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AGING EFFECTS EVALUATION OF A BEECHCRAFT STARSHIP MAIN WING

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ABSTRACT

The use of fiber-reinforced composites in aircraft structural components has significantly increased in the last few decades due to their improved specific strength and stiffness and superior corrosion resistance and fatigue performance with respect to their metal counterparts. Furthermore, current economic conditions require the use of most military and commercial aircraft beyond their original design service objectives therefore, it is necessary to understand aircraft in-service induced damage to ensure the airworthiness and structural integrity of aging airframes.

Most aging aircraft studies conducted thus far have focused on metallic structures; however, as more composite components are being certified and used on aircraft structural components, it is crucial to address this aging concern for composite components as well.

The primary objective of this paper is to summarize highlights of the findings of the aging study conducted on a Beechcraft Starship composite main wing after 12 years of service. The starship program was officially launched in 1982. Objectives were to produce the most advanced turboprop business airplane feasible at the time and to promote the use of composites in a business aircraft. The first Beechcraft starship was flown on February 15th, 1986. The second joined the test flight program in June 1986, and the third was ready for flight in the early spring of 1987. FAA certification was obtained on June 14 th, 1987 and a total of 53 airframes were built. Because of economic constraints and the prohibitive costs to support a small fleet, the original equipment manufacturer (OEM) gathered and scrapped the majority of its Starship airframes in 2003.

This paper provides a summary of the Starship main wing teardown activities, and results of the aging study. Results found suggest that the composite structure maintained its structural integrity over its service life and did not show significant degradation or detrimental signs of aging.

INTRODUCTION

As more commercial and military airplanes are required to maintain operational capability beyond their original design life objective, it has become necessary to answer the questions of their continued airworthiness and structural integrity. Most research conducted on aging structures thus far has focused on metallic components; however, with the increasing use of composite materials in primary and secondary structures, it has become necessary to address the long-term structural integrity of aging composite components as well. For advanced composite materials to be used in aircraft primary structures, it is necessary to demonstrate equivalent levels of safety, durability, and damage tolerance with respect to metallic structures. These materials also improve profitability to the operators in terms of initial and maintenance costs. Composites offer great advantages over metals: improved specific strength and stiffness, the ability to be tailored to design requirements in various directions, enhanced cost advantages (especially assembly), operating and maintenance cost savings and the potential of tremendous weight savings, which is closely coupled to fuel savings.

The Beechcraft starship aft wing, which is the subject of the current investigation, is the oldest primary structure built using composite materials for a small business aircraft application. In the late 1970s Beechcraft was leading the small business aircraft market as a result of the success of its King Air twin aircraft. However, the King Air aircraft design was over 15 years old and company executives had concerns about losing market shares in the future if new innovative designs were not introduced. As a result, in 1979, Beechcraft started working on a new pressurized, all-composite twin-engine business turboprop, the Starship, which would become the most ambitious development project in general aviation. The objectives of the program were to design and build the most advanced turboprop aircraft at the time and to promote the use of composite materials in airframe structures. The Starship received FAA certification in June 1987 and the (OEM) built a total of 53 airframes; but due to poor demand, only a few were ever sold.

In an attempt to characterize the structural integrity of the composite wing after 12 years of service, the National Institute for Aviation Research (NIAR) acquired the aged structure and conducted several nondestructive and destructive tests to assess its structural integrity. Generated data can be used to understand aging mechanisms on composite parts currently in service and to reveal main differences between damage mechanisms and damage accumulation in metallic versus composite components. This data could aid in future inspection and maintenance plans for composite structures to ensure their continued airworthiness and safety.

Non destructive evaluation was conducted per the OEM specifications to detect any potential damage or defects that could have been introduced during manufacture or service.

Thermal analysis was conducted using both Dynamic Mechanical Analysis (DMA) and Differential Scanning Calorimetry (DSC) to determine the aged material's glass transition temperature (Tg) as well as its degree of cure. Image analysis was conducted to characterize the state of the structure at the microscopic level and to detect possible flaws induced during manufacture or service. Physical tests were conducted to establish moisture and porosity levels in the composite structure and compare them to the design values. Mechanical tests will be used to evaluate the aging effects on the mechanical properties of the structure and to detect any changes with respect to the properties established during certification.

A full-scale static and residual strength test was carried out on the article to evaluate its "residual" life using the production wing with service history. The wing was tested to limit load, then subjected to an entire fatigue lifetime, followed by a residual limit load test. The intent was to demonstrate the load-carrying capability of the structure after 12 years of service.

The ultimate goal of the investigation was to assess the overall structural integrity of the composite wing after 12 years of service, to identify possible changes in the material properties due to environmental effects and/or flight service, to provide data to help understand aging mechanisms in composite structures, and to gain confidence in the long-term durability of composite materials.

TEST ARTICLE DESCRIPTION

The Starship aircraft shown in figure 1 is a pressurized twin-engine turboprop constructed primarily of advanced composite materials. Approximately 70% of the airframe weight is composite structure [1]. The composite aircraft features a variable sweep forward wing, twin vertical stabilizers mounted on the tip of the main wing (aft wing) and a ventral stabilizer located in the bottom aft portion of the fuselage. Pitch control is achieved using elevators located on the forward wing, yaw control is achieved using the rudders located on the wing tip vertical stabilizers and roll control is achieved using the main wing ailerons.

The structure under investigation is NC-8 main (aft) wing. The main (aft) wing is a monocoque structure constructed mainly of sandwich composite panels. The wing skins, spars, and ribs are sandwich panels fabricated using graphite-epoxy facesheets co-cured to Nomex Honeycomb core [2 and 3]. A schematic of the wing is shown in figure2.

Figure 1. Beechcraft Starship Airplane in Flight

The wing skins were designed to carry bending loads similar to spar caps, in a wing conventional design. The skins were fabricated using graphite epoxy skins co-cured to Nomex honeycomb core and were cured in one piece, 54 feet tip to tip. Stacking sequence, core thickness, and density varied depending on strength and stiffness requirements in a given area. During assembly, the precured panels were secondarily bonded together using paste adhesive. In addition to the skins, the aft wing assembly incorporated three full span spars, a main landing gear (MLG) spar, a curved leading-edge spar, five full chord ribs, and a main landing gear rib, as depicted in figure 2.

The aft wing main components (skins, ribs, and spars) were cured separately and subsequently bonded together in a secondary bonding operation using H- and V- joints, shown in figures 3 and 4. The H-joint is a procured, woven graphite epoxy H section that is bonded to the skin using film and paste adhesive. After bonding the H-joint to the skins, the spars are then secondarily bonded to the skins using paste adhesive. Similar to the H-joint, the V-joint is a precured V-section secondarily bonded to the skin and subsequently bonded to the spars using film adhesive.

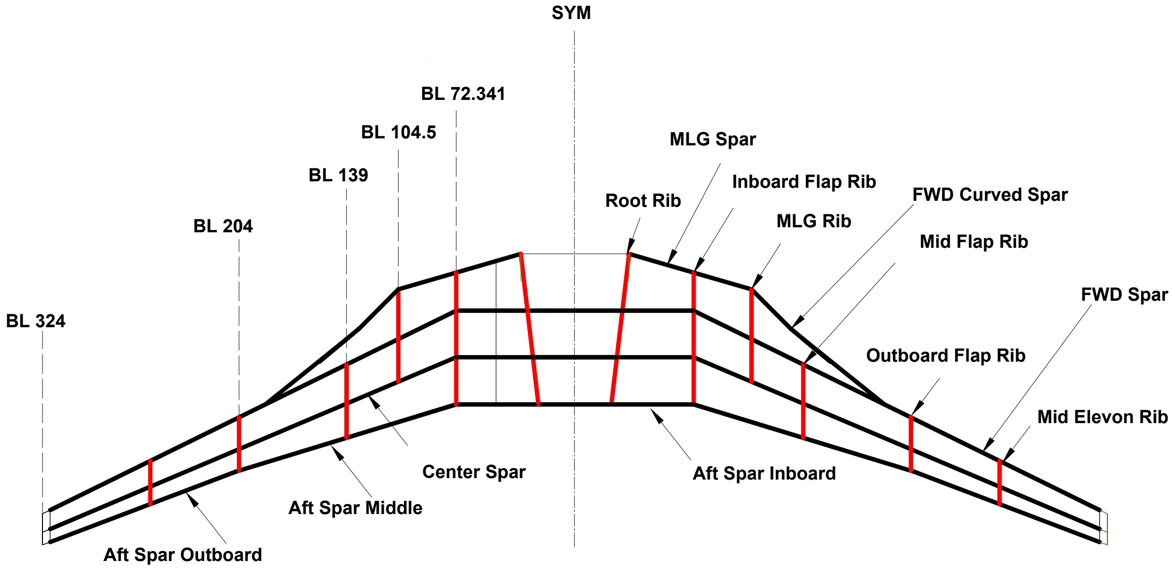


Figure 2. Aft Wing Structural Details

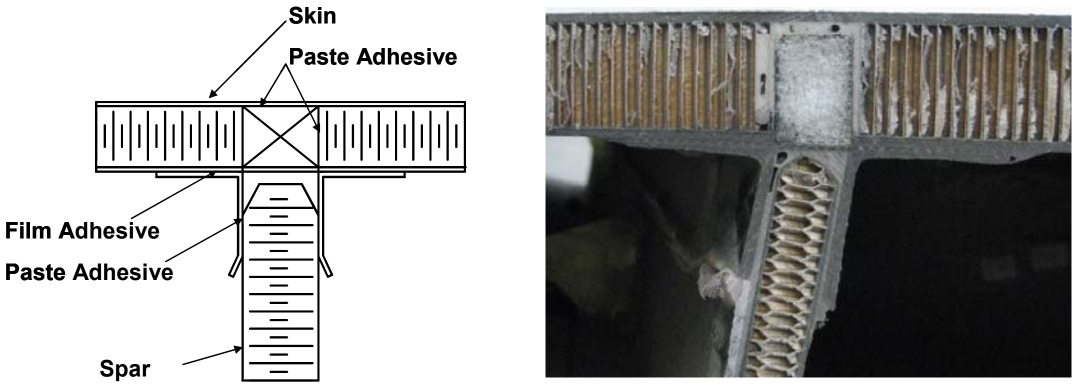


Figure 3. Beechcraft Starship Aft Wing Structural H-Joint Details (left) and H-Joint Extracted from BL78 Upper Skin Center Spar (right)

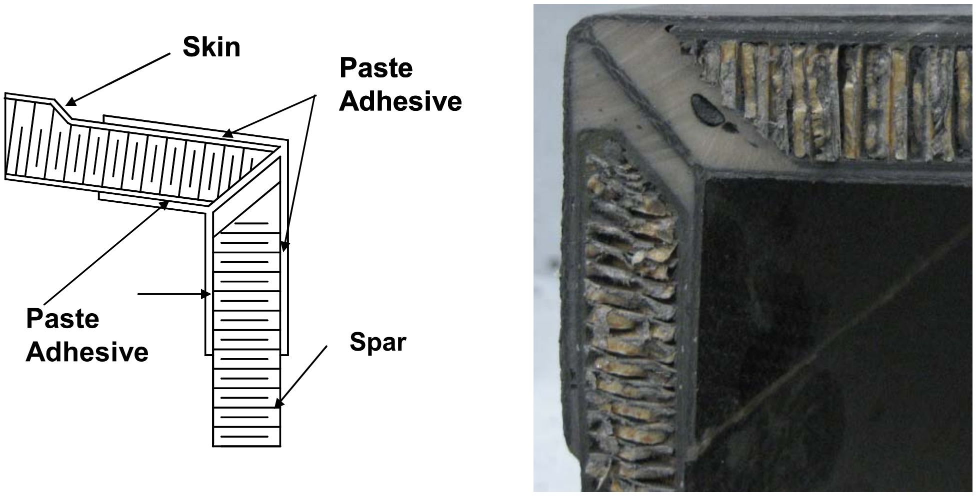


Figure 4. Beechcraft Starship Aft Wing Structural V-Joint Details (left) and V-Joint Extracted from BL78 Lower Skin Front Spar (right)

MATERIAL SELECTION/ QUALIFICATION

The best commercially available materials available at the time were selected based on ultimate strain capability for damage tolerance requirements, resin cure temperature, and glass transition temperature for toughness, environmental requirements, and process economy [2] The material selected was AS4/E7K8 and a wide variety of material weaves were used for maximum design flexibility [2].

Material qualification was conducted using the test matrices and statistical analysis methods published in MILHDBK 17. Material qualification data established the lamina properties for the various material forms considered.

LIGHTNING PROTECTION SCHEME

Lightning protection was achieved using a hybrid woven graphite/aluminum fabric as the surface ply in all exterior surfaces [2]. The aluminum wires used are 0.004″ in diameter and are capable of spreading the attachment energy over a larger surface, thus limiting damage from a 200 kA strike to the outer ply [4].

SUPPORTING DATA FOR CERTIFICATION

The Starship was certified to FAA part 23 regulations, commuter category option, amendment 34 plus special conditions [4 and 5]. These special conditions addressed the tests and analyses needed for composite structure substantiation and included damage tolerance substantiation, residual strength substantiation, and environmental effects considerations.

Certification was achieved through analysis supported by test. Finite element analysis using NASTRAN was conducted to determine the structure's internal loading, which was used along with analytic and test data to calculate margins of safety. Full-scale structural tests were used to validate the analytical predictions. Two analytical tools were developed and utilized for substantiation: LASP (Laminate Software Analysis Package) and SPAID (Sandwich Panel Analysis Impact/ Delamination) [5] and were used in conjunction with NASTRAN.

LASP was used to calculate laminate material properties using lamina properties for various environments. LASP was also used to apply the internal loads from NASTRAN to the given laminate and compute individual ply stresses or strain. Margins of safety were then calculated using stress interaction failure criteria. The finite element model was also used for analytical predictions in hot/wet environments using LASP hot/ wet lamina properties and was validated using moisture-conditioned full-scale components.

The SPAID analytical tool was used for stability analysis of panels under shear and compression loading and was used to predict buckling and TOD (Threshold of Detectability) failure loads from which margins of safety can be derived.

STARSHIP AFT WING TEARDOWN OBJECTIVE

The objective of the teardown of the Starship graphite epoxy main wing was to evaluate the aging effects on the structural integrity of the composite structure after 12 years of service. The main goal was to evaluate the structural health of the aged composite structure after 1800 flight hours accumulated during 12 years of service.

To accomplish this task, the research was subdivided into several subtasks: nondestructive and destructive tasks. The goal of the nondestructive inspection was to characterize the state of the structure after 12 years of service, to investigate the existence/extent of flaws introduced during manufacture or service using OEM NDI specifications.

The objective of the destructive inspection/evaluation was to conduct mechanical tests, thermal analysis, physical tests and image analysis and to compare the data to that generated during the design phase, whenever possible. A full-scale test was also conducted on the production model and subjected the wing to the most critical static load case that the article sustained during certification. The static limit load test was followed by fatigue spectrum loading, where the article was subjected to the equivalent of one lifetime of fatigue cycles, then it was concluded with another limit load test. The objective of the test was to evaluate the structural response of the aged wing as compared to that of the article used for certification.

NONDESTRUCTIVE INSPECTION (NDI) PRIOR TO FULL SCALE TEST

Because of transportation constraints, the main wing was cut into two pieces at approximately LBL 50. The Left-Hand wing was used for destructive evaluation and the Right-Hand was used for the full scale test.

Visual inspection, tap testing (TT), and Ultrasonic (UT) NDI were used to inspect the Right-Hand wing. Tap testing was conducted on the entire wing surface and was used to detect areas of possible damage/ defects. Any suspicious areas were inspected using UT to confirm the TT results. The initial TT examination of the upper aft wing skin did not reveal any damage or defect in the test section (RBL 100-RBL324) but revealed a disbond in one location as identified by the inspectors and shown in figure 5.

This area was inspected with the UT procedure for verification. The UT confirmed the disbond in an area approximately 15.50″ by 12.00″. The “damaged” area was repaired using a wet lay-up bonded repair according to the OEM specifications. During the repair, it was found that the area identified as a disbond was potted and that the ultrasonic and tap testing signals obtained were caused by sound attenuation through the potting material and not because of damage.

Initial inspection of the lower skin revealed two delaminations away from the test section, in the area where the wing was cut and a small dent at approximately BL 230 (Butt Line) close to the rear spar.

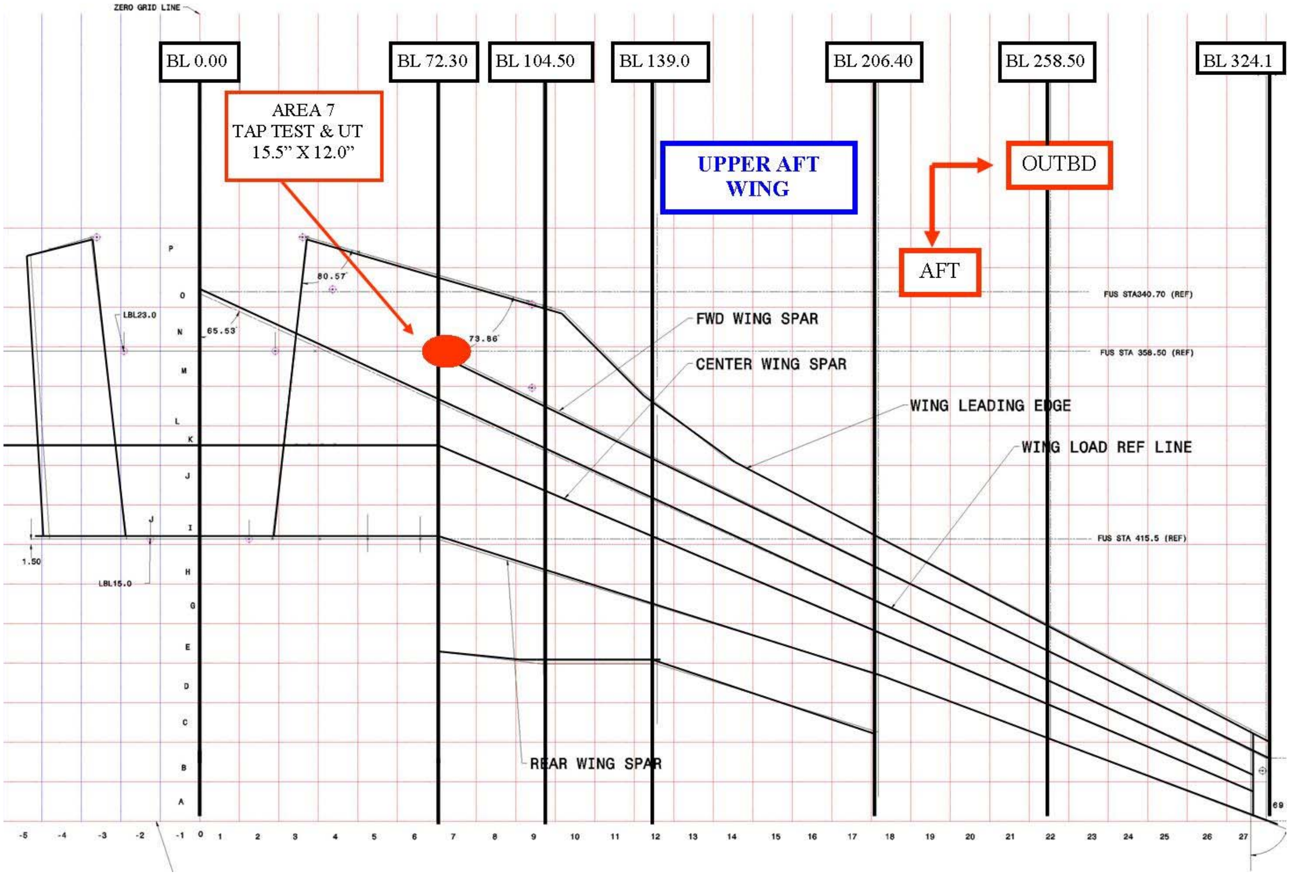


Figure 5. Beechcraft Starship Upper R-H Aft Wing Inspection Map

NON-DESTRUCTIVE INSPECTION OF THE L-H WING USED FOR DESTRUCTIVE EVALUATION

Through Transmission (TTU) scans of the L-H upper and lower wing skins are shown in figure 6. TTU NDI showed no gross flaws induced during manufacture or service in the skins. OEM records suggest that porosity levels in the upper skin flanges exceeded 2.5%.

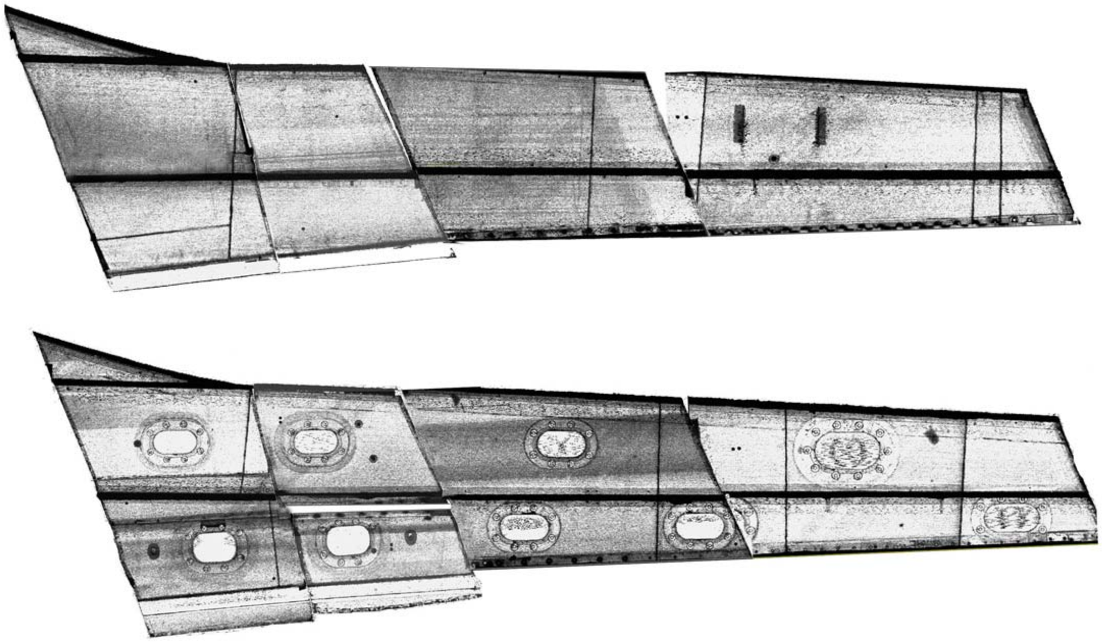


Figure 6. Beechcraft Starship TTU Scans of the L-H Upper and Lower wing skins

THERMAL ANALYSIS

Thermal analysis was conducted on coupons extracted from both the upper and lower skins to evaluate any possible changes in the thermal properties of the material after 12 years of service. The thermal tests conducted included Dynamic Mechanical Analysis (DMA) and Differential Scanning Calorimetry (DSC). DMA tests measure the response of a material to a periodic stress and provide information about the modulus and the damping of the material.

DMA curves provide two values of glass transition temperature (Tg) a value based on the onset storage modulus or material fiber stiffness loss and a value based on material damping/maximum viscosity, which is the peak of Tan Delta, as shown in figures 7 and 8. The storage modulus is a characteristic of the material fiber stiffness, whereas the damping is a characteristic of the matrix of the material. The Tg value based on the onset of storage modulus is always more conservative than the value obtained using the peak of Tan Delta.

Coupons extracted from the upper skin yielded average Tg values of 156.4°C (313.6°F) (Onset of Storage Modulus) and 177°C (350.7°F) (Peak of Tan Delta), respectively. Coupons extracted from the wing lower skin yielded average Tg values of 153°C (307°F) (Onset of Storage Modulus) and 175.5°C (347°F) (Peak of Tan Delta), respectively. Figures 7 and 8 show examples of DMA data obtained for samples extracted from the upper and lower skin facesheets. The Tg values obtained are consistent with the value that would be expected for the E7K8 resin system. Figure 7 shows two peaks of TAN δ : one occurring at 125.4°C and the latter at 175.8°C. DMA data shown in figure 7 is for a coupon extracted from the upper skin lower facesheet at

BL 52 and FS 353 (fuselage station). Unlike lower skin coupons, most of the upper skin coupons had AF 163 film adhesive in both facesheets. The first TAN δ peak corresponds to the adhesive Tg.

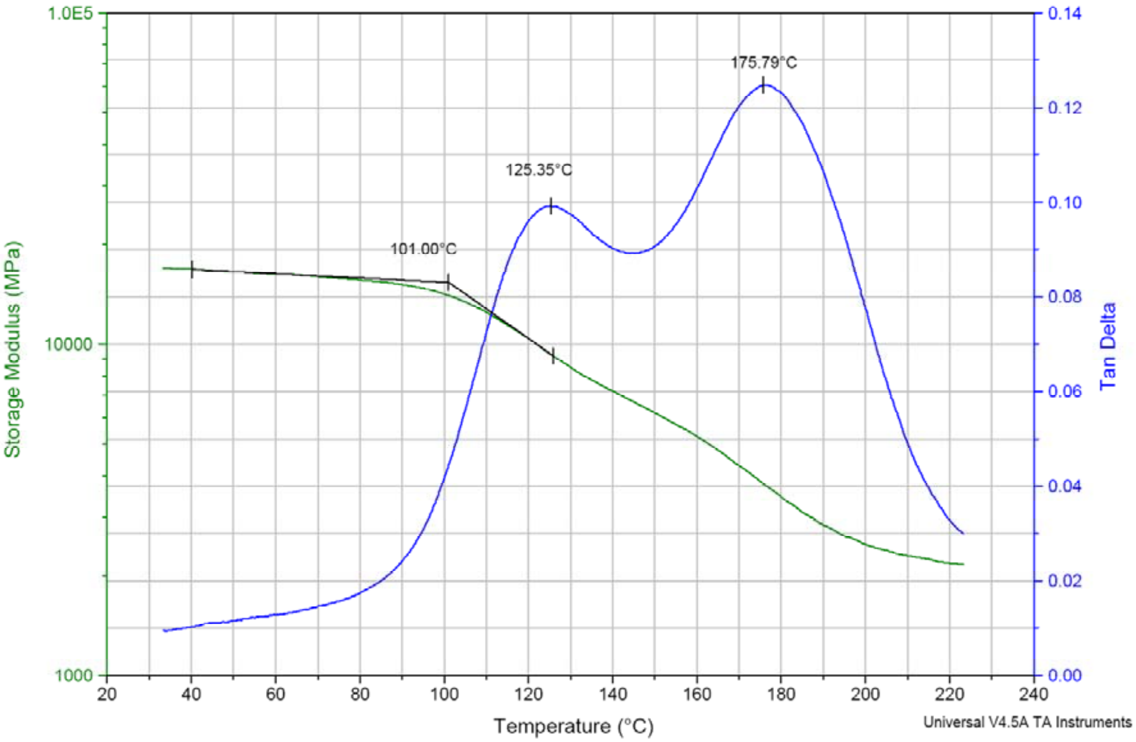


Figure 7. DMA Results for a Sample Extracted from US BL 52 LF15 FS 353

DSC tests, per ASTM D3418-03, were also conducted on specimens extracted from both skins to evaluate the degree of cure of the material. In a DSC test, samples are heated at a constant heating rate and the difference in heat input between the test sample and a reference material due to energy changes is monitored. Transitions due to changes in morphological or chemical reactions in a polymer can be detected as the sample is heated and the corresponding changes in heat flow and specific heat capacity can be calculated. Sample DSC curves are shown in figures 9 and 10.

DSC tests conducted on the upper skin samples yielded an average heat of reaction of 1.4 J/g, an average exotherm onset temperature of 186°C and an average exotherm peak of 212°C. DSC tests conducted on the lower skin samples yielded an average heat of reaction of 2.3J/g, an average exotherm onset temperature of 182°C, and an average exotherm peak of 211°C. For both upper and lower skin coupons, the heat of reaction values were very small indicative of fully cured laminates. To precisely determine the degree of cure of the aged structure, DSC tests will be conducted on an AS4/E7K8 prepreg sample to determine the heat of reaction required to fully cure the sample. All the heat of reaction values obtained from subsequent tests will be normalized with respect to this value to obtain a cure conversion % indicative of the degree of cure of the samples extracted from the part.

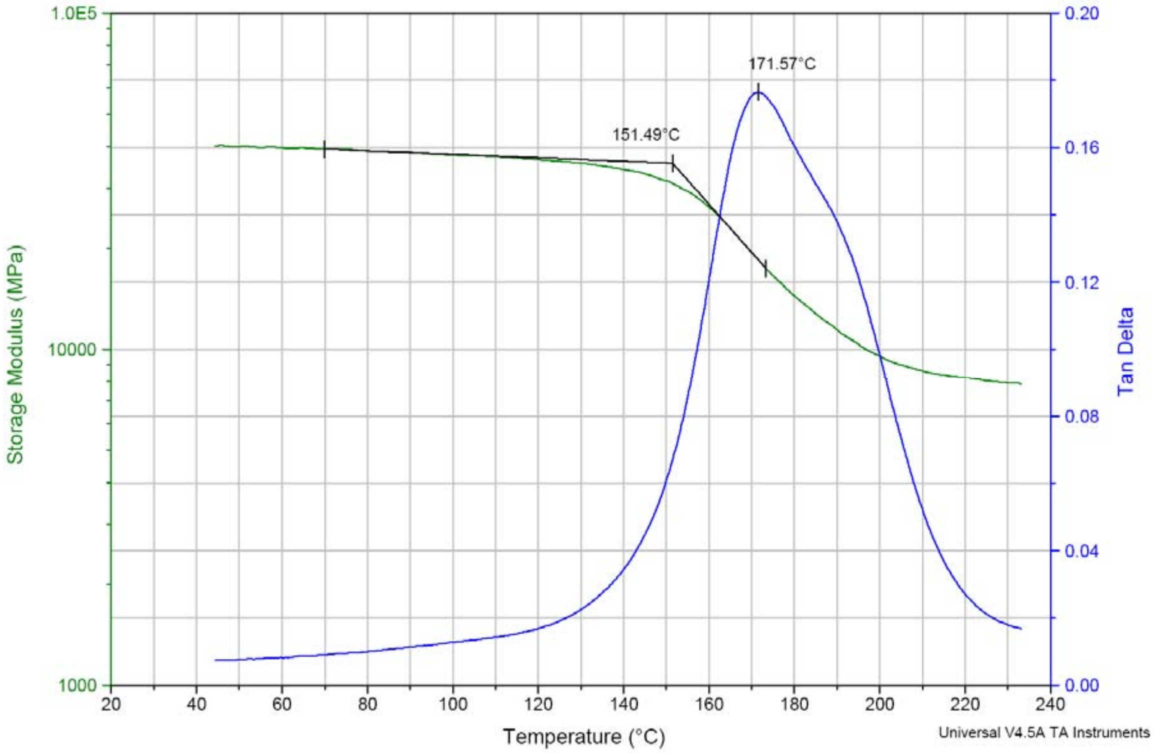


Figure 8. DMA Results for a Sample Extracted From LS BL208 UF16 FS450

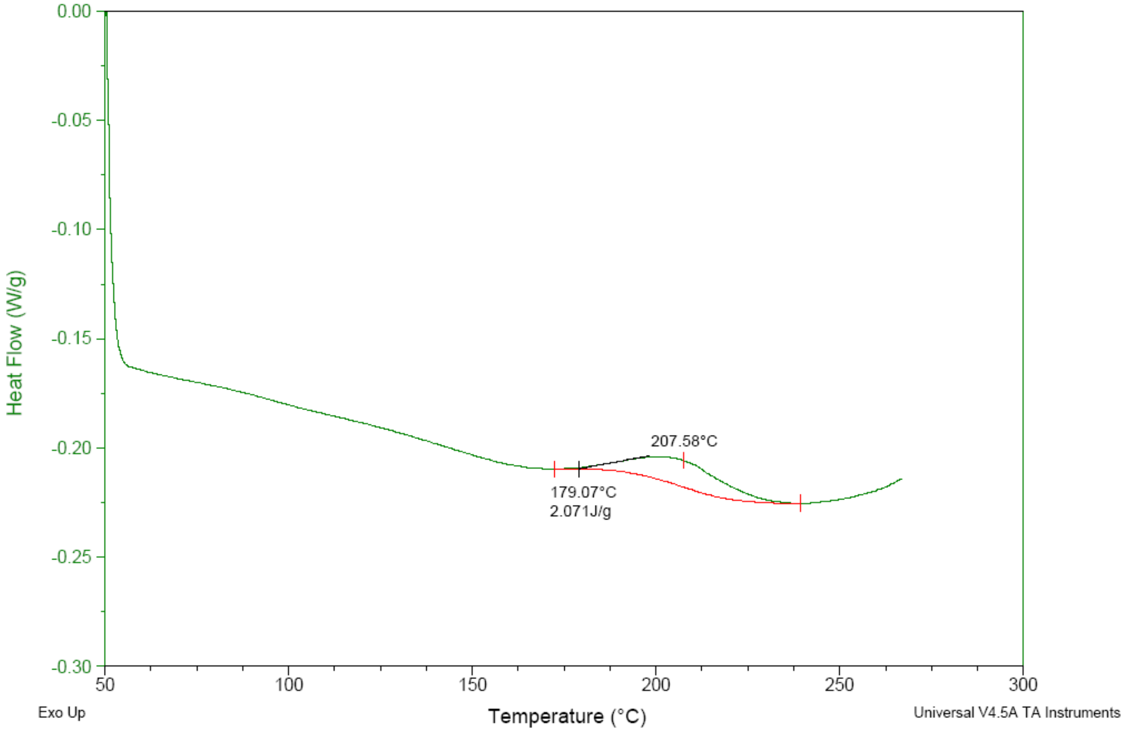


Figure 9. DSC Data for a Sample Extracted From LS BL50 LF28 FS 394

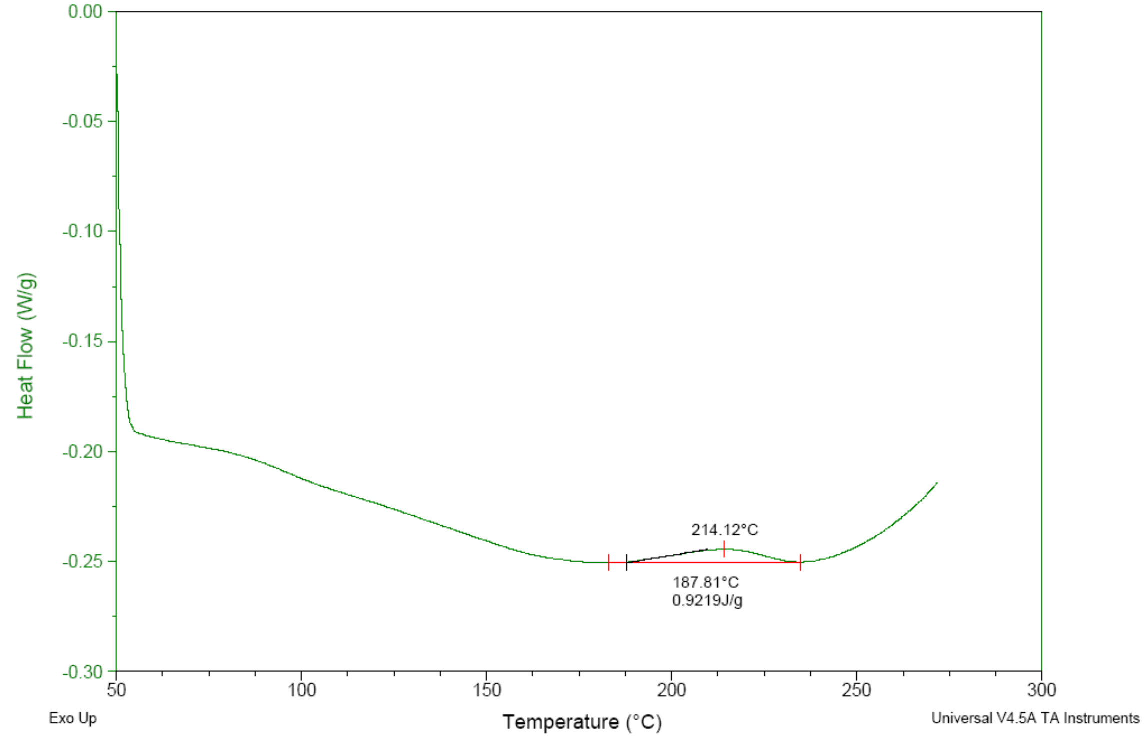


Figure 10. DSC Data for a Sample Extracted From US BL140 UF17 FS 431

MOISTURE CONTENT EVALUATION

Moisture content in the aged structure was quantified using ASTM D 5229 using coupons extracted from both skins. Figures 11 and 12 show the moisture loss as a function of time for selected skin samples. The maximum moisture content was found to be 1.065% for the upper skin and 1.286% for the lower skin. This is very consistent with the moisture analysis data generated by the OEM and the moisture analysis data published in the NASA report [6] for the T300/5208 system, which predicted a 1.1±0.1% total weight gain expected in the structure in service due to moisture uptake.

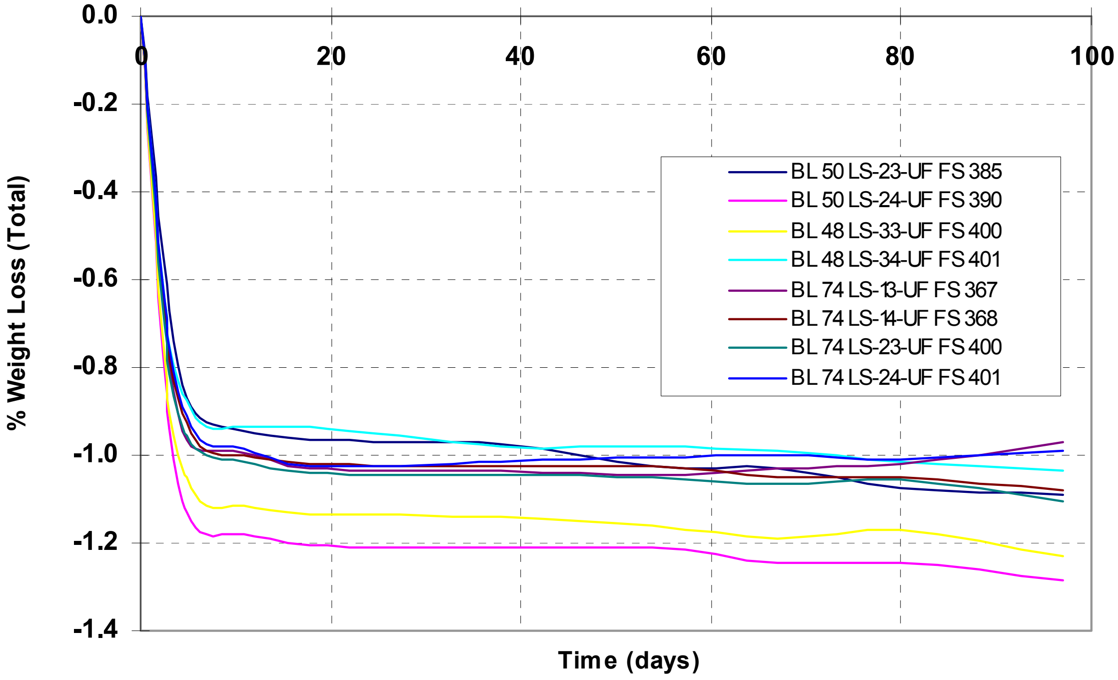


Figure 11. Moisture Loss as a Function of Time for Coupons Extracted From the Lower Skin

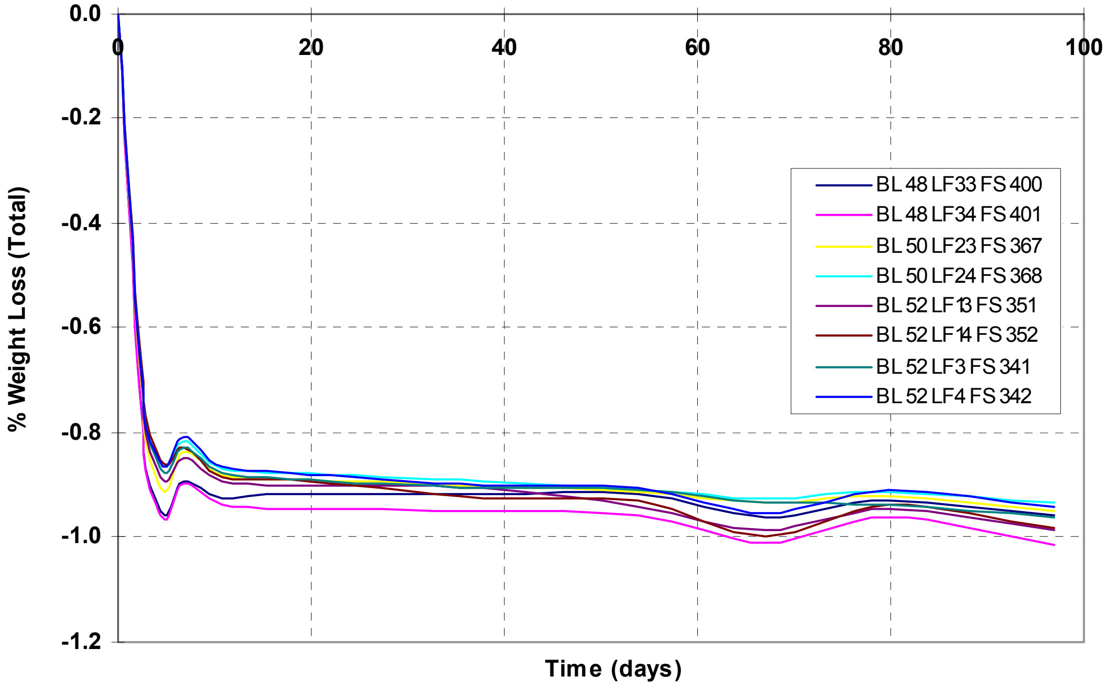


Figure 12. Moisture Loss as a Function of time for Coupons Extracted from the Upper Skin

FULL-SCALE STRUCTURAL TEST

A full-scale structural test was conducted to evaluate the aging effects on the response of the wing and estimate the "residual" life of the component using the production article that has service history. This was also a unique opportunity to use a production model to validate the component's (Starship aft wing) structural integrity after 12 years of service. It used the same team that conducted the full-scale tests during certification for the production article which minimizing test variability. The Full-scale test setup is shown in figure 13.

A baseline Nondestructive Inspection was conducted according to OEM specifications prior to subjecting the structure to limit load test. An NDI grid was drawn on the structure for ease of inspection and flaw growth monitoring. Visual inspection, TTU, and tap testing were used for the inspection.

The load case that was chosen for the full-scale structural test was Load Condition 4A- or maximum positive moment, the most critical load case. During this test the wing suffered damage during certification at 122% LL (limit load), 135% LL and 141% LL before sustaining UL (ultimate load). This load case was the most severe in terms of the magnitude of the compression loads (maximum moment) applied to the wing's upper skin.

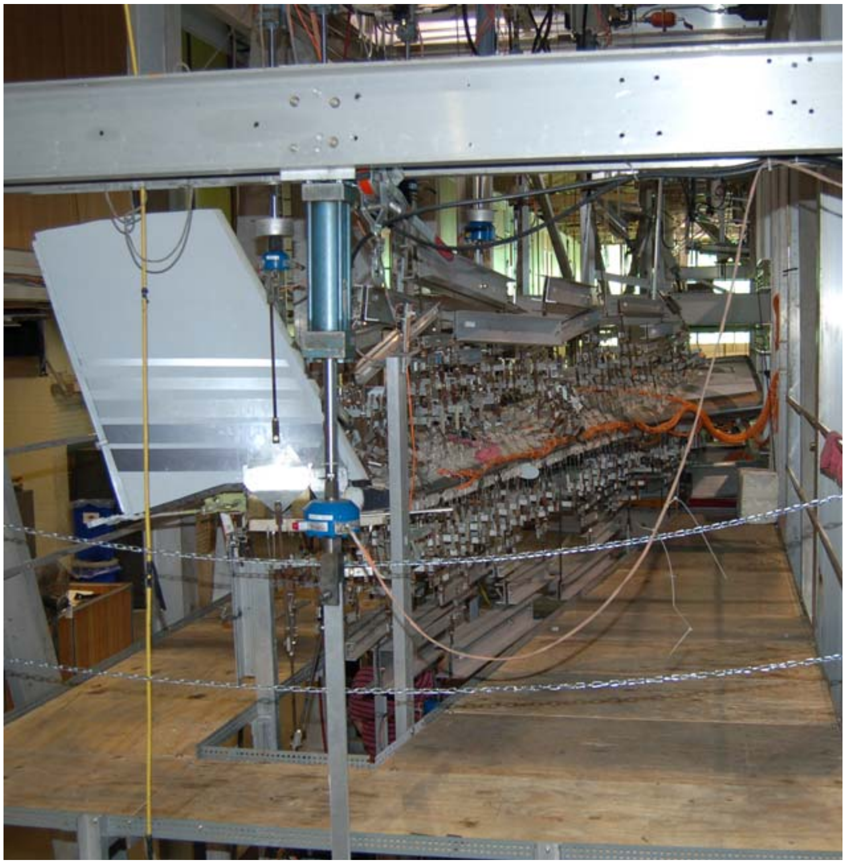


Figure 13. Full-Scale Test SetUp

The shear/moment and torque introduced matched the static 4A values very closely (maximum positive bending condition applied during certification) from BL 100 to BL360 thus the test section of interest was outboard of RBL 100. A plot of the moment diagram (as a function of load station) is shown in figure 14.

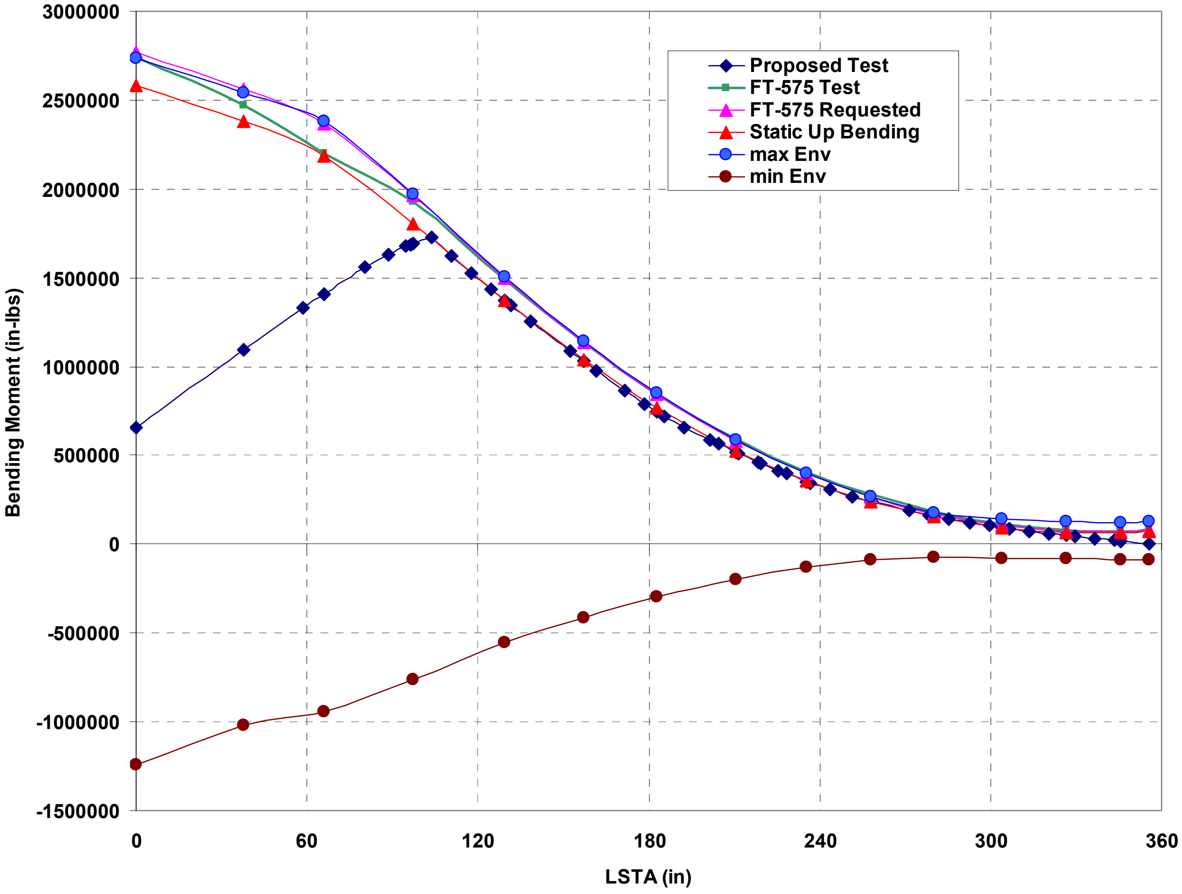


Figure 14. Bending Moment versus LSTA

The full-scale test article was instrumented using strain gages and deflection transducers to monitor test article deformation during the test. Strain gage locations were based on the analysis conducted during certification, which identified the wing critical stress and strain areas. The locations chosen were the same as those used for the certification test article and are shown in figure 15. The intent was to be able to compare the displacements and strains of the production article with service history to that of the certification test article.

The wing was loaded to 100% limit up-bending load at 10% load increments and load, strain, and displacement data was acquired during the test. A photograph of the deformed wing at limit load is shown in figure 16.

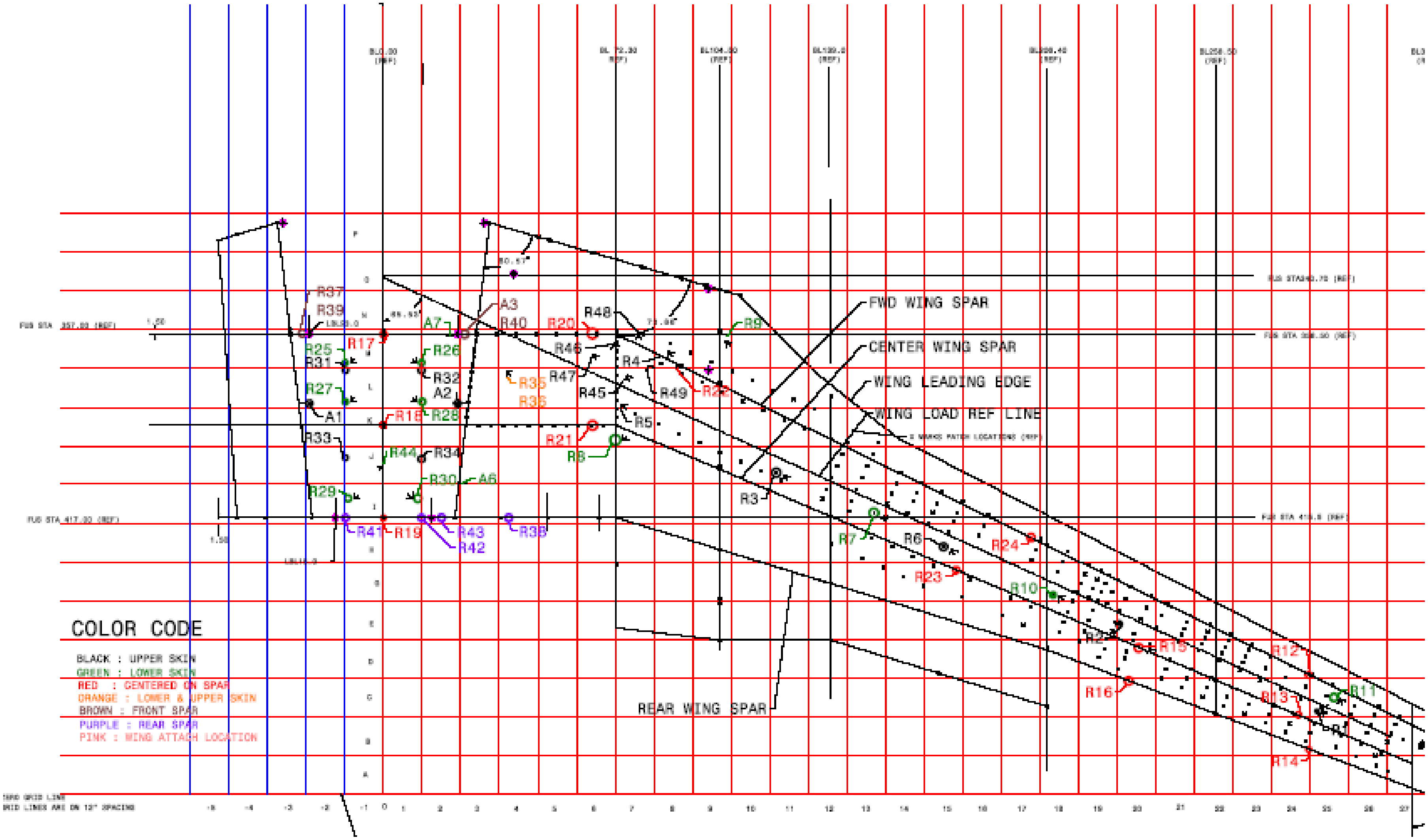


Figure 15. Starship R-H Main Wing Strain Gage Identification and NDI Grid

Figure 16. Deformed Wing at Limit Load

The strain versus % LL comparison between current test and wing maximum up-bending certification test (Cond 4A) is plotted in figures 17 and 18 for strain gages R6A (compression, upper skin) and R10 (tension, lower skin) shown in figure 15. As shown in both figures, strain data from the aged test article correlates very well with strain data from the certification article subjected to the same load case. This demonstrates that there is no major change in the overall structure stiffness/compliance and structural response.

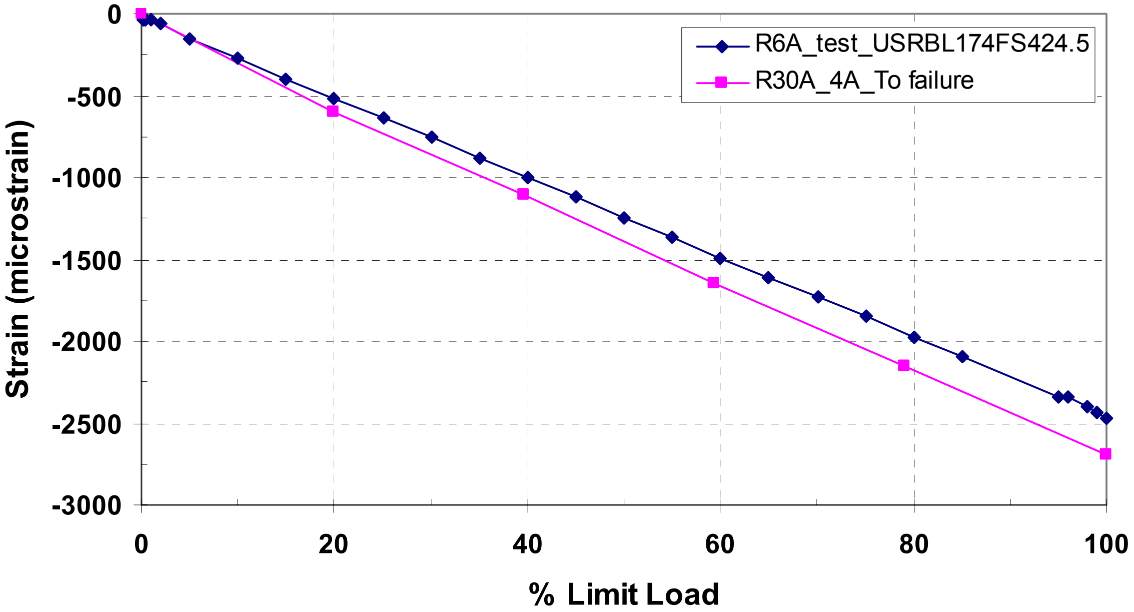


Figure 17. Strain vs % LL (Current Test vs Static Max Upbending Test to Failure)

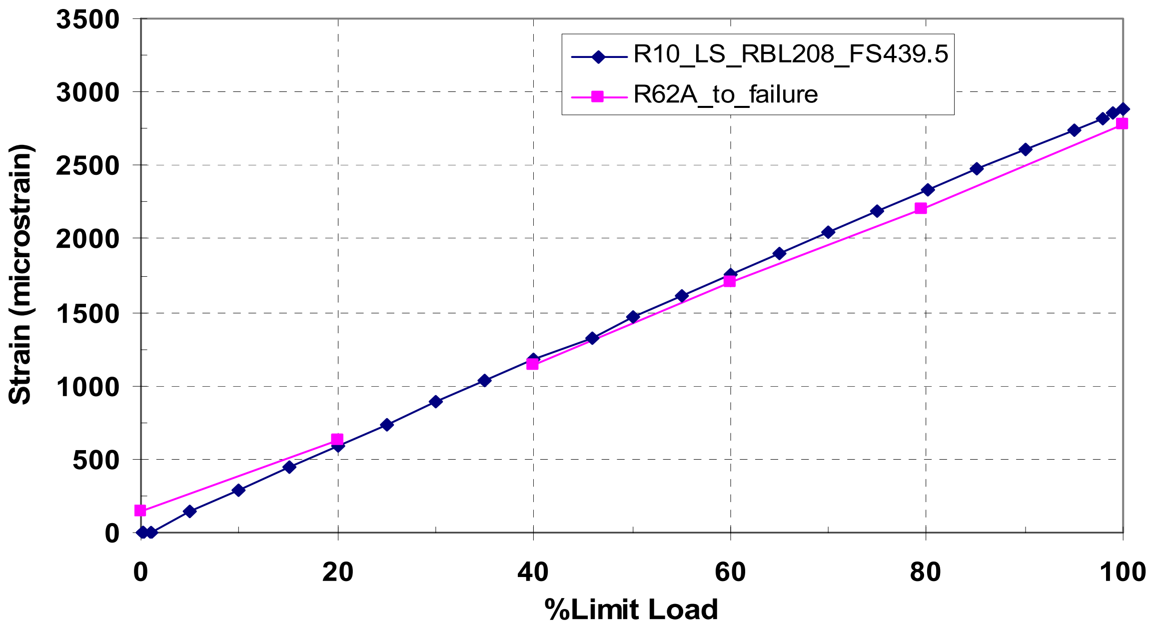
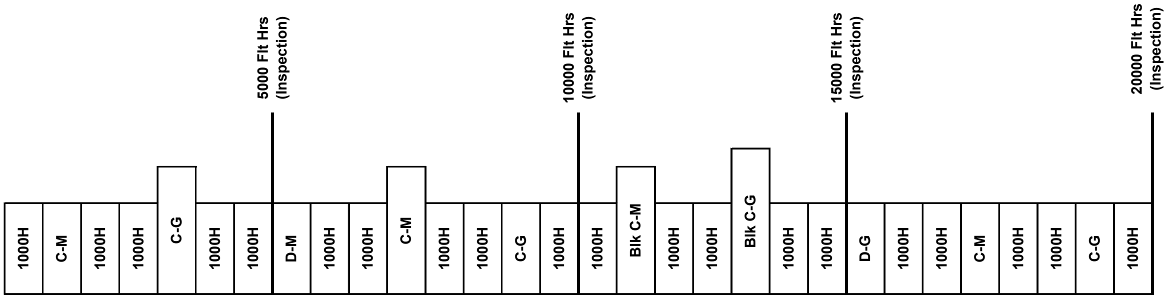


Figure 18. Strain vs % LL (Current Test vs Static Max upbending test to failure)

After completing the full-scale limit load test, the aft wing was subjected to an entire fatigue lifetime to investigate the durability of the aged aft wing. Fatigue load applied were the same as those developed for the full-scale certification article and included gust, maneuver, landing, and taxi loads. All fatigue loads were applied with a 15% LEF (load enhancement factor). Landing loads were not included as the structure did not have a landing gear or engines attached. Relieving loads were added to the landing gear and engine mount fittings to reduce the bending moment at the root of the wing (wing box). Due to the wing fixturing (cantilever wing), negative loads (upper skin tension loads) were truncated and only positive loads (upper skin compression) were applied. The wing was subjected to 200395 cycles of fatigue, 1 lifetime equivalent to 20000 service hours. The spectrum loading sequence is shown in figure 19.



1 test lifetime = 20000 hours consists of 219395 total cycles

Figure 19. Spectrum Loading Sequence

After completion of the durability test, the aft wing was inspected and subjected to a limit load residual strength test. The wing sustained 100% positive bending test and residual strength data correlated very well with certification data demonstrating no detrimental aging effects on the structural integrity of the article.

CONCLUSIONS

The Starship main wing teardown evaluation demonstrated that the structure held extremely well after 12 years of service with no obvious visual signs of aging as would a metal structure with a similar service history exhibit.

Thermal analysis results showed no evidence of degradation in the thermal properties of the material and that the skins are fully cured/cross-linked.

Physical tests showed moisture levels indicative of a structure that has reached moisture equilibrium (consistent with other long-term service exposure data published in the literature).

LH NDI showed no major defects/damage in the skins introduced during manufacture or service

Full-scale test results of the "aged wing" correlated very well with the results obtained for the certification article.

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