Paper Number: **1840**

Title: **Development of Stitched Composite Structure for Advanced Aircraft**

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ABSTRACT

NASA has created the Environmentally Responsible Aviation Project to develop technologies which will reduce the impact of aviation on the environment. A critical aspect of this pursuit is the development of a lighter, more robust airframe that will enable the introduction of unconventional aircraft configurations. NASA and The Boeing Company are working together to develop a structural concept that is lightweight and an advancement beyond state-of-the-art composites. The Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) is an integrally stiffened panel design where elements are stitched together and designed to maintain residual load-carrying capabilities under a variety of damage scenarios. With the PRSEUS concept, through-the-thickness stitches are applied through dry fabric prior to resin infusion, and replace fasteners throughout each integral panel. Through-the-thickness reinforcement at discontinuities, such as along flange edges, has been shown to suppress delamination and turn cracks, which expands the design space and leads to

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lighter designs. The pultruded rod provides stiffening away from the more vulnerable skin surface and improves bending stiffness. A series of building blocks were evaluated to explore the fundamental assumptions related to the capability and advantages of PRSEUS panels. These building blocks addressed tension, compression, and pressure loading conditions. The emphasis of the development work has been to assess the loading capability, damage arrestment features, repairability, post-buckling behavior, and response of PRSEUS flat panels to out-of-plane pressure loading. The results of this building-block program from coupons through an 80%-scale pressure box have demonstrated the viability of a PRSEUS center body for the Hybrid Wing Body (HWB) transport aircraft. This development program shows that the PRSEUS benefits are also applicable to traditional tube-and-wing aircraft, those of advanced configurations, and other structures where weight and through-the-thickness strength are design considerations. An overview of the development of PRSEUS technology for commercial transport aircraft is the subject of this paper.

INTRODUCTION

NASA has created the Environmentally Responsible Aviation (ERA) Project to explore the feasibility, benefits, and technical risk of advanced vehicle configurations and enabling technologies that will reduce the impact of aviation on the environment. A critical aspect of this pursuit is the development of a lighter, more robust airframe that will enable the introduction of unconventional aircraft configurations that have higher lift-to-drag ratios, reduced drag, and lower community noise. The Hybrid Wing Body (HWB) configuration is a significant improvement in aerodynamic performance compared to traditional tube-and-wing aircraft. In a HWB aircraft, the center body (which includes the passenger cabin) is wider and flatter than a traditional tubular fuselage to allow the center section to act as a wing and produce lift. With this arrangement, the wings blend into the center section to reduce drag. This arrangement impacts not only the shape of the vehicle, but also the location of the engines, the control requirements, and the internal structure as load transfers from the outer wings to the wide inner wings and the center section. The structural challenge to creating a large pressurized HWB design is the non-circular pressure cabin which must be lightweight and economical to produce. Developing a structural concept that supports the HWB cabin design is the primary technical challenge to implementing this large lifting-body design [1].

To address this challenge, researchers at NASA and The Boeing Company (Boeing) are working together to develop a new structural concept called the Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) [2-8]. PRSEUS is an integral structural concept that evolved from stitching technology development started in the NASA-Boeing Advanced Composites Technology (ACT) Program in the 1990's [9]. The goal of the ACT wing program was to develop stitching technology to reduce structural weight and fabrication cost of a conventional wing on a large commercial transport aircraft. Through-the-thickness stitching was demonstrated to arrest damage and prevent delamination. After ACT, Boeing worked with the Air Force to further stitching technology for application to military transports, resulting in stitched composite landing gear doors on the C-17. NASA continued to study stitched structures independently.

While working with the Air Force, Boeing developed the PRSEUS concept. NASA began to work with Boeing on PRSEUS development under the NASA Subsonic Fixed Wing program. This project was moved into ERA in 2010. In the PRSEUS concept as applied to a HWB, flat panels support large bending loads in both in-plane directions along with the pressure load associated with internal cabin pressure. The use of a traditional composite material system would require fasteners to suppress delaminations and to join structural elements, ultimately leading to fastener pull-through problems or heavy pad-ups in the fastener regions. In contrast, through-the-thickness stitches, applied through dry fabric prior to resin infusion, replace these fasteners throughout each integral panel. This approach eliminates fasteners and their associated holes, which significantly simplifies the assembly process, reduces part-count, and removes a primary source of crack initiation throughout the life of the aircraft. Through-the-thickness reinforcement using stitches at discontinuities, such as along flange edges, has been shown to suppress delamination and turn cracks, which increases the design space and leads to lighter designs [2]. Additionally, the infusion and cure processes for PRSEUS panels require high temperatures, but only vacuum pressure, which eliminates the need for an autoclave. This manufacturing approach leads to substantial cost savings and eliminates the out-time concerns associated with traditional prepreg. The PRSEUS concept was evaluated analytically and experimentally using the building block approach described herein [10-19]. An overview of this development of PRSEUS technology is the subject of this paper.

HWB STRUCTURAL CONCEPT

While the blended wing shape provides many aerodynamic advantages, this shape also presents structural challenges for the center fuselage section due to the noncircular cross section of the fuselage, as shown in Figure 1. Although significantly lighter than conventional aluminum structures, even the most highly efficient composite primary structures used on today's state-of-the-art aircraft would not be adequate to overcome the weight and cost penalties introduced by the airframe of the HWB. In the HWB, design of the pressure cabin region is primarily driven by out-of-plane loading considerations where secondary bending stresses are developed, in which case, a traditional layered material system would require thousands of mechanical attachments to suppress potential delaminations and to join structural elements, ultimately leading to fastener pull through problems in the thin gauge skins. Another disadvantage of a conventional composite solution is the high manufacturing cost associated with the highly contoured airframe. Not only would complex outer moldline tooling be needed, but all of the interior stringers and frame members would require individual toolsets, which adversely affects affordability. Any credible HWB structural solution must operate effectively in out-of-plane loading scenarios while simultaneously meeting the challenging producibility requirements inherent in building a highly contoured airframe.

In addition to the secondary bending stresses experienced during pressurization, another key difference between the HWB shell and the traditional cylindrical fuselage is the unique bi-axial loading pattern that occurs during maneuver loading conditions, as shown in Figure 1. For the HWB, the load magnitudes are nearly equal in each in plane direction (Nx and Ny) compared to conventional tube-and-wing aircraft arrangements where the fuselage is more highly loaded in the Nx direction, along the stringer, than in the Ny direction, along the frame. This single difference in loading has a profound effect on the structural concept selection because the loading dictates that the optimum panel geometry should have continuous load paths in both directions (Nx and Ny), in addition to efficiently transmitting internal pressure loads (Nz) for the near-flat panel geometry, as shown in Figure 1. Additionally, for a conventional skin-stringer-frame built-up panel, the frame shear clip is typically discontinuous to allow the stringer to pass through uninterrupted in the primary longitudinal loading direction. If such an arrangement is used for the HWB, the frame (attached by a discontinuous shear clip to the skin) would be less effective in bending and axial loading than a continuous frame design that is attached directly to the skin, ultimately resulting in a non-competitive design.

To overcome these challenges, an improved fuselage panel should be designed as a bi-directionally stiffened panel, where the wing bending loads are carried by the frame members and the fuselage bending loads are carried by the stringers. Additionally, the panel design should include continuous load paths in both directions, stringers and frames that are highly tailored, thin skins designed to operate well into the post-buckled design regime, and crack-stopping features which to minimize damage propagation. Incorporating these features into a new composite structural concept is necessary to overcome the inherent weight penalties of the non-circular pressure cabin.

PRSEUS CONCEPT

The PRSEUS design and fabrication approach incorporates damage arrestment, improved load paths, and other weight reducing design features, which result in a very efficient stiffened panel concept. The PRSEUS panel concept is a combination of dry carbon warp-knit fabric, pultruded rods, foam core, and stitching threads. The fabric consists of AS4 carbon fiber layers with a (44/44/12) fiber architecture, where the

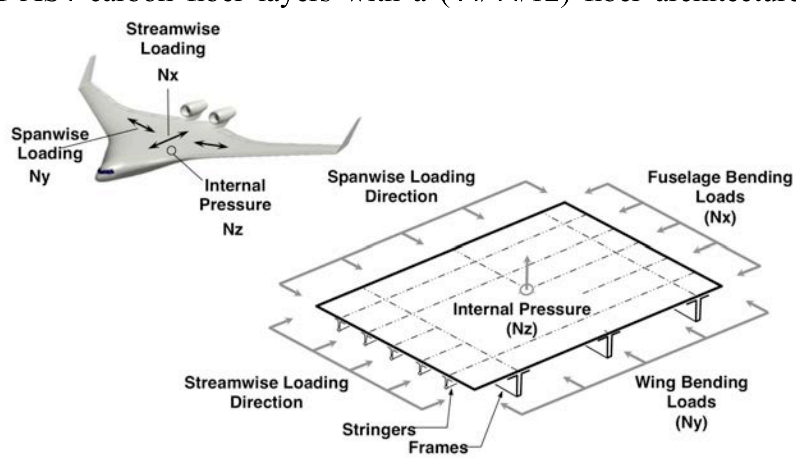


Figure 1. Combined loading on a HWB pressure cabin.

values are percentages of (0/±45/90) degree plies. Each stack has a nominal cured thickness of 0.052 inches. Multiple stacks of the warp-knit material can be used to build up the desired part stiffness, strength, and configuration. These materials are brought together in a unique manner to create a stiffened panel geometry that utilizes resin infusion and out-of-autoclave curing to reduce recurring fabrication costs and allow the construction of very large panels. The resulting panels are one-piece unitized assemblies with a highly integrated stiffened panel design enabled by the use of through-the-thickness stitching, which ultimately leads to unprecedented levels of fiber tailoring and load path continuity between the individual structural elements.

Structural continuity is maintained by eliminating mechanical attachments, gaps, and mouse holes to provide uninterrupted load paths between the skin, stringer, and frame elements, as shown in Figure 2. The stringer contains a precured high-stiffness pultruded rod, made of Toray unidirectional T800 fibers with a 3900-2B resin above the thin web and the flanges are stitched to the skin. Stacks of fabric are used for all webs, flanges, tear straps, and the skin. Foam-filled frames are perpendicular to the stringers and also have flanges which are stitched to the skin. The frames contain a small keyhole for the stringer to pass through. This design creates efficient load paths in both directions which are beneficial to the stability and bending resistance of the panel by shifting the neutral axis away from the skin. Vectran threads are used to stitch the stiffeners to the skin and at other discontinuities. Since all of the interfaces are stitched together to provide through-the-thickness strength, a high degree of fiber tailoring is possible even with composite material systems which are known to be brittle, layered, and prone to delamination. Extra thickness in the skin and flanges is not needed to resist out-of-plane motion.

The stitching is also used to suppress out-of-plane failure modes. Stitching arrests cracks and controls damage propagation within a layered material system. By strategically placing stitch rows along the key structural interfaces, traditional resin dominated failure modes can be eliminated, so that the optimum strength of the panel can be more nearly realized when fiber dominated failure modes are facilitated prior to local resin failures. Using through-the-thickness stitching to locally reinforce the out-

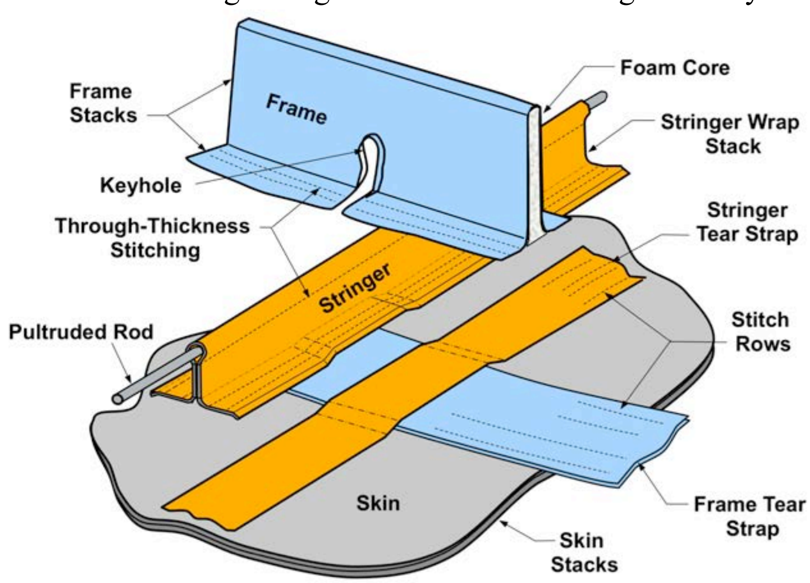


Figure 2. Exploded view of the Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) concept.

of-plane-direction interfaces not only makes integral construction possible, stitching also enables a new type of damage arrest and fail safe redundancy into the structure that was previously reserved for ductile materials and not normally associated with brittle composite systems [4-6].

The resulting bi-directionally stiffened panel design is ideal for the HWB pressure cabin because the design is highly efficient in all three loading directions, and the stitching on the panel reacts pull-off loading and increase panel survivability. These features are also applicable to barrel fuselage sections with thin skins and for wing structures to improve structural efficiency and reduce weight. This approach would allow thin fuselage skins to safely buckle and cause minimal disruption of the transverse stiffener element, thereby allowing the stringer to pass through a frame or wing rib cap.

MANUFACTURING

Developing the manufacturing process to build large stitched panels was necessary to apply this technology to large commercial transport aircraft. This unitization is enabled by the use of dry material forms, single sided stitching, and the unique self-supporting preform design that is used to eliminate internal moldline cure tooling. Using these technologies, complicated stitched preforms can be fabricated without exacting tolerances, and then accurately net molded in a single oven cure operation using high precision outer moldline tooling. Since all of the materials in the stitched assembly are dry, there are no out-time or autoclave limitations as with prepreg systems, which can restrict the size of an assembly because the assembly must be cured within a limited processing envelope. HexFlow VRM 34 resin infusion is accomplished using a soft-tooled fabrication scheme where the bagging film conforms to the inner moldline surface of the preform geometry and seals against a rigid outer moldline tool. The success of this approach has been demonstrated on PRSEUS panels up to 30-feet long, as shown in Figure 3. The panel shown contains rod-stiffened stringers, foam-filled frames, and integral caps. Integral caps are similar to the foam filled frames in that the stringers pass through the integral caps at keyholes, but the integral caps are solid laminates and only occur at locations where one panel joins to another. All elements are stitched together with no need for fasteners or fittings within the panel. Additional manufacturing details are presented in References 20-21.

Completed panels can be mechanically joined together using the integral cap features to further reduce the number of separate details and eliminate fasteners through the exterior surface of the panel. As such, the fasteners are loaded in shear and any pull-off loading is reacted directly into the adjacent panel through the stitched integral cap layers.

Figure 3. PRSEUS 30-foot-long bulkhead panel.

BUILDING BLOCKS

A series of building block tests were defined to explore the fundamental assumptions related to the capability and advantages of PRSEUS panels. Since the application primarily being considered is the HWB center body, only thinner and lightly loaded structures are considered in this project. The building block tests addressed tension, compression, and pressure loading conditions of the HWB pressure cabin as illustrated in Figure 4. The emphasis of the development work has been to assess the loading capability, damage arrestment features, repairability, post-buckling behavior, and response of flat panels to out-of-plane pressure loading. Each building block test was accompanied by analysis for prediction and post-test comparisons. Analysis work is not described herein, but is described in the documentation of each test. A summary of the building-block activities is described in the following sections.

All test articles described herein were fabricated at the Boeing stitching center in Huntington Beach, CA. The design, analysis, and testing activities were divided between NASA and Boeing.

Coupons and Elements

Coupon and element tests were used to evaluate basic material properties and the behavior of specimens cut from PRSEUS panels. Testing of characteristics unique to PRSEUS such as the damage arrestment associated with stitching and the bending characteristics and stability are discussed herein. All specimens were evaluated analytically and the results compared to test data to demonstrate an understanding of the specimen response and an ability to predict PRSEUS behavior.

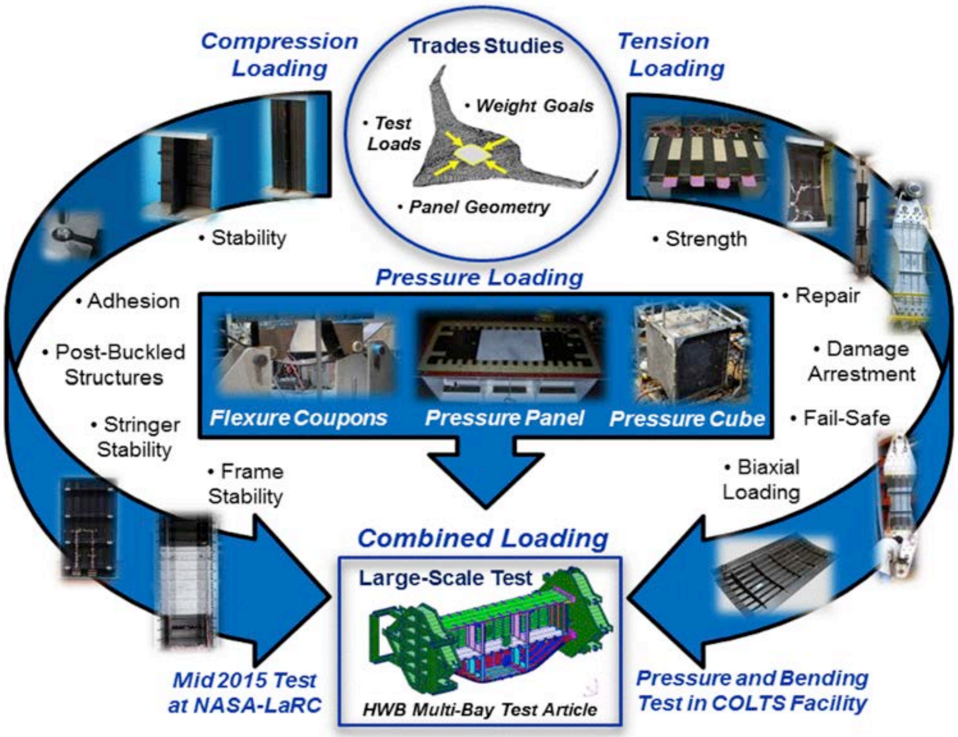


Figure 4. Development path leading to the HWB large-scale test article.

DAMAGE ARRESTMENT

The transformational aspect of the stitched interface is that stitching provides the capability to stop damage propagation within a brittle material system, which permits the undamaged regions of the structure to continue bearing load. Such an approach is similar to the characteristic redundancy in a metallic structure that is designed to accommodate yielding and load redistribution prior to failure.

The crack turning and arrestment failure modes are illustrated in Figure 5 where flat tension coupons with stitched and unstitched laminates were loaded to failure [3]. As tension loads were increased in the stitched coupons, damage emanating from a centerline slot was first arrested horizontally at the vertical stitch row. Then, as the crack turned vertically, the crack split the 0-degree fibers before the crack was arrested again at the horizontal stitch row. Once the damage was stopped in the opposite corners of the skin bay, increasing load levels caused the specimen to fail in the upper corner location, labeled as “Primary Failure” in the far right photo of Figure 5. Subsequent testing of unstitched configurations proved that this complex crack turning failure mode could not be replicated in unstitched coupons since the unstitched specimens failed horizontally across their net sections, labeled as “Primary Failure” in the far left photo in Figure 5.

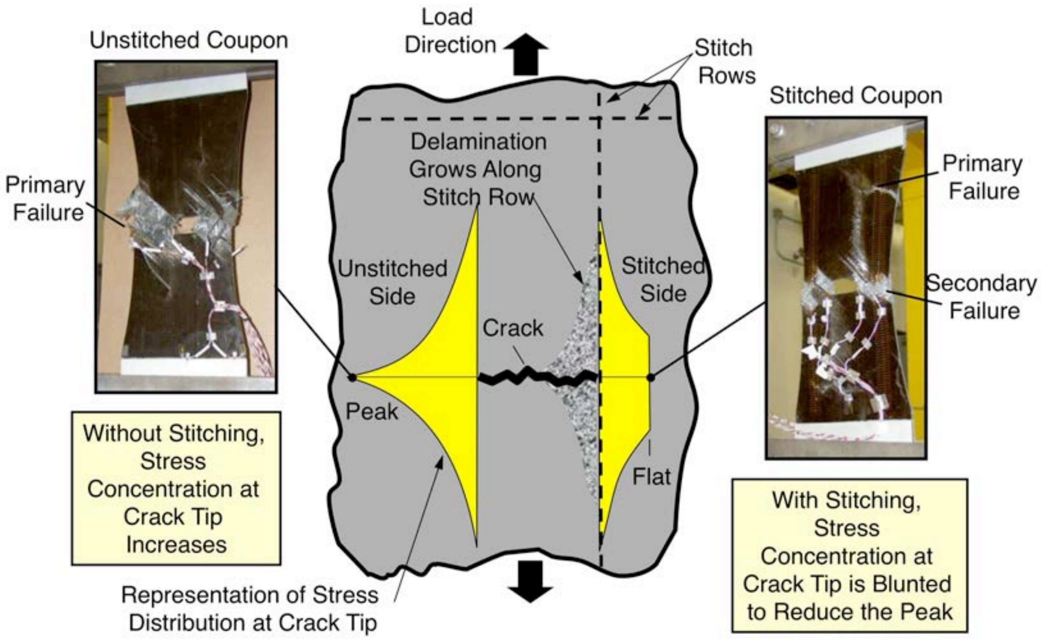


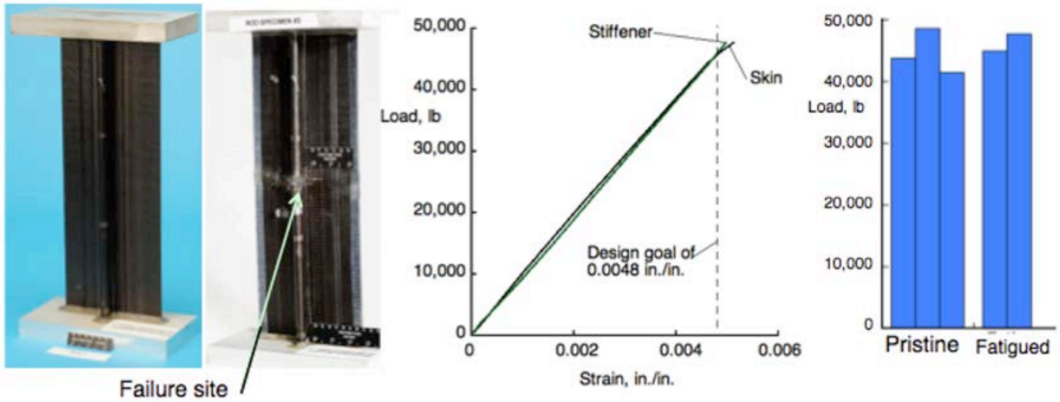
Figure 5. An example of how stitching blunts the stress concentration at the crack tip.

Since the only difference between the two specimens was the stitching, these tests indicated that the peak stresses at the crack tip were no longer capable of advancing the crack front beyond the vertical stitch row. This condition remained even as the loading was increased, until the crack zone expanded in the vertical direction, along the stitch row, until the crack reached the horizontal stitching where the crack was once again arrested. Under increasing load, the final failure occurred at this location. This simple test demonstrated that the fundamental damage arrestment design approach was possible using stitching and that further testing was warranted with larger more complex test specimens.

STABILITY AND POST-BUCKLING

The initial trade studies evaluating PRSEUS potential for HWB applications showed that the unitized design features of the PRSEUS skin and stiffening elements would have a favorable effect on the column stability of PRSEUS panels and the benefit of having the stiffener flanges stitched directly to the skin would remove the tendency of separation between skin and flanges after buckling occurs [2]. The first phase evaluating PRSEUS stiffener stability examined the behavior of single-frame and single-stringer specimens loaded in compression [7,19].

To demonstrate the structural stability of the PRSEUS stringer, an analysis and testing effort was undertaken that would quantify the benefits of the stiffeners being stitched directly to the skin under both local and global buckling constraints. A single-stringer specimen and test results are shown in Figure 6. The failure strains were greater than the goal of 0.0048 in./in. in specimens loaded statically to failure. In each case, the skin of the specimen buckled locally at a load well below the failure load and the eventual failure was a strength failure prior to inducing a global buckling mode failure. Therefore, this evaluation demonstrated that strength-induced failures occurred at strains greater than the design allowable of 0.0048 in./in. compressive strain and before a column instability mode occurred, showing the column stability of



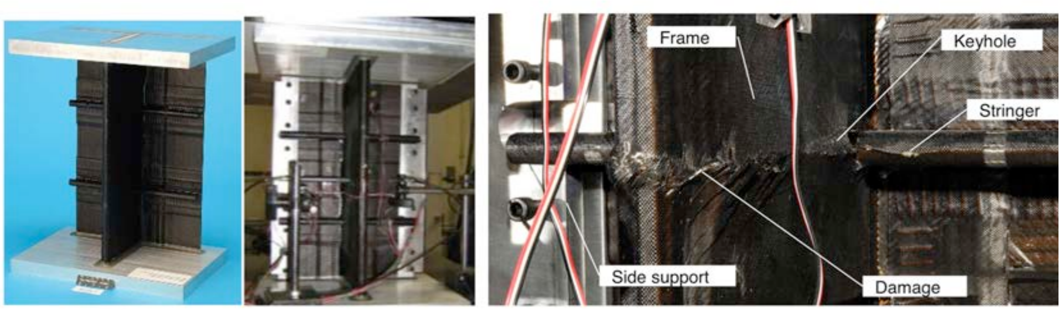
a) Pre-test b) Failed c) Compressive strain d) Failure loads

Figure 6. Single-rod specimen behavior in compression loading.

the PRSEUS stringer cross section. Additionally, several single-stiffener specimens were compression-loaded in a fatigue spectrum and then tested to failure. These specimens failed in the same manner and at approximately the same loads as the non-fatigued specimens, as shown in Figure 6d.

The compression loading capability of the integral frame design was also investigated. There are two primary differences between a PRSEUS frame geometry and a conventional design. The PRSEUS frame is taller, which affects the buckling and bending capability, and there are no mouse holes or shear ties. Incorporating these differences into the design leads to a more efficient material distribution and placement of the neutral axis which ultimately improves the overall section stiffness making the frame more stable under compression loading.

Single-frame specimens were subjected to unidirectional compressive loading to failure to evaluate these features. A single-frame specimen prior to testing and after failure is shown in Figure 7 and described more thoroughly in Reference 19. The short columns remained stable until net section strength failures occurred at the stringer keyhole in the frame webs where the frame area is the smallest, demonstrating that frame buckling is not a critical failure mode under pure compression loading.



a) Pretest b) In the test machine c) Failure location

Figure 7. Behavior of single-frame specimens in compression loading.

Panels

Multi-stringer and multi-frame panels were constructed to evaluate the behavior of larger structures subjected to unidirectional loading. Panels were evaluated in the pristine condition as well as subjected to barely visible and discrete source damage.

DAMAGE ARRESTMENT

The viability of the damage-arrestment design was demonstrated using a 3-stringer panel with 6-inch stringer spacing and 20-inch frame pitch, as shown in Figure 8. The goal of this test was to show that damage propagating from the slot cut through the center stringer would be arrested first by the adjacent stringer flange stitching, and then at the frame flange stitching. This tension-loaded specimen was statically loaded to failure and was able to arrest damage in both the horizontal and vertical directions as the damage propagated from the saw-cut tips. Because damage was fully contained within the 2-bay damage zone bordered by the adjacent stringers and frames, the panel was able to continue carrying load well beyond the discrete source damage (DSD) test goal set for 100% design limit load (DLL) [8].

With the undamaged regions of the panel working to their full capability, the final failure occurred near the frame at 132% of DLL, well above the design requirement. The failure behavior was not catastrophic and demonstrated that by using stitching to arrest damage and turn cracks, a more favorable internal load distribution could be established that unloaded the crack tip and stopped damage from progressing beyond the stitch rows until the fibers in the undamaged regions of the panel could be loaded to failure.

Similar testing was also completed on a large curved 7-stringer 5-frame specimen panel, shown in Figure 8, which was subjected to combined internal pressure and axial loading [10]. This panel was tested at the Federal Aviation Administration (FAA) Full-Scale Aircraft Structure Test Evaluation and Research Facility. Similar favorable damage-arrestment and crack turning phenomena were observed in this test as with the tension-loaded panel described in this section. In the curved panel, damage emanated from the saw-cut and arrested before the specimen eventually failed at 185% of DLL in the grip region of the specimen. The large increase in loading between the initial

a) Flat tension-loaded panel

b) Curved combined-load panel

Figure 8. Discrete source damage panels subjected to combined internal pressure and axial loading.

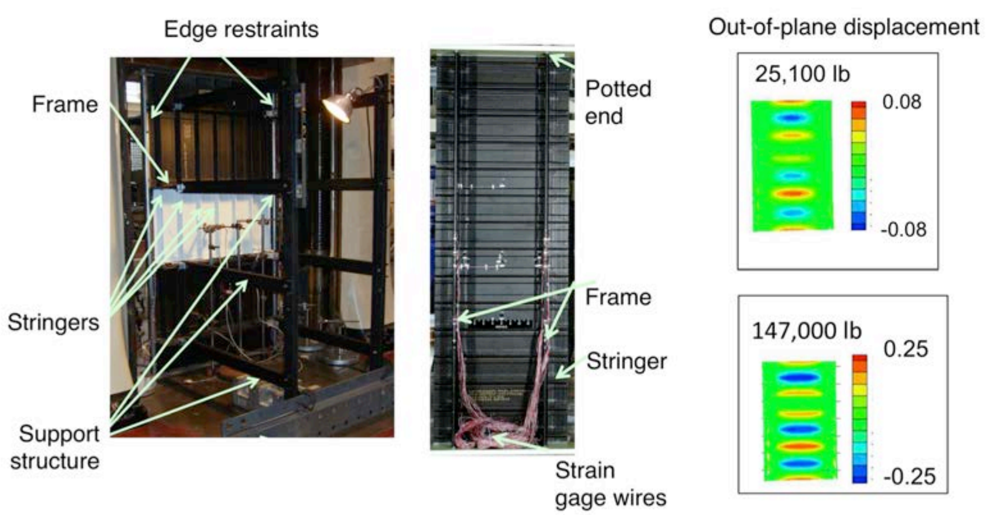
crack growth and final panel failure load demonstrates the robust nature of the stitched interfaces and how high levels of residual panel strength can be achieved through a combination of stitching and stiffener tailoring.

The capability to definitively stop and redirect laminate cracking, separation, and splitting plays an important role in the PRSEUS panel design approach because PRSEUS reduces the design sensitivity to large notch loading conditions. By limiting the size of damage progression and by reducing the stress intensity at the crack tip, the remaining undamaged structure is able to operate at full design capability. While this behavior is an important aspect for meeting the DLL requirements set for the large notch testing, the behavior is also relevant for meeting the design ultimate load (DUL) conditions; specifically for the barely visible impact damage (BVID), or small notch design sizing conditions.

STABILITY AND POST-BUCKLING

A 7-stringer, 4-frame panel, shown in Figure 9, was loaded in compression in the stringer direction to assess the panel buckling behavior. Side supports on the unloaded edges and supports at the frames prevented the panel from entering a global buckling mode. Numerous buckles occurred in the skin bays between the stiffeners. Changes in the strain and displacement patterns indicated that the stringers continued to support load well into the post-buckled range [11].

A 2-frame 16-stringer compression panel, shown in Figure 9, was loaded in compression in the frame direction. Although local skin bucking between the stiffeners occurred at 23,000 lb, the panel continued to support loading to approximately 147,000 lb until a strength-based failure occurred at the panel edges and the frame keyhole. The presence of high strains at the panel edges and in the frame webs at the stringer-frame intersections precipitated a strength failure prior to the buckling of the frames. Measured full-field out-of-plane displacements of a portion of unstiffened side of the panel are in Figure 9 and demonstrate the significant post-buckling behavior observed [12].



a) 7-stringer panel b) 2-frame panel c) Displacements for 2-frame panel

Figure 9. Compression-loaded panels and test results. Displacements are in inches.

Frame displacement measurements indicated little deformation for loads less than 120,000 lb, with no sign of global buckling prior to the strength failure which occurred at 147,000 lb. This result indicated that the panel withstood approximately six times the local buckling load prior to failure, or approximately 73,000 lb per frame, and ultimately exceeded the allowable material strength before encountering a general panel buckling mode. The final failure runs through a keyhole in both frames, under the restraints and to the edge of the panel, seemingly connecting the locations of peak strains predicted by the finite element analysis [12].

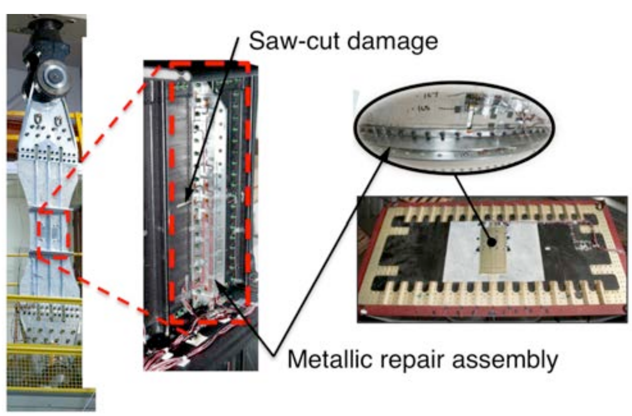
INTERNAL PRESSURE

A 2-frame 16-stringer PRSEUS panel was placed in a pressure fixture and the panel was pressurized to 28 psi when a failure occurred in the central stringer. This failure arrested at the stitch line in the web and did not progress into the flange. The panel continued to support pressure to 30 psi when testing was stopped, so the panel could be preserved for experimentation with repair technology.

PANEL REPAIR

As with any structural concept, as excess margins are driven out and the concept becomes more integrated, repairing the structure becomes more difficult. This generalization holds true for the highly optimized PRSEUS concept and is somewhat exacerbated by the use of the pultruded rod. To address this concern, a series of bolted repair specimen tests was conducted under tensile and bending load conditions [17, 18]. A PRSEUS panel with a severed rod stiffened stringer was repaired using metallic details and is shown in Figure 10.

In each test, the bolted repair substantially exceeded the DUL requirement. Tension-loaded panels failed outside of the repaired regions (suggesting specimens with reduced edge effects would have generated even higher values) and the pressure-loaded panel supported 30 psi without failing. The results showed that even the severed rod stiffened stringers were easily repaired using mechanically attached details that were capable of moving load away from the damaged regions and then redistributing the load back into the undamaged sections of the panel through the repair fasteners.



a) Repaired rod stiffener b) Repaired exterior skin

Figure 10. Photographs of the repair panels.

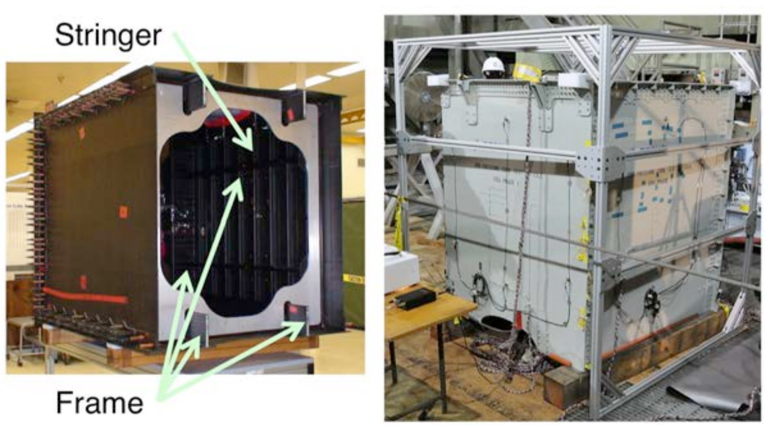
Built-Up Structure

A cube subcomponent specimen was fabricated to better understand and address the difficult structural transitions encountered in the flat-sided pressure panels that are indicative of the HWB pressure cabin. The cube was conceived as a risk reduction article to reduce the likelihood of premature failure of larger pressurized structures. The test article was constructed of six PRSEUS panels that were bolted together at their edges to create a pressure tight cube, as show in Figure 11. This test article was then tested in an over-pressure condition to simulate an equivalent bending moment in the corners as would be encountered in a full sized structure [16].

The cube specimen supported more pressure than the maximum bending moment requirement before an internal aluminum splice fitting failed at 48 psi internal pressure loading. The bending stresses generated by internal pressure of 48 psi in this 4-foot-long test article were representative of the bending stresses which were anticipated in the 10-foot-long bays of the planned 30-foot-long test article under the 18.4 psi maximum internal loading condition. This result validated the assumption that the integral cap design used to join the panels would be capable of meeting the loading requirements of a larger, or scaled-up flat-sided pressure vessel [16].

Large-Scale Multi-Bay Pressure Box

The knowledge gained from the earlier steps of the building block development program was used to develop a large-scale multi-bay box test article. This multi-bay pressure box test article was the last step in the building block process for the HWB center fuselage section. This test article was an 80% scale component representing a potion of the most heavily loaded portion of the HWB center section. The multi-bay pressure box panel arrangement consists of 11 PRSEUS panels that form the exterior shell and floor members, along with four interior sandwich rib panels that were used to divide the box width into thirds, as shown in Figure 12. End fittings were added at the corners of the pressure-tight cell to impart bending loads that simulate the loads of the wing carry-through structure that would be induced during a flight maneuver. Linear and nonlinear finite element analyses were performed to validate the design of the multi-bay pressure box [22,23].



a) Before floor panel installed b) Instrumented and ready for testing

Figure 11. Photographs of the pressure cube.

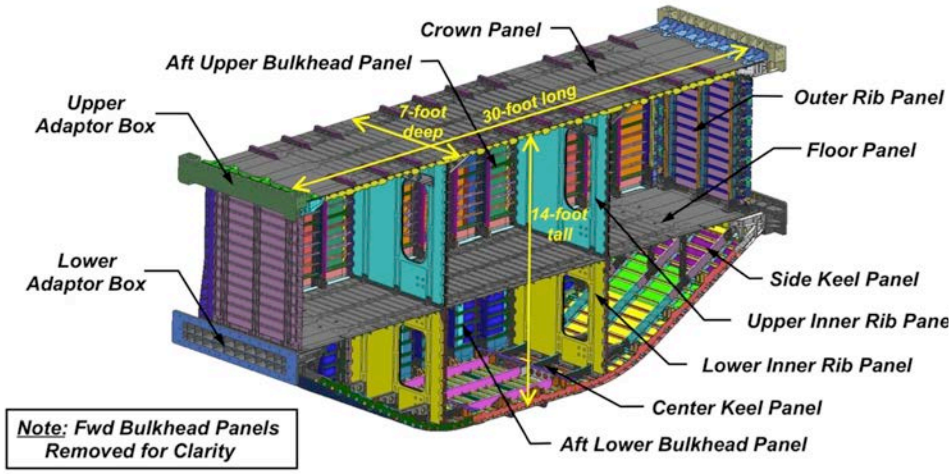


Figure 12. Multi-bay pressure box design.

This test article was used to demonstrate structural performance and manufacturing scale-up. The manufacturing process demonstrated the inherent differences in fabricating the 8-foot-long building block panels and the 30-foot-long multi-bay pressure box panels. The refinement of manufacturing techniques and processes has demonstrated the capability of PRSEUS technology to be more broadly applied to primary structures on transport aircraft. A photograph of a 30-foot-long panel prior to being assembled into the double deck closed box multi-bay pressure box test article is shown in Figure 3. The components of the multi-bay pressure box are shown in Figure 13.

The multi-bay pressure box was assembled at the Boeing C-17 assembly site in Long Beach, CA. The cured panels were loaded into an assembly fixture where they were mechanically joined together using the integral cap features that locate the panels, reduce the number of metallic fittings, and eliminate fasteners through the exterior surface of the panels. A photograph of the completed multi-bay pressure box is shown in Figure 14.

The multi-bay pressure box has been subjected to a series of loadings in the Combined Loads Test System (COLTS) Facility at the NASA Langley Research Center [24,25]. A photograph of the test article between the platens in the COLTS Facility and a graphic of the COLTS arrangement are shown in Figure 15. A series of ten tests were conducted to evaluate the response of the pristine test article to critical load conditions. Four actuators were used to rotate the platens relative to each other to apply mechanical loads to the test article to simulate flight load conditions. Pressure was pumped into the test article to simulate cabin pressure. In each case, loading was quasi-static and slow enough to ensure that the actuators stayed in sync with each other and with the pressure load.

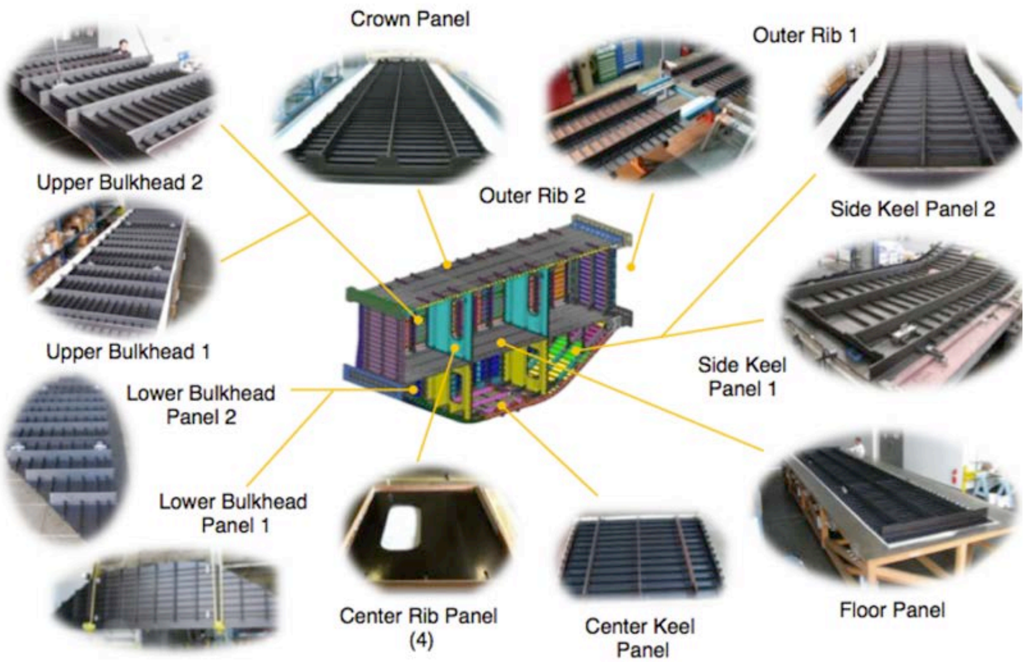


Figure 13. Panels for the multi-bay pressure box.

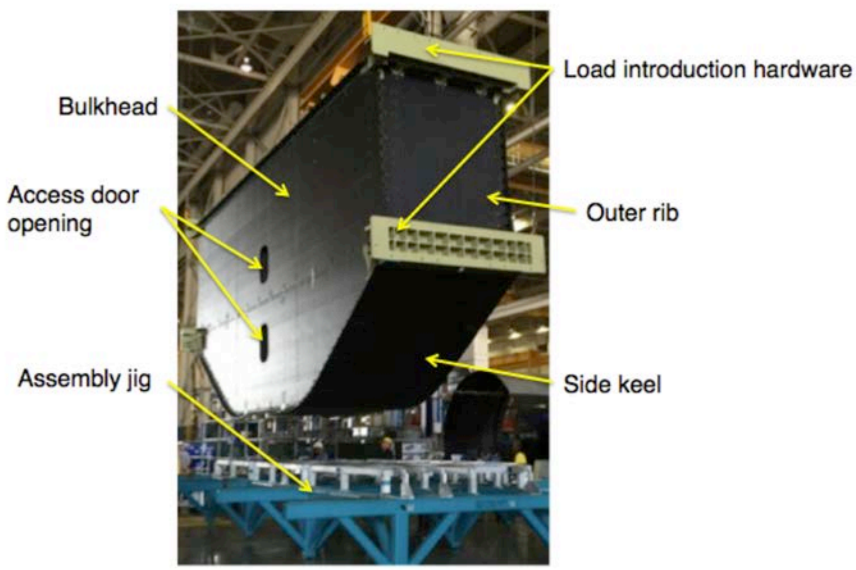


Figure 14. Multi-bay pressure box prepared for installation into the holding fixture.

The multi-bay pressure box has been subjected to up-bending and down-bending flight maneuver load conditions and internal pressurization. Five loading conditions were applied to the pristine multi-bay pressure box. These loading conditions are 1) an internal pressure load only, where DUL is 18.4 psi; 2) a load simulating a 2.5-g bending condition which subjects the crown panel to compressive loads; 3) a negative 1-g bending condition which subjects the crown panel to tensile loads; 4) a

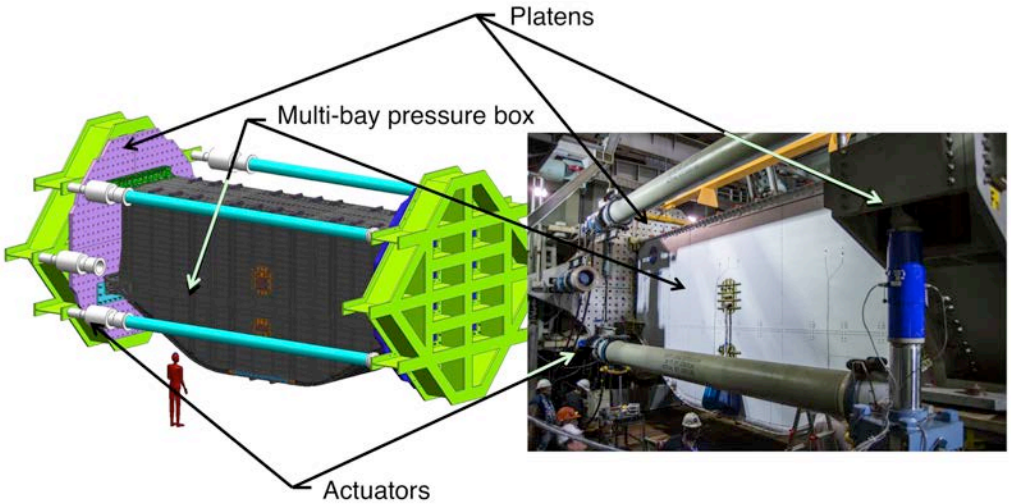


Figure 15. Multi-bay pressure box in test chamber.

combination of pressure and negative 1-g bending; and 5) a combination of pressure and 2.5-g bending. The pristine test article was subjected to all of these conditions to DUL. The test article survived these DUL tests with no obvious damage. The test article displayed significant post-buckling behavior in a manner consistent with the deformation predicted by the nonlinear analysis. The results of the testing and a preliminary comparison to analytical predictions are presented in Reference 25.

After the completion of the pristine structure tests, BVID was inflicted to the forward upper bulkhead and center keel panels. The structure was then subjected to DUL in all five loading conditions to demonstrate the ability of the structure to sustain critical loads in the damaged condition. The test article was then subjected to a loading of 10% greater than DUL in the 2.5-g bending condition with pressure and without pressure. No damage growth from the impact sites is visible. Ultrasonic scans are being conducted to determine the extent of non-visible damage. All DUL testing has been completed and test results demonstrate the viability of the PRSEUS concept for HWB center section type structure.

CONCLUDING REMARKS

NASA and Boeing have been developing technology to improve damage tolerance and reduce the weight of composite structures for commercial transport aircraft applications through the use of through-the-thickness stitching for over 20 years. Most recently, under the NASA ERA Project, a partnership between NASA and Boeing has advanced this technology in an attempt to encourage and enable advanced aircraft configurations such as the HWB design.

Stitching through the thickness has been shown to suppress delaminations, arrest damage, and remove or eliminate the need for fasteners in the acreage of composite panels. Removing the need for fasteners removes the need to drill holes, add doublers to account for stress concentrations around holes, and eliminates the need to inspect the holes through the life of the aircraft.

In the current stitched structural concept, PRSEUS, the addition of a pultruded rod to the stringer in one direction and a tall foam-filled frame perpendicular to the stringer improves the bending stiffness in both directions compared to traditional construction, which is critical to the HWB configuration. PRSEUS also provides efficient load paths by integrating all panel elements into one unit prior to cure, which eliminates the need for shear clips and other added elements which add weight to the structure. So the PRSEUS panel architecture is a significant step beyond state-of-the-art conventional layered composite systems.

A building-block test program starting with coupons and ending with a 30-foot-long large-scale pressure box test has been successfully executed to demonstrate the viability of a PRSEUS center body for the HWB transport aircraft. This building block program included testing and analysis of numerous PRSEUS test articles, so that designs could be refined and the risk of premature failure could be reduced as more complex parts were required to demonstrate the critical PRSEUS capabilities.

This final step in the building-block process is the 80%-scale multi-bay pressure box tested in the COLTS Facility at the NASA Langley Research Center. The multi-bay pressure box has been fabricated from PRSEUS panels and has undergone testing under combined load conditions representative of critical flight conditions. This test article has been subjected to up-bending and down-bending flight maneuver load conditions and internal pressurization in a ground test program that demonstrates that the technology is capable of meeting the structural weight goals established for the HWB airframe. The test article was loaded to DUL in all critical conditions in the pristine conditions and then again after imparting BVID to the interior and exterior of the test article. The test article demonstrated post-buckling behavior as anticipated and little if any damage growth from the impact sites. All DUL testing has been completed and test results demonstrate the viability of the PRSEUS concept for HWB center section type structure. While this development program was aimed at demonstrating PRSEUS viability for the HWB center body, the benefits demonstrated could also be applied to traditional tube-and-wing aircraft configurations, other advanced configurations, spacecraft, and other structures where weight and through-the-thickness strength are design considerations.

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