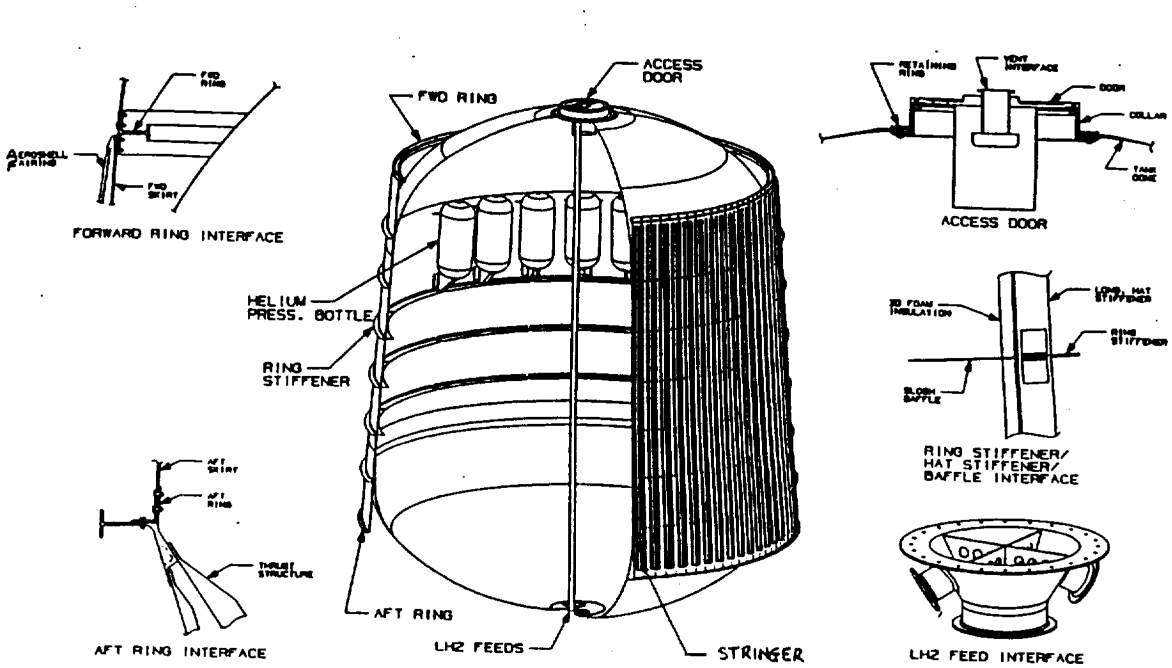

FIGURE 6. Design Features of DC-Y LH2 Cryotank

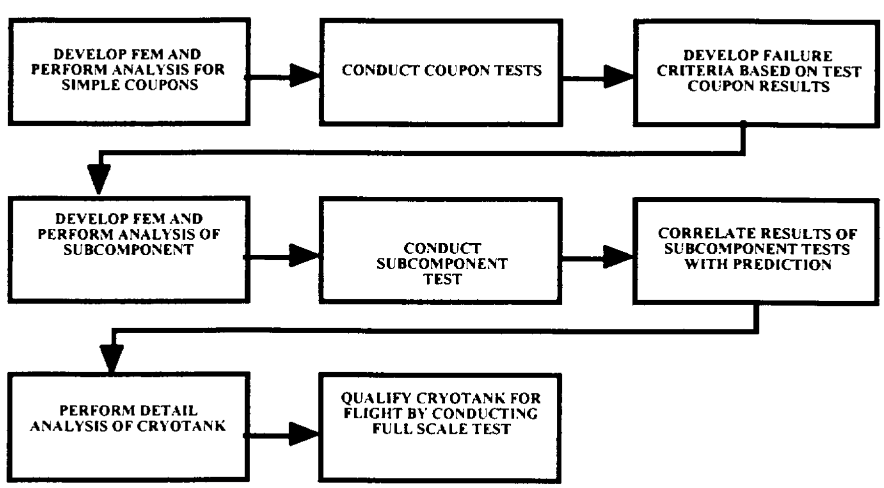

FIGURE 7. Analysis Approach

The general analysis approach for skin/stringer bondline was based on development of NASTRAN 3D solid element and numerous test coupon data obtained from DC-XA Program. Various adhesives (including FM300, EA9394, EA9330, CREST7450) were used in the bond strength tests at ambient and cryogenic temperature. These test data provide significant contribution to the analytical prediction of bondline failure. Overall procedure of this approach is summarized in Figure 7. In the bondline analysis of skin/stringer for DC-Y LH2 cryotank, the adhesive strength was based on data gathered from DC-XA Program. Various tests at room temperature (+22 deg. C) and cryogenic temperature (-100 and -268 deg. C) for double lap bonded joint coupons were conducted with EA9394 film adhesive chosen as an interface material. This adhesive works well with IM7/8552 graphite prepreg cloth, which was the material being used for the composite LH2 tank.

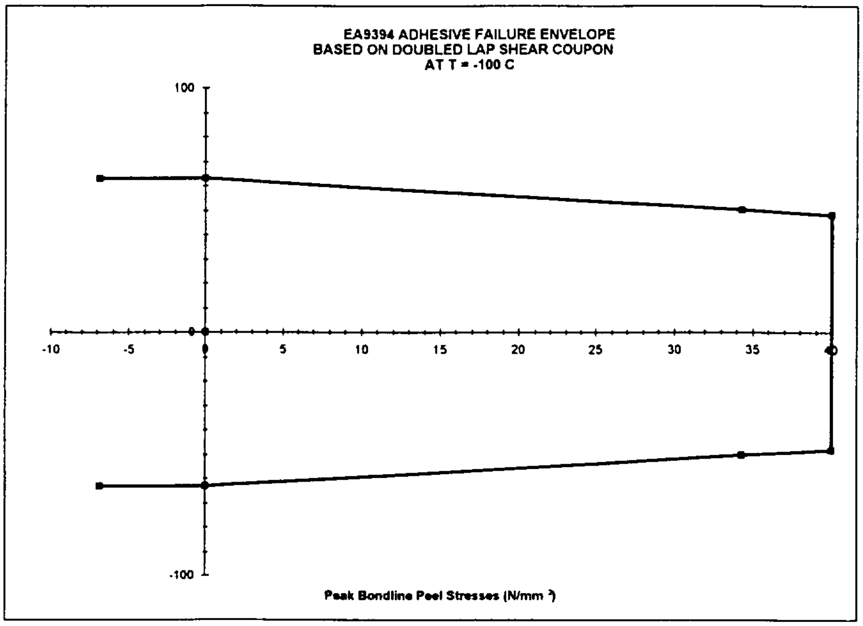

FIGURE 8. EA9394 Adhesive Failure Envelope at Cryogenic Temperature of -100 Deg. C

One of the early tasks in the approach was to create a finite element model of the bonded joint coupons for test correlation analysis. Initially, the coupon was fabricated and subjected to a failure load. This load was then applied to the solid element NASTRAN model to calculate the bondline shear and peel stresses for the test specimens. The stresses, using the element centroidal values, were calibrated with fine model meshes to match the failure load. Results from the analysis were then used to develop a failure envelope for the bonded joint as illustrated in Figure 8.

The next subsequent task is to build finite element model, perform analysis, and conduct test for the subcomponent hardware. In the DC-Y Program, the results for subcomponent were obtained from the analysis and test data of the 0.8 m bottle, Y-Joint, Belly Band Joint and Secondary Attach Bracket Joint, which was designed during the time of DC-XA Program. These data were readily available and can be utilized in the analysis of DC-Y LH2 cryotank, hence, avoiding unnecessary design and testing cost. Next step in the process is to review and correlate the analysis results to the prediction. The output of this step is to enhance the predicting capability of the failure envelope so that accurate analysis can be performed when it is time to build the full-scale cryotank.

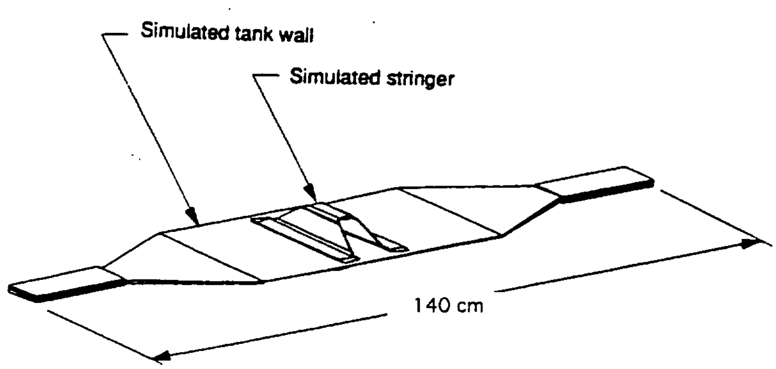

FIGURE 9. Stringer Hoop Pop-off Test Specimen

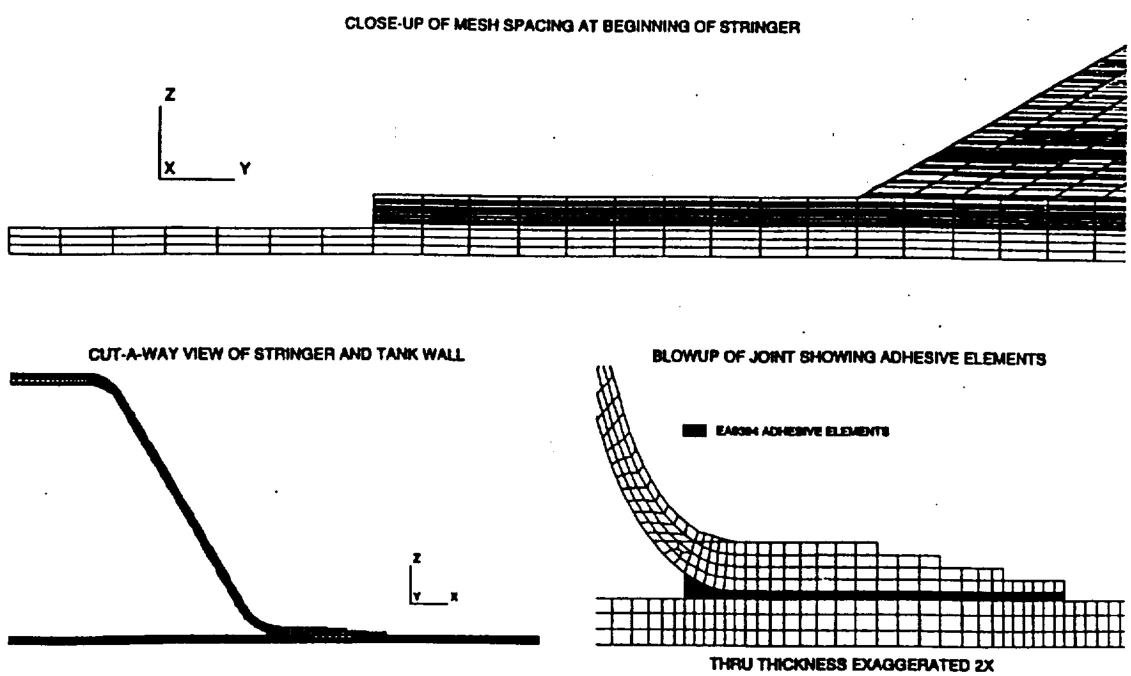

FIGURE 10. NASTRAN Model of Skin/Stringer Test Specimen

Because the DC-Y LH2 cryotank is subjected to various types of loading, continued concerns keep raising, particularly the pop-off at stringer end or midspan in areas where tank wall bending produces high local peel stress. Although the budget was limited, the decision to construct some sort of stiffened specimen was executed. As a result, three types of specimen were fabricated; one for the investigation of stringer pop-off under simulated hoop strain, the other two were to study the stringer interaction with meridional strain and to determine the crippling strength. The sketch for the stringer pop-off specimen is shown in Figure 9 and its finite element model in Figure 10. The model in Figure 10 consists of 3D solid elements. At the critical areas where the bondline terminates, the mesh spacing is 0.63 mm. This spacing is derived based on the fact that it matches the peak stresses in the closed form solution and it was also used in the correlation models of the DC-XA Y-Joint and Bellyband Joint. To validate the analysis results, testing on the specimen would normally conducted as part of the procedure. Certainly, having results of the stringer pop-off test available would add more confidence to the understanding of the skin/stringer joint. Unfortunately, limited amount of budget has delayed the test to future date. Currently, the test for the stringer pop-up has been re-scheduled to start in the second quarter of 1999 at NASA-LaRC facility under agreed cooperative effort. Nevertheless, the investigation team on the DC-Y Program has decided to go forward with the analysis of the LH2 cryotank, using on the available coupon test data from DC-XA Program and relying on Boeing's capability of correlating test results with prediction.

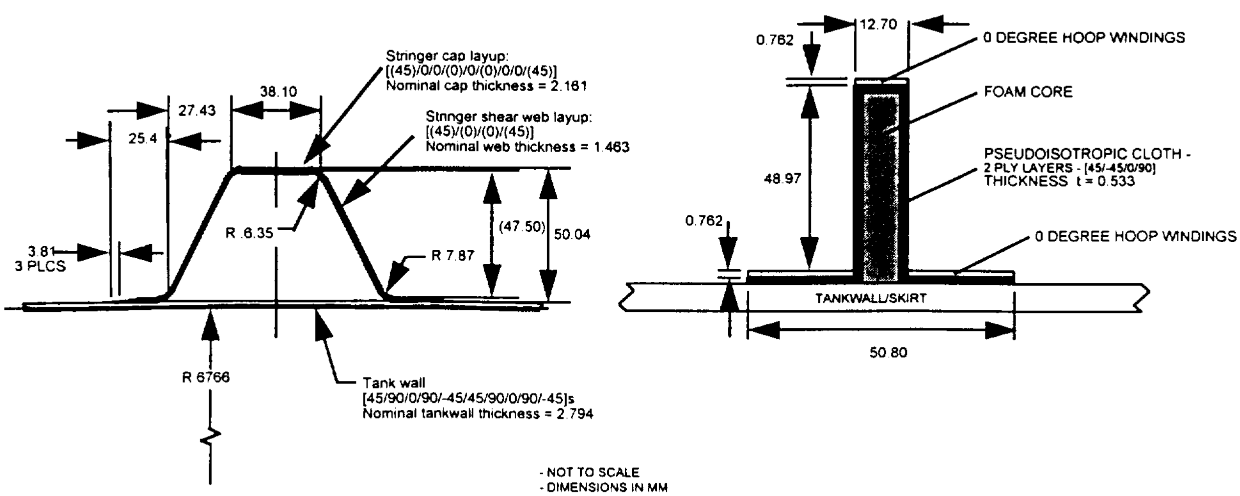

FIGURE 11. Cross Section of Stringer and Frame for DC-Y LH2 Cryotank

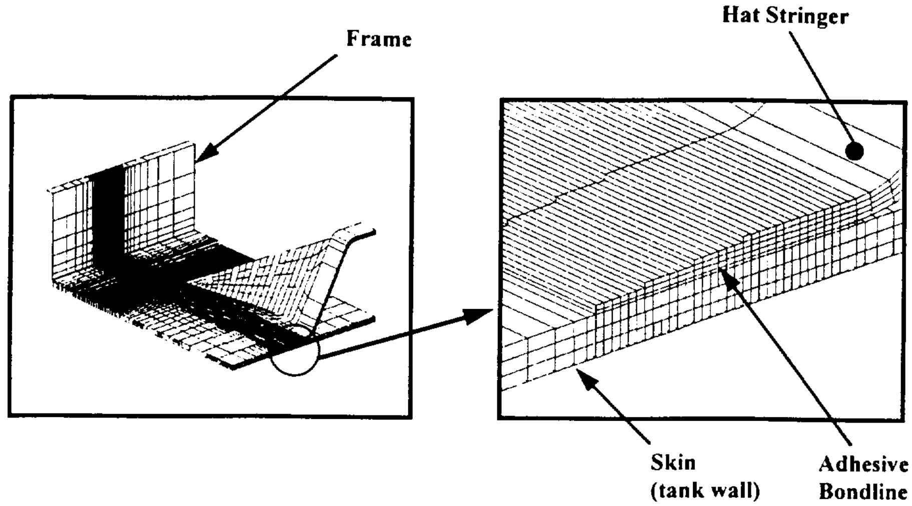

FIGURE 12. NASTRAN Local Model of Skin/Stringer/Frame

In order to fully understand the behaviors of adhesive bondline at the interface of the skin and stringer, it is necessary to analyze a full-scale cryotank configuration as part of the analysis procedure. Because of the time constraints, the existing DC-XA skin/stringer design is used as a baseline study for the DC-Y LH2 cryotank. Due to symmetry, only part of the cryotank is modeled to avoid unnecessary computing time. Model was constructed from centerline of stringer to midpoint between stringer spacing (hoop direction.) Using the same modeling philosophy as was done for the coupon test specimen and subcomponent joints, the NASTRAN model for the skin/stringer configuration was composed of 3 D solid element for entities such as stringer flange, bondline and skin (tank wall). Again, mesh spacing of 0.63 mm. was used in both hoop and longitudinal direction in region of concern. The web of the circumferential frame was modeled with shell elements to minimize the number of degrees of freedom and to keep the model size at an acceptable level. The design configuration for the hat stringer and the circumferential frame and their local idealization are illustrated in Figure 11 and 12, respectively.

In this particular analysis, the stringer has a centerline-to-centerline spacing of 21.3 cm. and the bondline thickness is 0.25 mm. With the model, which consists of 20492 elements and 25676 nodes, shown in Figure 12, analysis for the DC-Y LH2 cryotank was performed for various loading conditions which include axial load of 300 N/mm, internal pressure of 165 Kpa, and cryogenic temperature induced load at -268 deg. C. Typically, the structural integrity of the bondline would have been based on the failure envelope derived from a series of doubled lap shear coupon tests performed on the EA9394 Adhesive and also from the stringer pop-off test. However, as mention earlier that the budget limitation has delayed the stringer pop-off test activity. Therefore, the level of confidence with the analysis prediction of the cryotank is somewhat reduced. Having results from the stringer pop-off test would certainly enhance the accuracy of the failure envelope. Nonetheless, it is believed that the results from numerous coupon tests and a well-model correlation with various joints performed on DC-XA Program can still give reliable failure prediction for the bondline. The next step, prior to building the full-scale, is to determine quantitatively the structural adequacy of the adhesive bondline. In structural analysis, the parameter used for failure indication is known as M.S. (margin of safety) This parameter simply compares the ratio of the allowable strength of the adhesive to its critical applied stress. Positive M.S. means that the bondline is capable of withstanding the environmental loads, while negative value requires modification to the joint design. As illustrated in Figure 13, the analysis approach outlined in this paper will usually provide a more realistic value for M.S. Without combination of experimental work and finite element modeling effort, the usage of conservative interaction strength, shear and peel, of adhesive bondline may lead to an unnecessary redesign effort for the skin/stringer joint. Consequently, a significant cost may be incurred for not utilizing the actual strength of the adhesive bondline.

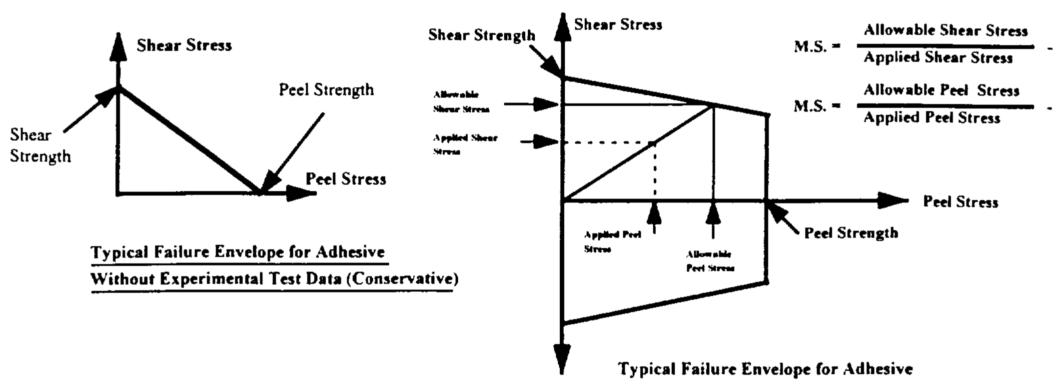

FIGURE 13. Method for Determining Margin of Safety

4. LESSONS LEARNED AND SUGGESTIONS

The structural integrity of adhesive bondline has always been recognized as a complicated problem because of many factors involved. Some are controllable, some may be depending on the skills of the analysts. Thus, there are no absolute or concrete ways to perform bondline analysis. The approach mentioned in this paper is just one of the plausible method which have been adopted by Boeing engineers during the design study of DC-Y LH2 cryotank. The major steps outlined in this approach were executed in the DC-XA Program and the results of the flight demonstration have proved that the LH2 cryotank was intact, i.e., it was able to withstand the intended applied loads. As with any study, there are lessons learned which need to be addressed in order improve the analysis methodology for future programs.

One of the lessons learned during the study of DC-Y LH2 cryotank is that component testing, for example, the stringer pop-off test, should be conducted before budget runs out. Another lesson is to request more budget to conduct additional coupon tests for adhesive, particularly at low temperature such as -268 deg. C. In the DC-Y study, limited tests were performed at this cryogenic temperature. Most of the data used in the development of failure criteria were conducted at -100 deg. C. In the modeling area, it is suggested that the bondline area should be well represented with sufficient solid elements. This would help to provide much better understanding of the joint behaviors. In most practical situations, the model, although computationally efficient, often involved considerable simplification of the structural geometry, which in turn could complicate the engineering interpretation of results.

There are other influences which are beyond the analyst's control, but have important contributions to the results. For instance, the method of construction and inspection of the skin/stringer structure could alter the analytical prediction significantly. Thus, it is suggested that a good quality control should be implemented to reduce the variation in the outcomes. This will certainly help enhancing the correlation work and eliminating concerns regarding the competent level of manufacturing capability.

5. CONCLUSIONS

Although the approach presented in this paper can be applied to any skin/stringer bondline analysis, the method of obtaining experimental data and developing finite element model is unique for each design situation. Factors such as joint geometry, material properties, stacking sequence, ply orientation have significant influences on the outcomes of adhesive stresses. The accuracy of results will not only depend on the data from testing but also from the fidelity of the finite element model. It should be recognized that early analysis planning and conducting appropriate coupon and subcomponent tests are essential to having successful failure prediction on the adhesive bondline. The developed finite element model must not be employed as a stand-alone tool but in parallel with experimental work. With continued enhancement, the approach presented here will become a useful technique for analyzing bonded joints in composite structures, particularly to the application of reusable launch vehicles.

6. ACKNOWLEDGMENT

The analysis approach in this paper was based on the work performed on the conceptual study of DC-Y LH2 cryotank by Boeing Advanced Structures Technology Group, Huntington Beach, California. This work was conducted under NASA/Boeing NRA 8-12 Partnership whose purpose is support the continued progress of SSTO concepts. Contributions from other key personnel at Boeing-Huntsville and NASA-MSFC were also significant to the success of the cryotank study.

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