BELL 525 VERTICAL FIN / AFT FUSELAGE AND TAILBOOM COMPOSITE/METALLIC HYBRID CERTIFICATION FATIGUE TESTING

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Abstract: This paper describes the certification fatigue test approach of the vertical fin, aft fuselage, and tailboom of the Bell 525, a super medium commercial transport helicopter. Specialized test methods, data collection and analysis are used for these composite/metallic hybrid structures. The approach for testing these full-scale components was developed in partnership with the National Research Council Canada (NRC). Testing for initial structural certification was completed at the full-scale structural test lab M-14 in Ottawa, Canada.

Keywords: Fatigue testing, Environmental Testing, Hybrid Structure, Rotorcraft

INTRODUCTION

As material options have expanded for aerospace structures, the structural engineers' task to design the most lightweight structure capable of sustaining the expected flight loads becomes more challenging. In particular, optimizing material selection for specific structural applications can lead to a high degree of heterogeneity in a given structural assembly. Many aircraft structures are now being designed with principal structural elements (PSE) that combine composite and metallic components. Composite / metallic hybrid structures provide substantial advantages for structural design; however, they also raise several challenges for certification, which add complexity and cost to aircraft development programs.

For both fixed wing aircraft and rotorcraft, one of these challenges is accounting for structural strength and fatigue tolerance for large scale structures, given the different damage mechanics, environmental tolerances, loading modes, spectra, coefficients of thermal expansion (CTE) and failure modes of the metallic and composite elements. Interfaces between these elements are particularly challenging, given potentially complex interactions at joints, with failure mechanisms driven by the interaction between the material characteristics. This drives a need for a certification approach that puts safety as its primary focus while striving to be as efficient as possible with respect to development costs and program schedules.

As a result, conducting substantiation analyses and tests to comply with structural certification requirements for these structures requires additional effort and consideration. This paper details the approach taken by Bell Textron to conduct fatigue testing on the composite / metallic hybrid aft fuselage / tailboom and vertical fin of the Bell 525. The approach generates the relevant data to show compliance to certification requirements by fatigue testing combined structures in environmental chambers to reduce the requirement for load enhancement factors (LEF). The National Research Council Canada (NRC) partnered with Bell to support the certification effort with full scale testing and developed specialized techniques and equipment to successfully complete them.

COMPOSITE / METALLIC HYBRID CERTIFICATION TEST APPROACHES

Challenges

One of the immediate issues when confronted with certification tests of full scale composite / metallic hybrid structures is that the traditional approach to metallic fatigue testing has been to limit or 'clip' the peak loads from the spectrum to ensure that crack growth retardation effects are reduced and test results may be conservative [1], whereas composite materials do not have notch tip plasticity and therefore high peak loads should be retained in a composite fatigue spectrum. Conversely, composite materials tend to be insensitive to higher cycle lower strain load conditions, which presents an opportunity from a spectrum truncation and hence test completion time point of view, whereas the truncation level requires careful analysis in terms of effect on metallic structures to validate that spectrum truncation does not excessively reduce fatigue damages that may affect crack nucleation or growth. These competing requirements can be addressed at the element or component level, but obviously cannot be overcome by such decomposition when testing the full test article. Another issue related to this is the inclusion of load enhancement factors (LEFs) to the spectrum loads to account for higher composite fatigue property scatter. The material scatter LEF is applied to the test loads to allow the total test scatter factor and hence cycles required to be reduced, increasing test efficiency. A second set of LEFs are applied to full scale test articles to compensate for environmental conditions that are typically impossible to replicate for the full test article. The inclusion of these LEFs is multiplicative to a load spectrum and can be quite significant, to the point where the modified load spectrum is no longer suitable for the metallic materials, with peak loads exceeding the acceptable 'clipping' level. Finally, and more specific to rotorcraft in the Bell 525 weight class, CFR 14 Part 29 rotorcraft have prescribed certification requirements for metallic and composite fatigue substantiation, with composite fatigue substantiation following a damage tolerance and fatigue evaluation approach, and the metallic materials requiring a fatigue tolerance evaluation (FTE) approach.

Previous Certification Test Approaches

Due to the above challenges and given the wide variability of specific structural designs and arrangements, the specific approach required to provide sufficient data to support certification can differ. Proposed and successful previous approaches include: conducting tests on two separate full scale test articles focusing on certification of the metallic and composite components independently; by using the building block approach to validate composite or metallic subcomponents at various levels of the pyramid; reserving the full scale test for one or the other material as was done for the F-35 [2]; or similarly, by careful test and validation of material performance and fatigue behaviour at the element and component level and using the full scale test for primarily for the metallic material, as in the Boeing 787 [3]. For reference, the approach recommended by Composite Materials Handbook 17 Volume III (CMH-17) [4], suggests that durability certification of composite / metallic hybrid structures use a building block approach and verify composite durability at the coupon, element or subcomponent level, and reserve the full-scale test for the metallic parts.

Material Property Scatter Factor LEF

As composite materials have generally flat S-N curves, leading to large fatigue scatter factors, the full-scale test, being a single article, would require many lifetimes of cycling to account for the greater scatter factor. During composite certification activities on the F/A-18, Whitehead [5] showed that in order to demonstrate B-basis reliability for an all-metal wing, a scatter factor of 2 was sufficient, but to establish a similar reliability for composite a factor of 14 was required. Since these high scatter factors impose unacceptable costs and time for testing, the generally accepted approach, which was proposed by Whitehead, and codified in CMH-17, is to use a combined load factor and life factor approach. This approach recommends increasing the applied loads in the fatigue test so that the same level of reliability can be achieved with a shorter test duration. The scatter factor LEF for the specific material type can be derived via coupon testing, but conservative values are available in open literature. A great deal of analytical and empirical research conducted by the National Institute for Aviation Research (NIAR) on material scatter LEFs has shown promising potential efficiency gains both by proposing refined material scatter factor LEFs based on more recent material property coupon testing and by proposing a Load Life Shift (LLS) approach, which combines a metallic durability and damage tolerance test with no material scatter LEFs, with an added damage tolerance phase where material scatter LEFs are incorporated [6].

Environmental Property LEF

Composite material properties in most instances are more sensitive to temperature and moisture than metals. The effects of temperature and moisture are accounted for in design by using the building block approach and conducting coupon, element and subcomponent tests in the expected service conditions. This provides sufficient information for design and can be used to determine an appropriate environmental LEF. For rotorcraft, CMH-17 notes: “To avoid increased costs associated with setting up and maintaining environmental chambers, tests can be conducted at room temperature ambient conditions provided the applied loads are adjusted for environment with the use of an appropriate load acceleration factor.” The recommendation is to conduct analysis and coupon testing to determine the environmental knockdown factor from room temperature ambient to the service condition and apply this factor to the applied load spectrum.

LEF Combination Considerations

Although the LEF approach allows an efficient way to validate structural life reliability, the combination of the material and environmental LEFs can result in an undesirably high load factor. For rotorcraft, the typical arrangement of engine exhaust that impinges on the aft fuselage and tailboom due to rotor downwash leads to relatively high temperature service conditions that results in commensurately high environmental LEFs. When combined with the material scatter factor, the resulting change to hybrid structure test loads could conceivably change the fatigue failure mode or even locally exceed the static strength of the underlying metallic structure. For hybrid structures, these high LEFs also present challenges, as local stress concentrations in metallic components would be subjected to stresses that diverge substantially from the anticipated service loads.

Bell 525 Certification Test Approach

For the specific challenge of supporting compliance to certification on the Bell 525, the empennage structures under consideration are located downstream of the turbine engine exhaust and are thus subject to high temperature (hot/wet) operating conditions. As discussed above, the traditional guidance for addressing this environmental effect on composite materials is to determine the effect of the operating conditions on the material properties via coupon testing. As the Bell 525 empennage is a hybrid structure and is subject to specific and generally higher temperature conditions relative to other aerostructure, it was not amenable to the traditional environmental LEF approach. The combined environmental LEF for hot/wet operating conditions combined with the material scatter LEF was considered to be unacceptably high and could have resulted in unrealistic premature failure of the underlying metallic structure, which would introduce non-representative damage of joints and fasteners, or in extreme cases, local yielding which may have invalidated the conclusions on fatigue strength.

As a result, the hybrid structure was validated by encasing the fatigue test articles in custom NRC designed heated enclosures. The enclosures were designed to maintain a hot/dry environment throughout fatigue and residual strength testing (RST). The use of heated enclosures allowed a significant reduction in the required environmental load factor, with the remaining difference between a hot/dry and hot/wet condition requiring only a small environmental LEF. Consequently, the test loads permitted both the composite and metallic structures to be appropriately evaluated simultaneously. The composite material scatter LEF which was selected for the tests was used as justification for additional lifetime scatter on the metallic components.

To technically de-risk the test schedule, simplify test spectrum generation and application and allow for more compact form factors, Bell elected to split the full-scale testing of the empennage area into two (2) separate full scale tests. The test designation and areas under consideration for each of these tests were:

Aft Fuselage / Tailboom Test

- Aft fuselage from approximately aft half of baggage compartment to tailboom interface (primarily composite)
- Fuselage / Tailboom Interface (primarily metallic)
- Tailboom from fuselage interface to area forward of vertical fin attachment structure (primarily composite)

Aft Tailboom / Vertical Fin

- Approximately 1/3 of aft portion of tailboom (primarily composite)
- Vertical fin attachment structure (composite), including h-stab attachments (metallic)
- Vertical fin structure to tail rotor attachment (primarily composite)

Both tests were to be operated throughout the cycling and residual strength test phase within heated enclosures capable of achieving an even temperature distribution throughout the test article within a tolerance band of ±5.5ºC. For the aft fuselage / tailboom test, an additional requirement was to achieve two zones of temperature control, one for the aft fuselage, and another for the tailboom.

TEST GOALS

Structural tests were conducted as part of the overall Bell 525 test program and provide structural data in support of the aircraft certification. The goals of the tests were to:

- Evaluate the damage tolerance of composite Principal Structural Elements (PSE) structures with intrinsic flaws and impact damages;
- Determine the fatigue strength of metallic PSE structures to determine a replacement time based on crack initiation time in an as-manufactured component;
- To perform strain surveys under static load conditions to collect strain, displacements and load reactions data to validate the airframe Finite Element Model (FEM);
- To demonstrate residual strength of the structure to the post fatigue test static requirements;
- To provide substantiating data to show compliance to the applicable CFR Part 29 requirements

Intrinsic Flaws / Impact Damage Strategy

Per the certification requirements for composite components, damage tolerance requires demonstration that catastrophic failure due to static or fatigue loads be avoided throughout the operational life or prescribed inspection intervals, while considering intrinsic or discrete manufacturing defects or accidental damage. Bell conducted a thorough analysis and threat assessment of the PSE's and incorporated intrinsic flaws into the test specimens in the locations where flaws would produce conservative test results. Further, the threat assessment was used to establish impact locations, and these were incorporated into the test articles prior to delivery to NRC. For the aft-fuselage / tailboom test, the impacts were Category 1 only or Barely Visible Impact Damage (BVID), for the Vertical fin / aft tailboom specimens the impacts included Category 1 and Category 2.

A difference in approach for the two test articles with regard to impact damage substantiation was taken. For the Aft Fuselage / Tailboom test, Category 1 damages were introduced prior to test start and validated along with the intrinsic flaws and metallic structural PSEs via cyclic testing at temperature to the target equivalent flight hours (EFH) followed by residual strength testing to limit and ultimate loads. Inspections throughout this phase were used to validate no growth in intrinsic or impact damages. Category 2 and 3 impact damages were then introduced to the test articles, and a spectrum test with sufficient EFH to conservatively cover a 'go-home' return to repair depot flight was conducted, followed by an RST to limit, again with inspections validating no growth. Finally, a spectrum test and repeated inspections of the Category 2 impacts followed by an RST to limit was used to establish the inspection interval for the Category 2 damages. This sequence is illustrated diagrammatically in the roadmap in Figure 1, below.

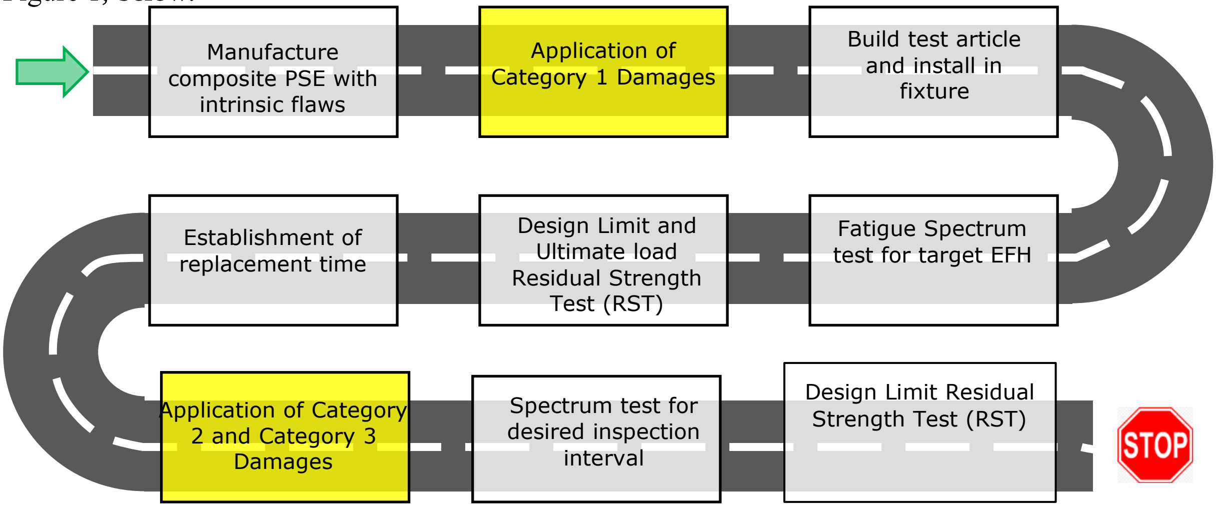

Figure 1: Aft Fuselage / Tailboom Testing Roadmap

For the Vertical Fin / Aft Tailboom test, some of the Category 1 damages were of sufficient size to be considered Category 2. As a result, the Category 2 inspection intervals were established during the initial cycling and inspection portion of the test and cleared by RST. The Category 3 damages were then introduced, and similarly to the other test, a spectrum test with sufficient EFH to conservatively cover a 'go-home' return to repair depot flight was conducted, followed by an RST to limit, again with inspections validating no growth. The Vertical Fin / Aft Tailboom sequence is illustrated diagrammatically in the roadmap in Figure 2, below.

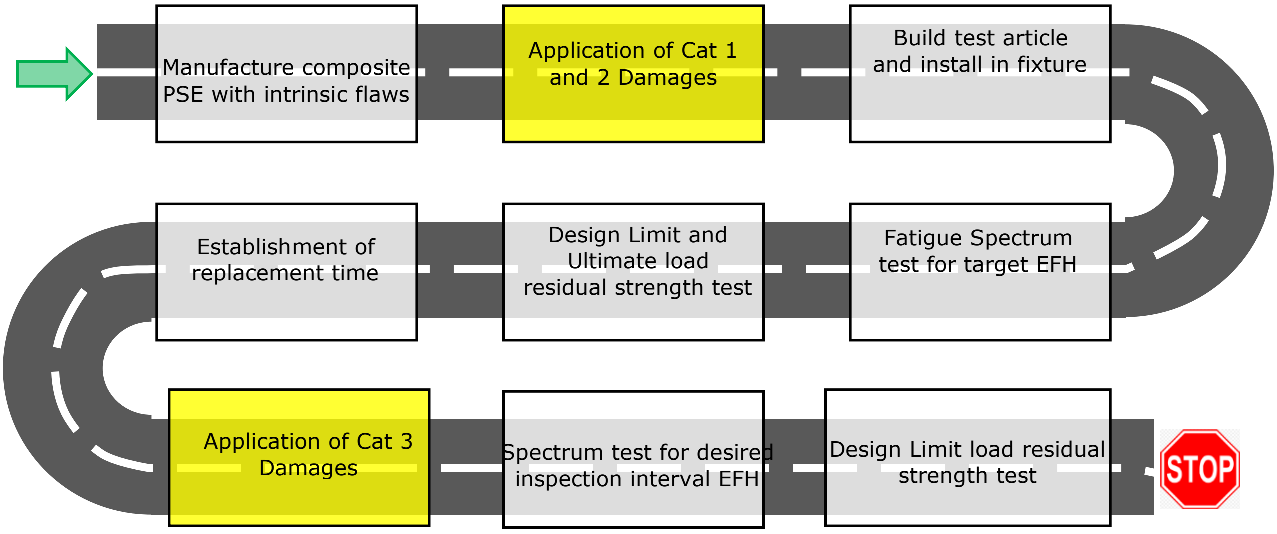

Figure 2: Vertical Fin / Aft Tailboom Testing Roadmap

BELL 525 STRUCTURAL TESTS AT NRC

Test Setup – Aft Fuselage / Tailboom

The test setup for the aft-fuselage / tailboom test consisted of a conventional design mounting the aft fuselage to a reinforced reaction plate, attaching a load introduction fitting near the aft end of the tailboom and applying the requisite bending moment, shear and torque loads at a single selected tailboom station via 7 hydraulic actuators. The test rig superstructure on the aft fuselage was attached to the NRC test facility reaction floor to support the reaction to applied loads, and a similar arrangement was applied at the aft end of the tailboom to react the opposing forces from the actuators. A passive counterbalance system consisting of custom-designed springs installed on the vertical actuators was used to counterbalance the load interface when hydraulics were inactive, while active counterbalance was applied by the vertical actuators themselves during testing. Strain gauges were installed on key features and locations to evaluate local stresses and validate FEM, respectively. Bending bridges measuring vertical and lateral bending moments and shear bridges measuring torque were installed at sections corresponding to those on the flight test to provide a point of comparison for the anticipated internal load measurements. The bending bridges were calibrated prior to installing the test article. Both strain gauges and bending bridges were installed with service temperature in mind, and specialized adhesives and coatings were used to ensure they would tolerate the elevated temperature. The test rig loading setup is shown conceptually in Figure 3.

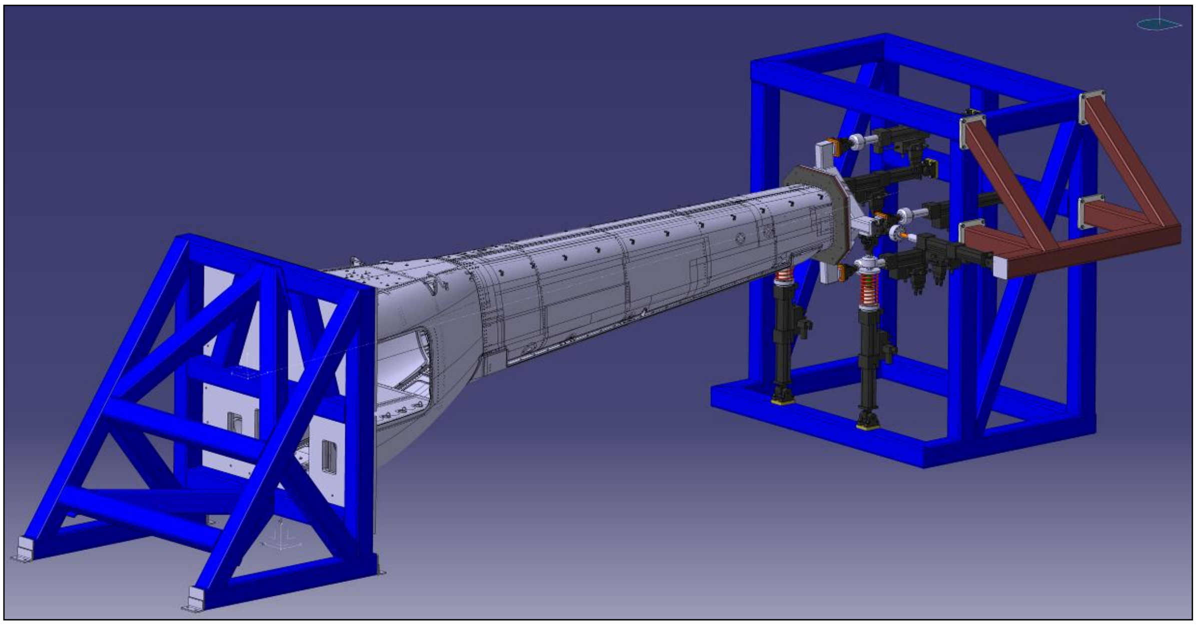

Figure 3: Aft Fuselage / Tailboom Test Rig

Test Setup – Aft Fuselage / Tailboom Heated Enclosure

To meet the temperature requirement over the required test area, NRC designed a custom stainless steel insulated heated enclosure. The enclosure was required to be removable to allow access to the test article during the frequent inspection intervals required for a test of this type. The heated enclosure was a two part enclosure, with an upper enclosure consisting of a 3-sided upside down u-shaped tubular steel skeleton frame to which were permanently fastened custom stainless steel panels on the interior and exterior, with 3 inches of rockwool fibre insulation sandwiched between them. These panels also contained penetration holes for blower / heater combinations, which were designed to interface with the article, and were sealed with high temperature sealant at all joints. This upper enclosure was designed to be removed vertically via the test bay crane to gain access to the entire article. The lower portion of the enclosure consisted of a similar tubular steel skeleton and custom stainless steel panels sandwiching rockwool insulation, with penetrations for blower / heater combinations. This lower portion rested on a wheeled dolly. The enclosure terminated immediately forward of the test section with 3 removable press fit closure panels, with additional insulation packed around any remaining opening and the final gap sealed with heat-resistant clear plastic used for composite process debulking, with edges sealed with composite manufacturing rated high-temperature seal tape. To prevent conductive heat transfer, phenolic plates were installed at the forward article interface and aft TRGB interface plates. Conceptual renderings of the enclosure are shown in Figure 4, with the article included in Figure 5.

During RST loading, the test plan called for a higher temperature zone for the tailbom and a lower temperature zone for the aft fuselage with an accepted transition zone just aft of the tailboom interface. To accommodate this, the heated enclosure had an insulated bulkhead built aft of the tailboom interface. This bulkhead was of similar construction to the rest of the enclosure, with any gaps plugged by additional insulation and sealed with heat-resistant clear-plastic.

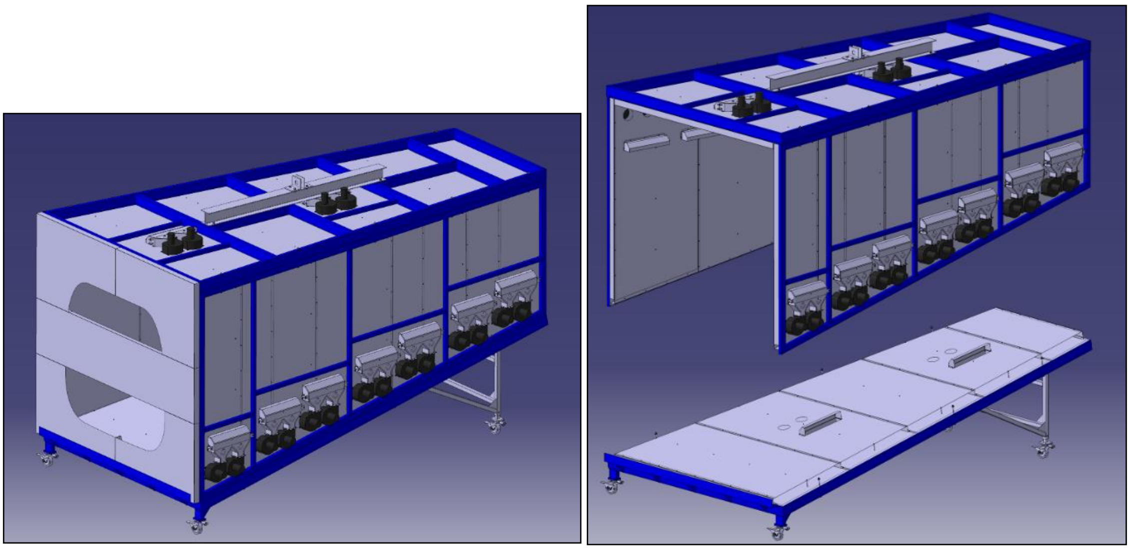

Figure 4: Aft Fuselage / Tailboom Heated Enclosure

In order to maintain temperature uniformity, NRC developed an in-house closed-loop control system that allowed multi-zone control via electrical resistance heaters coupled to blowers, with thermocouples in each zone and at the blower exists, as shown in Figure 6. Additional thermocouples mounted on the test article and coupled to the test load controller allowed real-time data acquisition and test monitoring to maintain temperature limits within tolerances. The multi-zone arrangement and closed loop control allowed for accurate temperature control and real-time adjustments to accommodate heat losses. This scheme was leveraged to allow multi-zone temperature differentials when necessary for RST.

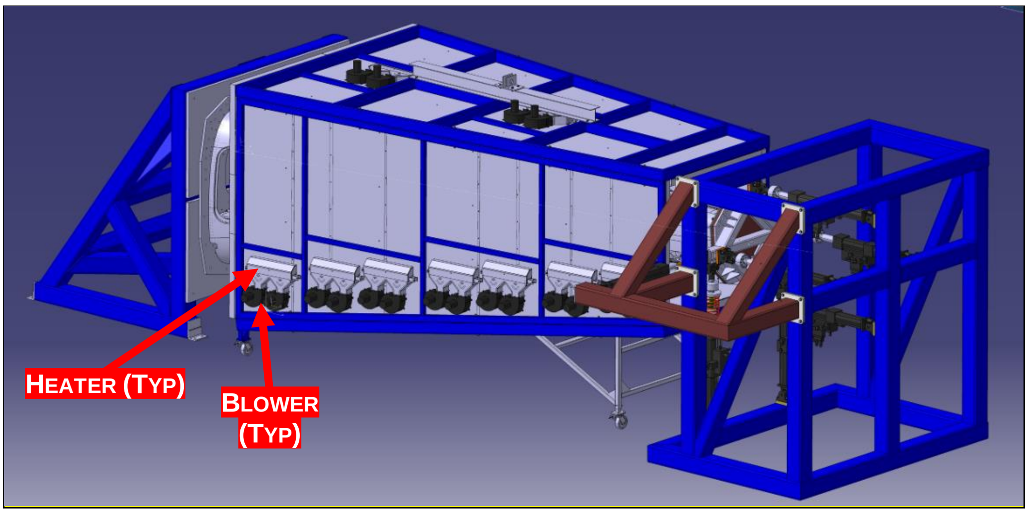

Figure 5: Aft Fuselage / Tailboom Heated Enclosure with Specimen

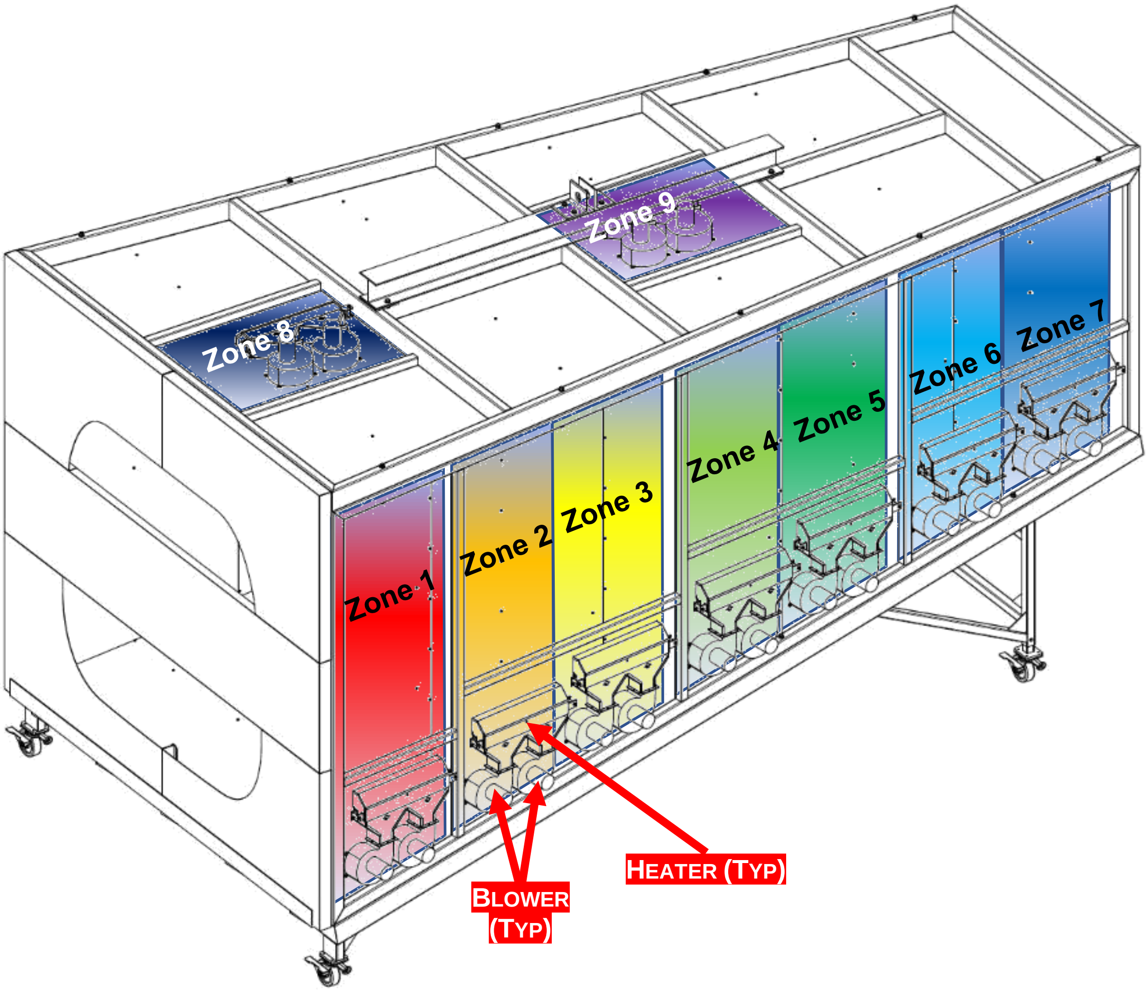

Figure 6: Aft Fuselage / Tailboom Heated Enclosure Temperature Control Zones

Test Setup – Vertical Fin / Aft Tailboom

For both loading and environmental chamber arrangements, the vertical fin / aft tailboom presented an additional challenge compared to the aft fuselage / tailboom test. The Bell 525 vertical fin is canted at an angle to the vertical, and loading actuators were required at the upper tail rotor gear box (TRGB), on the vertical fin itself, at the horizontal stabilizer and intermediate gear box (IGB). To achieve the targeted local bending moment, shear and torque values, the TRGB location required 7 actuators, the vertical fin 2, the horizontal stabilizer 6, and the IGB 2, for a total of 17 actuators. The compact arrangement resulted in more complex reaction structures, while creating more difficult access for inspections and a more challenging design for the environmental chamber. The article itself was rigidly attached to a reaction plate at approximately the 2/3 point down the length of the tailboom. The reaction plate, as well as the reaction structures onto which the actuators were mounted were attached into an overall self-reacting test rig superstructure, as shown in Figure 7.

Test Setup – Vertical Fin / Aft Tailboom Counterbalance

Similar to the aft fuselage / tailboom, the test article and some supporting structures were passively counterbalanced via 2 custom springs mounted on the horizontal stabilizer vertical loading actuators, with active counterbalance being supplied by these actuators during testing. The IGB interface and actuators, vertical fin interface and actuators, and TRGB fitting and actuators were counterbalanced using deadweight systems. The interfaces had built in pickup points and the force resultant from the mass was transferred via steel cables, that were, in turn, connected to one end of levers swinging on very low friction pillow blocks, with the opposite side of the lever located to place the deadweight masses adjacent to the test article. The IGB interface and vertical fin interface could not be counterbalanced with a single pickup point, therefore, a total of 5 pickup points and lever systems were used.

Using a low-friction bearing pillow block lever with cabling was found to be substantially superior to using a counterbalance pulley system, as the static and kinetic friction from the system was nearly zero, and there were no issues with cable twisting, pulley movement or cable sliding. The avoidance of these issues led to smoother response and fewer transient forces in the load train, resulting in better test cycle rate performance.

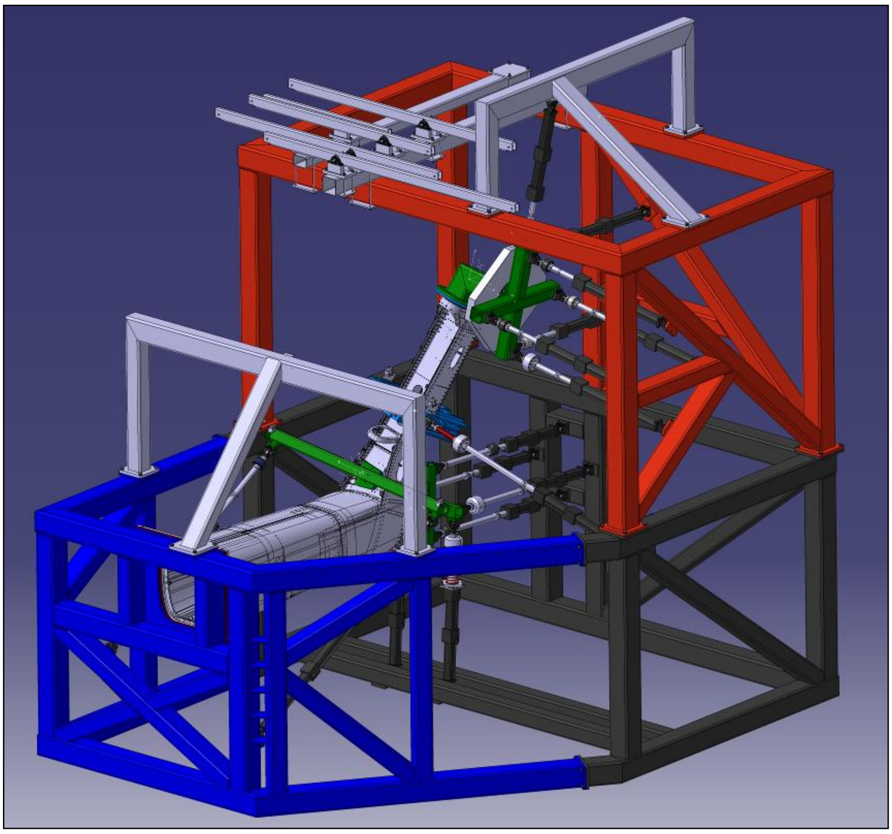

Figure 7: Vertical Fin / Aft Tailboom Test Rig

Unlike the aft fuselage / tailboom test, determining the force required for active counterbalancing at the vertical horizontal actuators was not accomplished by analysis. The geometry of the test article, varying density materials and custom test attachments made a center of gravity and mass distribution calculation very complex. As a result of these complexities, exhaustive calculation of the mass distribution of the zero-g counterbalance hydraulic loads were empirically determined to arrive at the correct combination of actuator loads that would result in the test bending bridges reading zero. Following the application of all other active and passive counterbalance loads to the loading interfaces and verification checks of bridge response to load application, a combination of tare loads on various actuators was derived that balanced the bridge readings to within limits accepted by the certification delegate and Bell on-site engineering staff.

Test Setup – Vertical Fin / Aft Tailboom Heated Enclosure

Due the multiple penetrations and tight geometry, a unitary enclosure design could not be achieved for this test. As a result, the heated enclosure consisted of a tubular steel skeleton frame resting on a wheeled dolly. Custom stainless steel panels with 3 inches of rockwool fibre insulation embedded on the inside face were fabricated to enclose the article on all sides. These panels also contained penetration holes for blower / heater combinations, which were designed to interface with the article, and were sealed with high temperature sealant at all joints. Additional penetration holes were made for the TRGB, and horizontal stablizer tubular elements. All panels on both left and right hand sides and rear were designed with buckle draw latches allowing removal without moving the supporting skeleton. The forward part of the article was enclosed aft of the actual attachment plate and rig reaction structure, with additional insulation placed surrounding the exit hole. In operation, all penetration holes were sealed with heat-resistant clear plastic used for composite process debulking and their edges sealed with composite manufacturing rated high-temperature seal tape. The reaction plate, TRGB and horizontal stabilizer interface fittings were installed with one inch phenolic plates between the internal and external metallic structures to reduce conductive heat loss. Further, the vertical fin interface actuators were equipped with phenolic threaded extensions that allowed them to apply loads to the fully enclosed interface while allowing the load cells to remain outside of the heated area. A conceptual rendering of the enclosure frame is shown without the rig reaction superstructure in Figure 8. The complete assembly, with reaction rig, is shown conceptually in Figure 9.

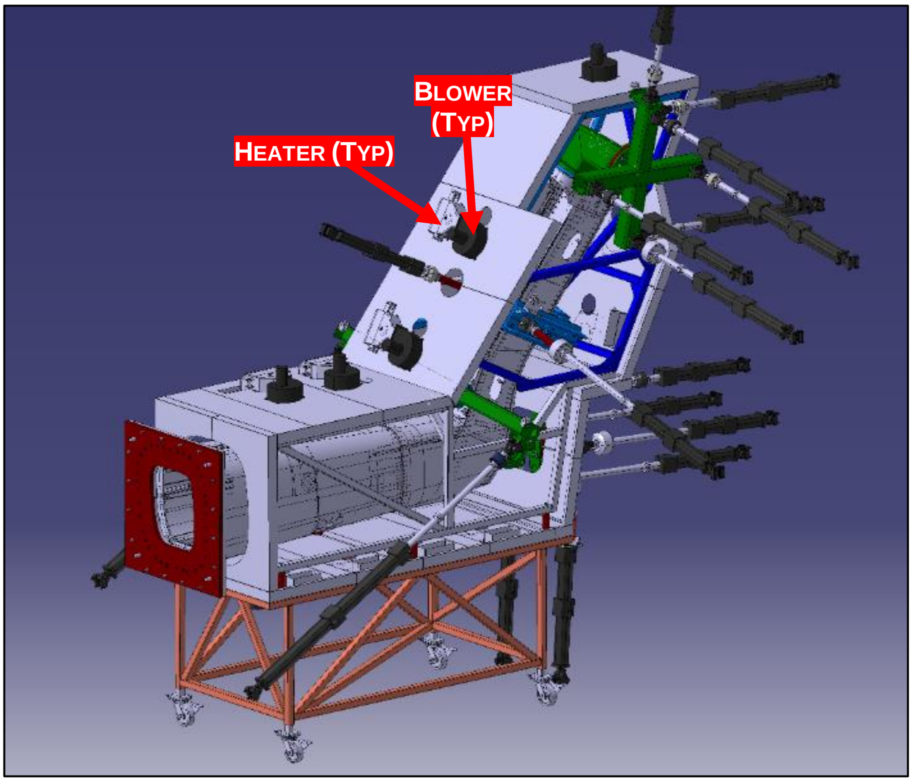

Figure 8: Vertical Fin / Aft Tailboom Test Article with Environmental Chamber – Superstructure Removed

Similar to the aft fuselage / tailboom test, a closed-loop heater controller was used to maintain temperature in the environmental chamber. Due to the more complex geometry and height changes, ensuring temperature uniformity within tolerance in the vertical axis of the vertical fin was challenging but successfully achieved.

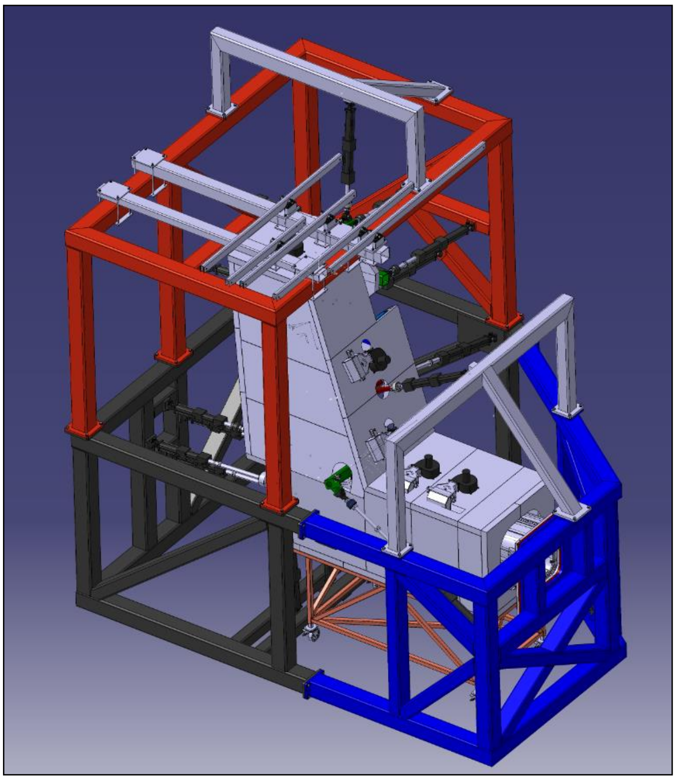

Figure 9: Vertical Fin / Aft Tailboom Test Rig with Environmental Chamber

BELL 525 STRUCTURAL TEST OPERATIONAL CHALLENGES

Operational Considerations with Environmental Chambers

Several operational lessons were learned during setup, commissioning and operation of the structural tests at temperature. Aside from the evident additional personnel safety considerations, the time required to soak the articles at the required temperature prior to test start up and to gain inspection access during cool-down required planning and scheduling, especially during RST. Soak times at test temperature were established to be approximately 30 minutes following trials during commissioning, but both chambers required approximately one and a half to two hours to reach temperature. Test article safety was maintained by having independent test and heater shut down limits that automatically disabled both hydraulic loading and heaters in the event thermocouples exceeded pre-set tolerances.

Instrumentation Variability due to Environmental Chambers

The strain gauges and bending bridges had been installed using specified techniques and high temperature adhesive for the expected temperature environment. Following the procedure, strain gauges and bridges were calibrated and zeroed at room temperature prior to test article installation in the test rig. However, during initial strain survey trials on the vertical fin / aft tailboom test (which was commissioned first) the first temperature application produced a deviation in strain gauge and bending bridge responses. After the survey was completed and the article returned to room temperature, it was noted that the bending bridges and strain gauges did not return to their previous ambient temperature zeros. A repeat high-temperature soak was conducted, resulting in further changes to the bridges and strain gauge readings at ambient temperatures. The working hypothesis was that the high temperature adhesive used to bond the strain gauges and bridges had not fully cured, which led to local changes in their zero reading. The application of strain survey loads at the required temperature validated that strain response and bridge response curves remained the same as at ambient conditions, therefore only the zeros were affected. After 4 repeated high temperature soak cycles, the ambient bending bridge and strain gauge readings appeared to be more stable between thermal cycles. The thermal bridge readings stabilized following the 4th temperature application. Changes to the bending bridge readings following repeated temperature applications at Room Temperature and zero mechanical loads are shown in Figure

10, with the behaviour at test temperature shown in Figure 11. As can be seen, the zero reading on the bridges at ambient temperature had stabilized after the 3rd temperature cycle, and the zero reading on the bridges at test temperature had stabilized by the 5th temperature cycle.

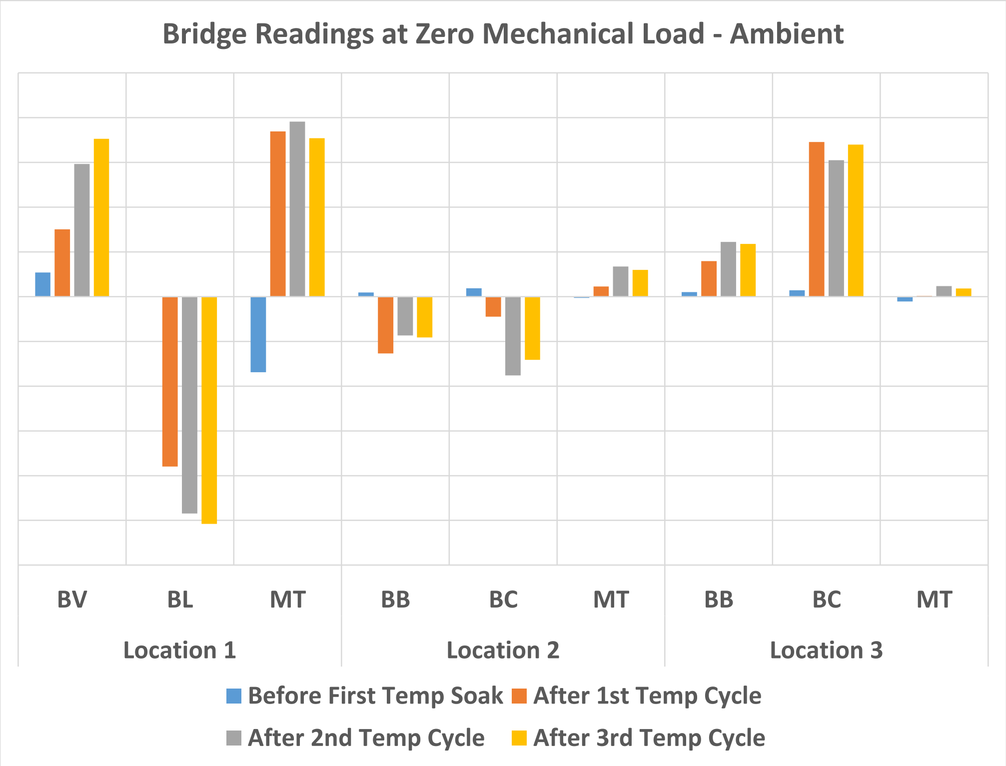

Figure 10: Bending Bridge Readings at Ambient Temperature After 3 Temperature Cycles

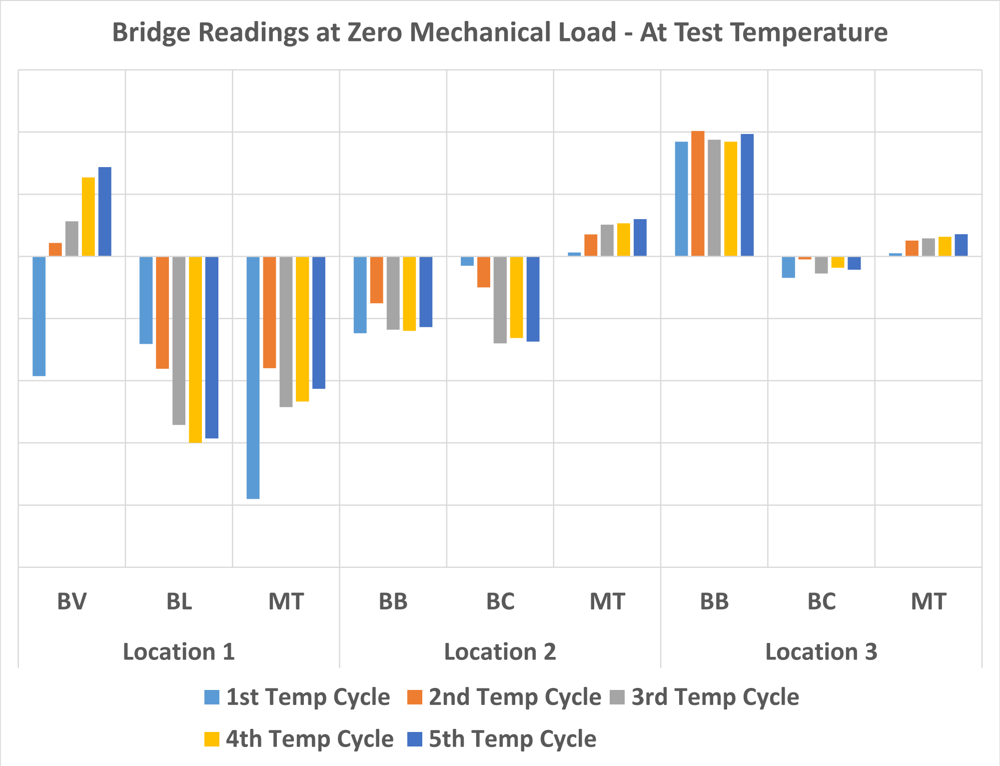

Figure 11: Bending Bridge Readings at High Temperature During 5 Cycles

Since the test schedule precluded removing the test articles and recalibrating the bending bridges to zero following the temperature soaks, it was decided to record the fixed temperature offset value to offset the initial zero that was set at test start after the zero-g reading at ambient and test temperature conditions was observed to stabilize. A similar approach was taken for the strain gauges. This finding had an effect on the test schedule as time was required to isolate the problem, and subsequently repeat the strain survey to determine test article performance. The impact from this finding was incorporated during the aft fuselage / tailboom test, where the test article was soaked at test temperature for 24 hours prior to applying any of the prescribed strain survey loads. This was repeated 3 times to confirm stabilization of the zero readings prior to fixing the offset bending bridge and strain gauge readings and commencing the aft fuselage / tailboom strain survey at test temperature.

Interface Considerations

For the vertical fin / aft tailboom test, the vertical fin air load interface or cradle was contained entirely within the heated enclosure, as shown (installed) in Figure 12, with heated enclosure panels removed. The cradle consisted of a series of plates and brackets that surrounded the vertical fin skins and spars. Wooden contour blocks with rubber on all 4 sides were used to interface directly with the article. A pre-torqued load on the surrounding steel plate bolts was intended to create sufficient compression load on the rubber such that the static friction prevented cradle movement during test load cycling. Following the initial strain surveys at test temperature, the position of the cradle had been noted to have moved slightly. Fortunately, the movement was insufficient to exceed the target tolerances of the bending bridge moments and torques. Further investigation revealed that the initial compression set by pre-torquing the plate bolts at room temperature was insufficient to maintain compressive friction on the skins at the test temperature, leading to movement. As a result, an alternate interface material was chosen and the compression torques were increased to compensate for the thermal effect. Strain gauges nearby were monitored to ensure no local overloading occurred. These changes also meant that the cradle would move excessively at ambient temperature, precluding any cycling without also being at the test temperature.

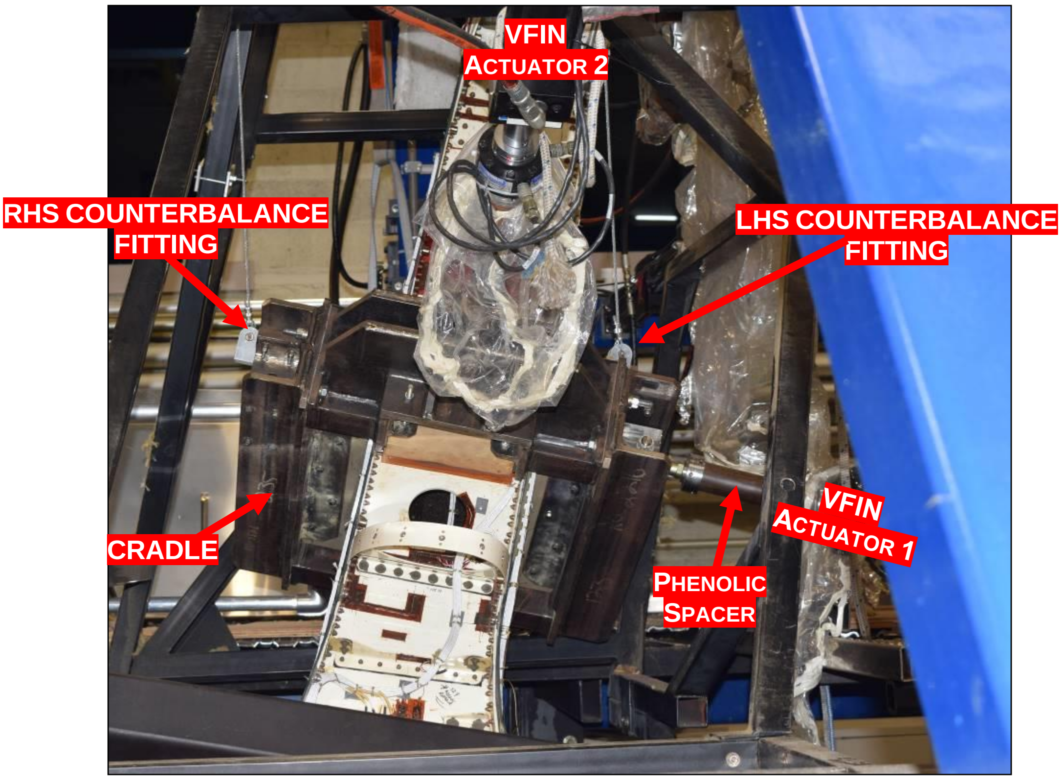

Figure 12: Vertical Fin Interface Cradle

BELL 525 STRUCTURAL TEST SIGNIFICANCE

The test campaign to achieve the initial certification design service goals for the aft fuselage / tailboom and vertical fin / aft-tailboom test articles began in 2019, sequentially, and both were successfully completed by 2021, with all test goals met. Throughout the campaign, the environmental chambers performed to specification, with no unanticipated schedule delays due to environmental chamber considerations, excepting the increased time to gain access for inspection. Structural findings informed the certification documentation and allowed Bell to provide sufficient substantiating data for certification application.

The approach of full-scale fatigue testing of structural components incorporating the expected service environment resulted in a combined LEF that was much closer to the initial design load spectrum. This meant that metallic structural findings on the test articles were considered to be representative of service conditions, which reduced test interpretation and analysis efforts and eliminated the need for additional testing of certain subcomponents. This justified the extra effort and costs required to conduct the tests in large custom environmental chambers. NRC has gained valuable experience in these test methods and this approach adds another potential solution to meeting the challenge of certification of composite / metallic hybrid aerostructures.

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