Development of the PRSEUS Multi-Bay Pressure Box for a Hybrid Wing Body Vehicle

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NASA has created the Environmentally Responsible Aviation Project to explore and document 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. Although such novel configurations like the Hybrid Wing Body (HWB) offer better aerodynamic performance as compared to traditional tube-and-wing aircraft, their blended wing shapes also pose significant new design challenges. Developing an improved structural concept that is capable of meeting the structural weight fraction allocated for these non-circular pressurized cabins is the primary obstacle in implementing large lifting-body designs. To address this challenge, researchers at NASA and The Boeing Company are working together to advance new structural concepts like the Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS), which is an integrally stiffened panel design that is stitched together and designed to maintain residual load-carrying capabilities under a variety of damage scenarios. The large-scale multi-bay fuselage test article described in this paper is the final specimen in a building-block test program that was conceived to demonstrate the feasibility of meeting the structural weight goals established for the HWB pressure cabin.

Nomenclature

BVID = *barely visible impact damage*
DLL = *design limit load*
DUL = *design ultimate load*
HWB = *hybrid wing body*
Nx, Ny, Nz = *running loads in x, y, z directions, respectively, in HWB*

I. Introduction

NASA has created the Environmentally Responsible Aviation (ERA) Project to explore and document 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 levels. The Hybrid Wing Body (HWB) arrangement offers a significant improvement in aerodynamic performance compared to a traditional tube-and-wing aircraft. However, the HWB design poses challenges in the design of a non-circular pressure cabin that is not only lightweight but also economical to produce. Developing a viable structural concept is the primary technical challenge to the implementation of a large lifting-body design like HWB.[1]

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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).[2-5] NASA and Boeing are exploring fundamental PRSEUS technologies that could someday be implemented on a transport-size airplane design. In ERA and previous programs, the PRSEUS concept was evaluated analytically and experimentally using a building-block approach[6-14] that culminates in the test of a large 30-foot-long multi-bay pressure box that will be subjected to combined bending and internal pressure loadings. The subject of this paper is the ongoing development of this multi-bay pressure box test article that will be tested in 2015.

II. HWB Structural Concept

While the blended wing shape provides many aerodynamic advantages, it also presents structural challenges for the center fuselage section due to its noncircular cross-section. 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 highly contoured airframe of the HWB. Particularly, in the pressure cabin regions that are primarily driven by out-of-plane loading considerations where secondary bending stresses are developed, 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. The other argument against a conventional composite solution is the high manufacturing costs 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 for the individual parts, which adversely affects affordability. Any credible HWB structural solution must operate effectively in out-of-plane loading scenarios while simultaneously meeting the arduous producibility requirements inherent in building the 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 Fig. 1. For the HWB, the load magnitudes are nearly equal in each in-plane direction (Nx and Ny) compared to conventional tube-and-wing fuselage 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 has a profound effect on the structural concept selection because it 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 Fig. 1. Additionally, for a conventional skin-stringer-frame built-up panel, the frame shear clip member is typically discontinuous to allow the stringer to pass through uninterrupted in the primary longitudinal loading direction. If such an arrangement were used for the HWB, the frame member (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 solution

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, stringer and frame laminates that are highly tailored, thin skins designed to operate well into the post-buckled design regime, and crack-stopping features designed to minimize damage propagation. Capturing such attributes is necessary to overcome the inherent weight penalties of the non-circular pressure cabin.

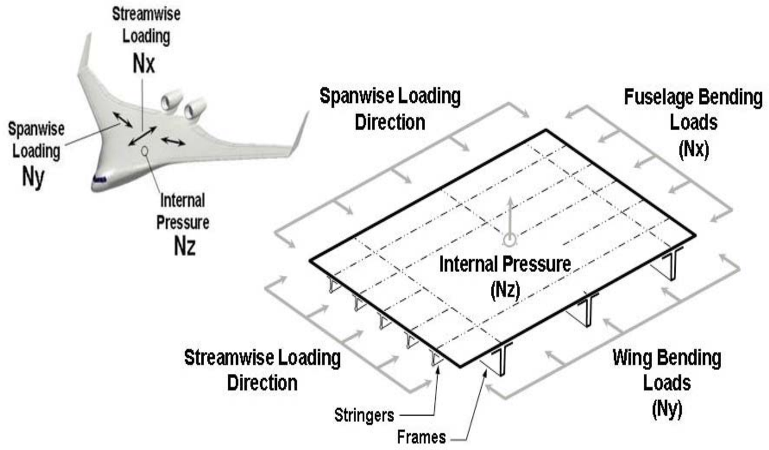


Figure 1. Combined loading on HWB pressure cabin.

III. PRSEUS Concept

The PRSEUS design and fabrication approach incorporates damage arrestment, improved load paths, and other weight reducing design features, which result in a highly effective stiffened panel concept. It is a conscious progression away from conventional laminated and bonded methods of assembly, and has evolved to become a one-piece cocured panel design with seamless transitions and damage-arrest interfaces. The highly integrated nature of the PRSEUS stiffened panel design is enabled by the use of through-thickness stitching, which ultimately leads to unprecedented levels of fiber tailoring and load path continuity between the individual structural elements. Advancing manufacturing technologies in the areas of warp-knit fabrics,[15] out-of-autoclave resin infusion processing,[16] through-thickness stitching technology[17] and, in particular, single-sided stitching[18-20] have made more highly integrated structural concepts like PRSEUS now possible.

A PRSEUS panel geometry consists of dry warp-knit fabric, pre-cured rods, and foam-core materials that are assembled and then stitched together as shown in Fig. 2. Load path continuity at the stringer-frame intersection is maintained in both directions by passing the rod-stringer through a small keyhole in the frame web. The 0-degree fiber-dominated pultruded rod increases local strength and stability of the stringer section while simultaneously shifting the neutral axis away from the skin to further enhance the overall panel bending capability. Frame elements are placed directly on the inner mold line skin surface and are designed to take advantage of carbon fiber tailoring by placing bending and shear-conducive lay-ups where they are most effective. The stitching is used to suppress out-of-plane failure modes. Suppressing these modes enables a higher degree of tailoring than would be possible using conventional laminated materials. The resulting bi-directionally stiffened panel design is ideal for the HWB pressure cabin because it is not only highly efficient in all three loading directions, but also stitched to react pull-off loading and increase panel survivability. These features are also applicable to barrel fuselage sections with thin skins and for wing structures. 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.

From the initial trade studies used to establish design parameters, the characterization of the PRSEUS concept continues to take shape in the context of the HWB research. A building-block approach is being used to develop the PRSEUS technology applied to the HWB fuselage as illustrated in Fig. 3. A series of fundamental tests have demonstrated that the PRSEUS panel assembly is capable of meeting the unique tension, compression, and pressure loading conditions of the HWB pressure cabin. The knowledge gained from these tests is being used to develop the large-scale multi-bay box test article. In addition to demonstrating the structural performance, manufacturing scale-up is also demonstrating the inherent differences in fabricating the 10-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 being used to assemble the double-deck closed-box multi-bay pressure box test article is shown in Fig. 4. A sketch of the multi-bay pressure box is shown in Fig. 5.

Ultimately, the multi-bay pressure box will be subjected to the combined bending plus internal pressure loading environment representative of an HWB center fuselage design envelope. Applied loadings will include 18.4 psi of internal pressure with no mechanical

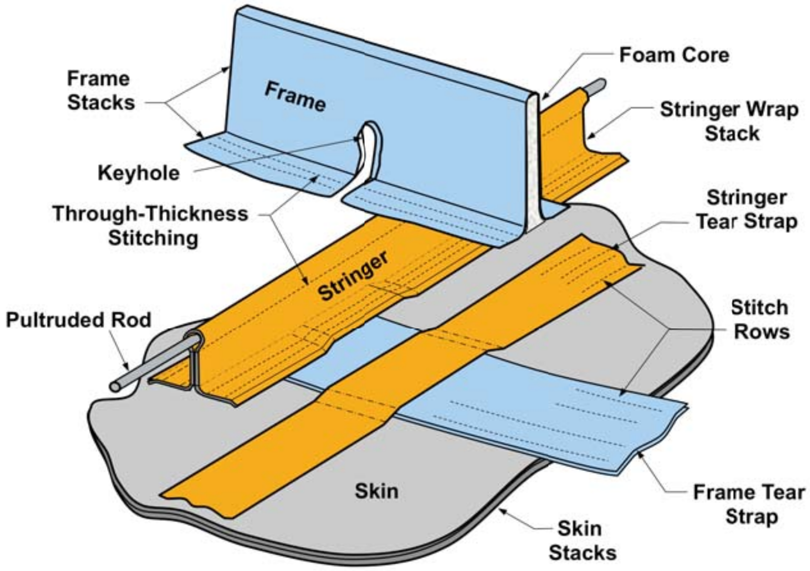


Figure 2. Exploded view of Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) concept.

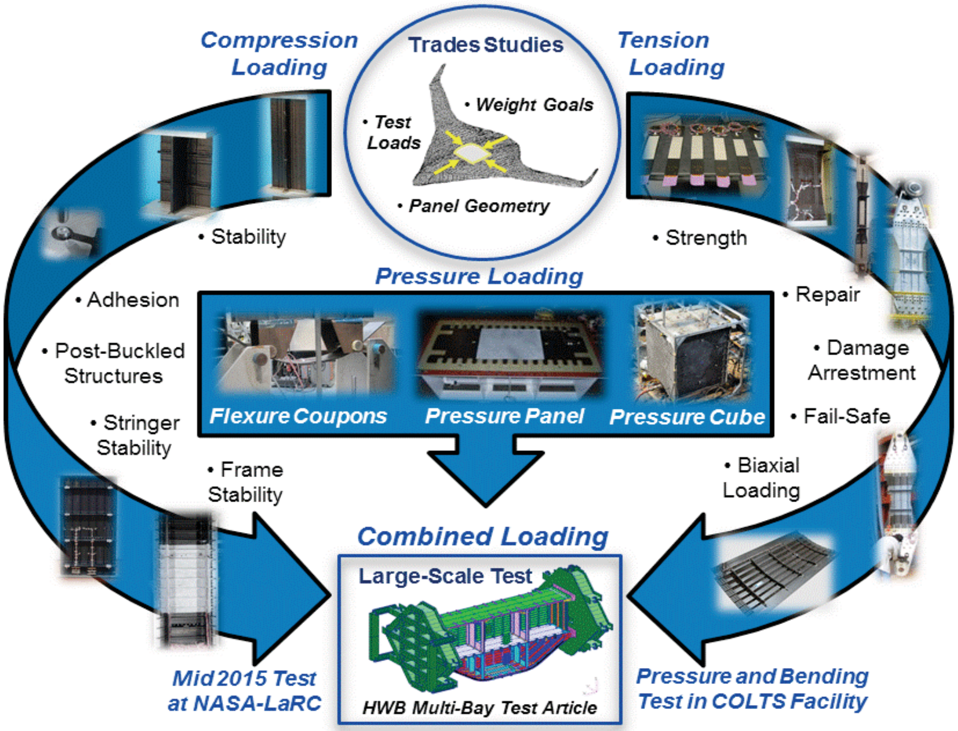


Figure 3. Development path leading to HWB large-scale test article.

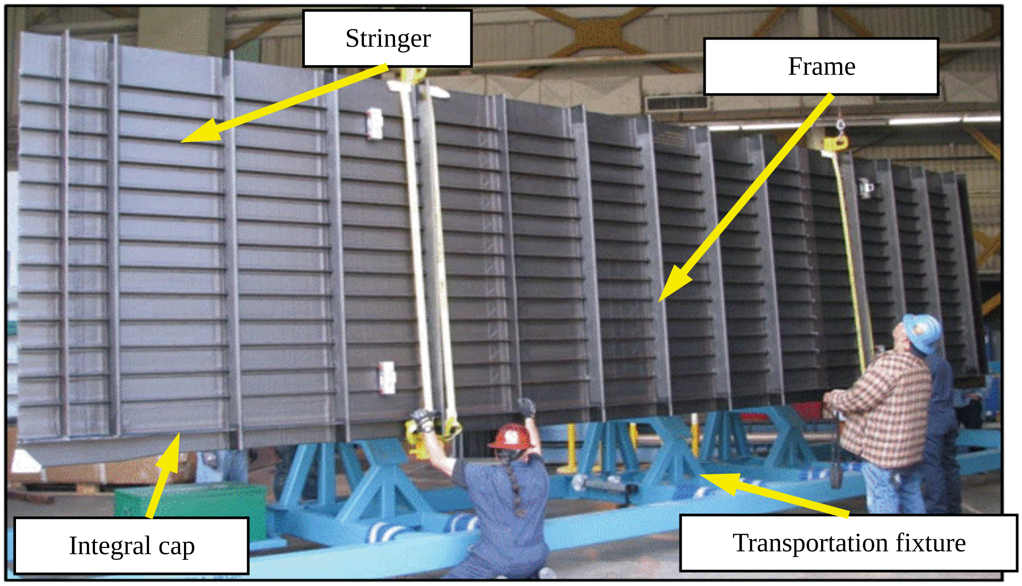


Figure 4. PRSEUS 30-foot-long bulkhead panel.

loads; mechanical loading to design ultimate load (DUL) in an up-bending configuration with no pressure, putting the crown in compression and the keel in tension; mechanical loading to DUL in a down-bending configuration with no pressure, putting the crown in tension and the keel in compression; the combination of internal pressure and up-bending; and the combination of internal pressure and down-bending.

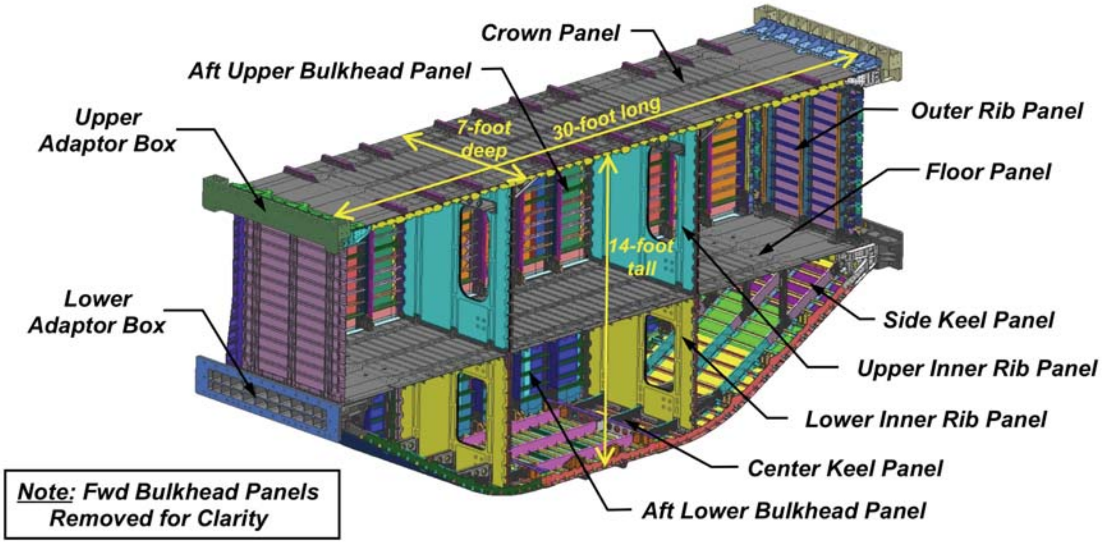


Figure 5. Multi-bay pressure box.

IV. Multi-Bay Pressure Box Design and Analysis

Although the test article design envelope was reduced to a ¾-scale representation to accommodate fabrication equipment limits, the magnitude of the internal running loads was maintained to retain the linkage between the test results and airframe weights that were generated for the baseline BWB-5-200G configuration.[4] This structural optimization was completed using an iterative global-local FEM-based analysis scheme that defined the critical load cases and sized the structure based on initial aircraft stiffness, mass distribution, and flight envelope, as depicted in Fig. 6. A subset of the critical external loads (maneuver, taxi, crash, and pressure) was generated by simulating the aeroelastic maneuvers across a nominal flight envelope using a NASTRAN Solution 144[21] loads model. The maximum internal forces were then isolated for the cabin structure, from which a simplified subset of load cases was sorted to structurally size the test article. Once the critical internal loads and panel gauges were established, the dataset was used to build a very detailed test article finite element model (FEM) with approximately 4.5 million degrees-of-freedom that was further modified to incorporate the specific point and line loads imparted by the loading platens in the test facility. The FEM uses shell elements to represent composite panels and metallic fittings. Beam elements are used to model top frame edges and pultruded rods in panel stringers. Connector elements represent fasteners. The loading fixtures of the test facility are modeled using a combination of shell and beam elements. The finite element model is shown in Fig 7. The skin, tear straps, frame caps, frame webs and stringer webs consist of "stacks" of carbon-epoxy layers. A single stack has the thickness of 0.052 in. and comprises seven plies with stacking sequence $[+45, -45, 0, 90, 0, -45, +45]_T$ and percentage of the 0, 45 and 90-degree fibers equal to 44.9, 42.9, and 12.2, respectively. Several pre-kitted stacks are used to build up the desired thickness and configuration. Stack material properties are used in the analysis and are shown in Table 1.[23] Material properties for the foam, pultruded rod, fittings and fasteners are also shown in Table 1.[23] This FEM was initially run in a linear mode by Boeing to structurally size the specimen details, and then later in a nonlinear mode by NASA to study the panel instability modes across the combined pressure-plus-axial loading conditions.[22-23]

As would be expected for a wing-type structure, the up-bending (2.5-g) and down-bending (-1.0-g) maneuver conditions were the primary design drivers for the cover panels, which in conjunction with the requirement of internally pressurizing the HWB cabin, forms the basis for the load cases that govern the structural sizing. The interaction of these combined pressure-plus-mechanical forces dictates how and in-what-order the loads are imparted onto the specimen in the test facility.

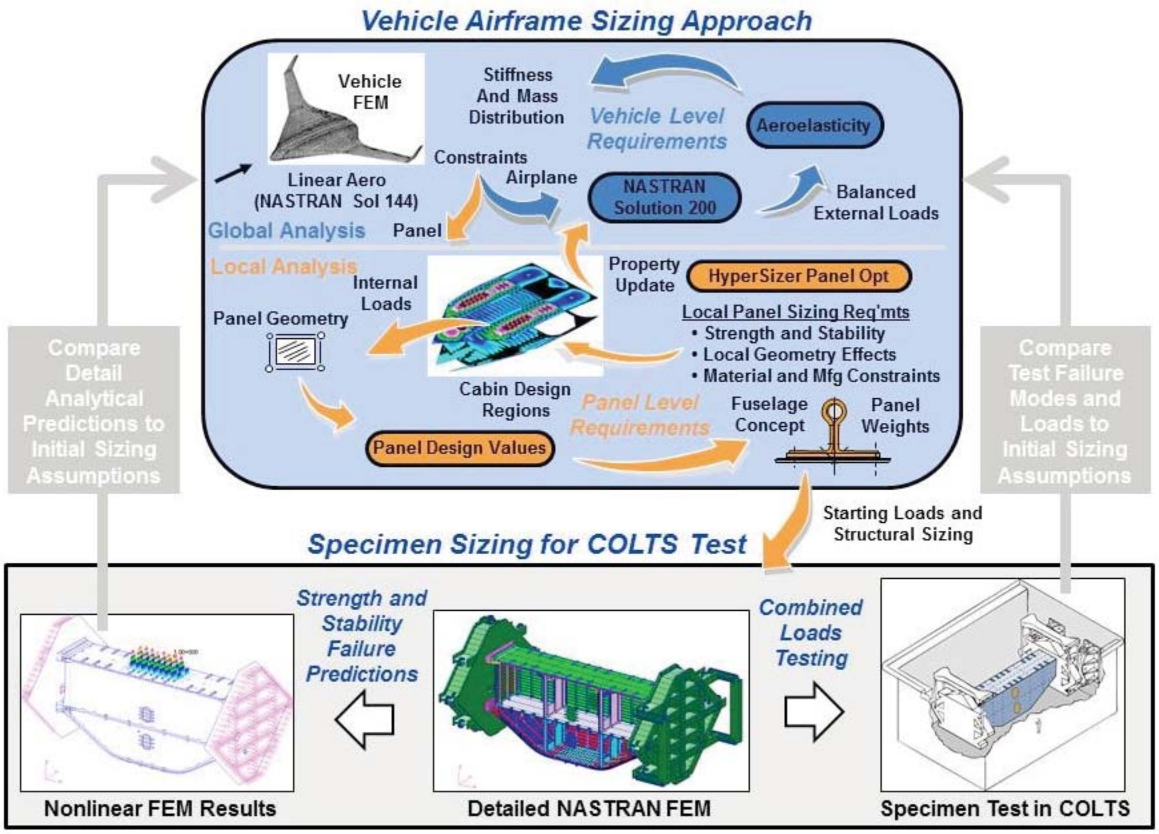


Figure 6. Relationship of vehicle-level and panel-level structural sizing to specimen analyses.

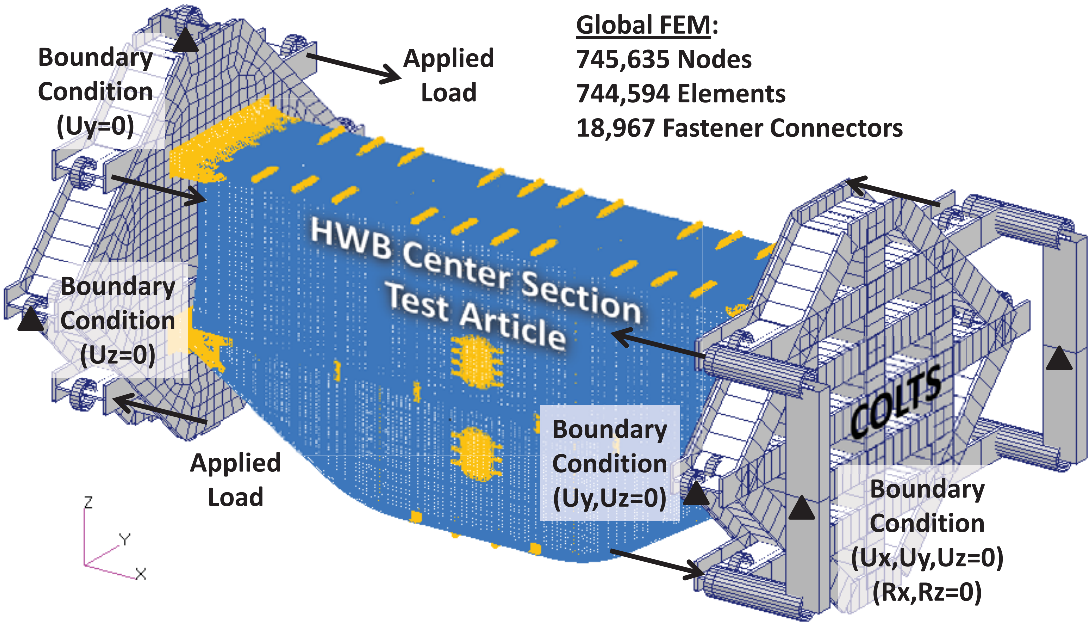


Figure 7. Finite element model of the test article and COLTS test fixture.[23]

Table 1 Composite and metallic material moduli and Poisson ratios of the test article.[23]

Material	E or E_{11}/E_{22} (Msi)	ν or ν_{12}	G or G_{12} (Msi)
Composite Laminate (One Stack)	9.74/4.865	0.40	2.37
Stringer Rod	20.1	0.30	
Frame Foam Core	0.01882		0.00725
Aluminum Fitting	10.3	0.33	
Titanium Fastener	16.9	0.31	
Inconel® Fastener	29.4	0.29	11.4

For each load case the lowest margin of safety at DUL and the structural component where the lowest margin of safety occurs were identified. Based on these findings[23] no failures are anticipated in the structure at load less than DUL for any of the planned loading conditions. Driving conditions for the design include pillowing of the skins between the stiffeners in the pressure-loaded load cases, local buckling of the crown skin in the up-bending load cases and local buckling of the center keel in the down-bending load cases. Analysis indicates that the strains induced by the pillowing will remain below the allowables. Additonally, panel tests previously conducted and their corresponding analysis indicate that local buckling of the crown and keel will not lead to a global failure. An example of the predicted out-of-plane displacements for the crown panel subjected to DUL in the 2.5-g up-bending condition is shown in Fig. 8. Local resin failures and load redistributions are expected, but no strains in the composite panels, metal fittings or fasteners should exceed design allowables at loads less than DUL. Additionally, the nonlinear analysis has been conducted for this load case for loading up to 30 percent over DUL to predict panel stability margins such as where critical strain locations occur in the crown and the upper bulkhead near the joint between the crown and the upper bulkhead. Extensive instrumentation will be applied to these areas to allow the acquisition of data in these regions to develop an understanding of the behavior of the test article under such loading. More details about the behavior for the up-bending load case and descriptions of the behavior for the other four load cases are presented in Ref. 23.

V. Multi-Bay Pressure Box Fabrication

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 are used to divide the box width into thirds, as shown in Fig. 9. End fittings are added at the corners of the pressure-tight cell to impart bending loads that simulate those of the wing carry-through structure that would be induced during a flight maneuver.

One of the principal goals in developing the PRSEUS fabrication technology is to demonstrate that stitched dry fabric panels can be infused and cured in an oven and still result in high quality parts and lower recurring fabrication costs compared to conventional composite processes. The PRSEUS fabrication sequence, as shown in Fig. 10, starts with the cutting of individual pieces of warp-knit fabric on a cutting table, which are then organized into kits. Foam cores are attached to the frame webs and stringer webs are stitched to create a pocket for the rod to pass through, creating pre-assembled stiffeners. All of these details are then delivered to the preform assembly fixture where they are properly positioned, and then stitched in place to create a self-supporting dry carbon preform. The preform is then transferred to an outer mold line cure tool for resin infusion processing where a pleated nylon vacuum bag system is placed directly over the preform and sealed down against the cure tool edges. The preform is then infused with resin and cured using an out-of-autoclave process. The initial cure takes place at 250°F, followed by vacuum bag and resin line removal, and then a 350°F free-standing post cure.[24,25] Since all of the materials in the stitched assembly are dry, there are no out-time limitations as with prepreg systems. The oven cure removes the size restrictions required for fitting the assembly in an autoclave. The goal of the panel fabrication was to demonstrate the ability to produce high quality, high fiber volume fraction, void-free laminates with highly accurate shapes in an out-of-the autoclave environment.

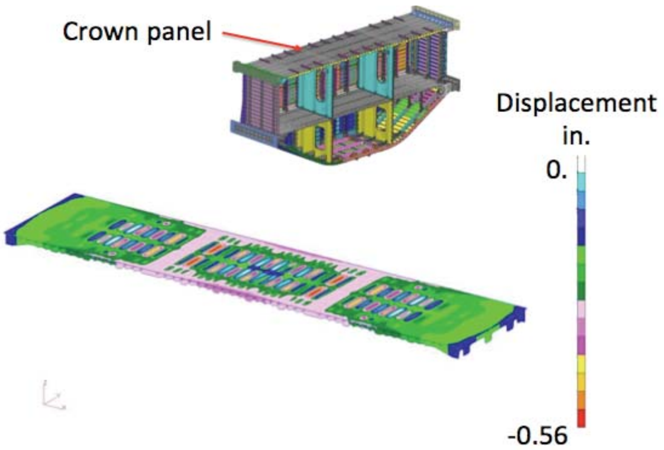


Figure 8. Crown panel out-of-plane displacements with visible local skin buckling at DUL for up-bending condition. Dimensions are in inches.[23]

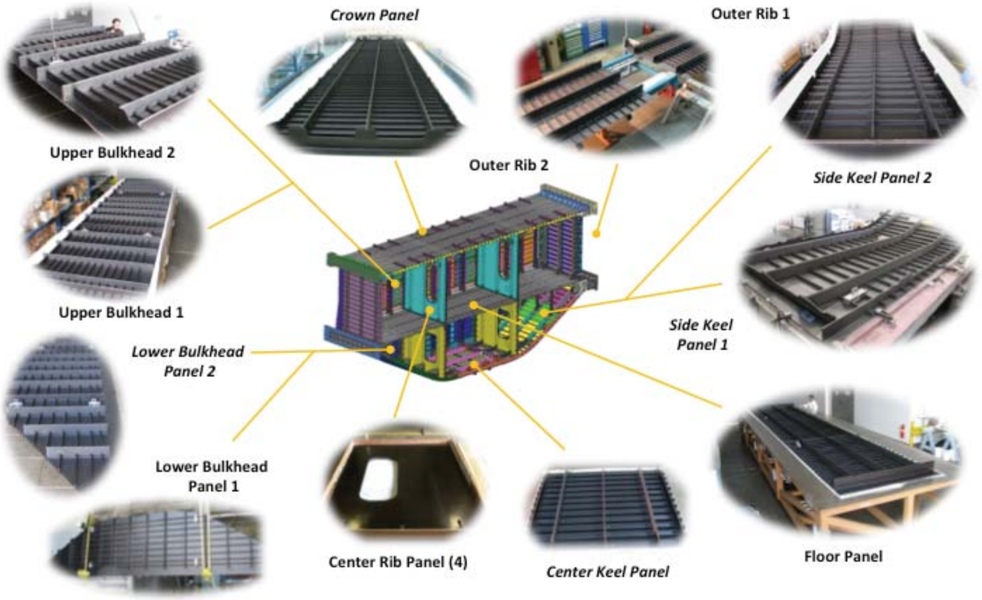


Figure 9. Composite panels in multi-bay pressure box.

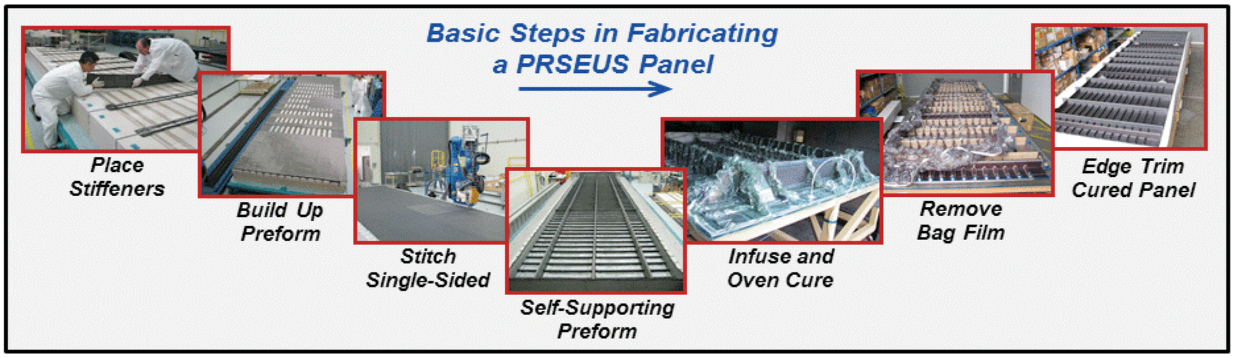
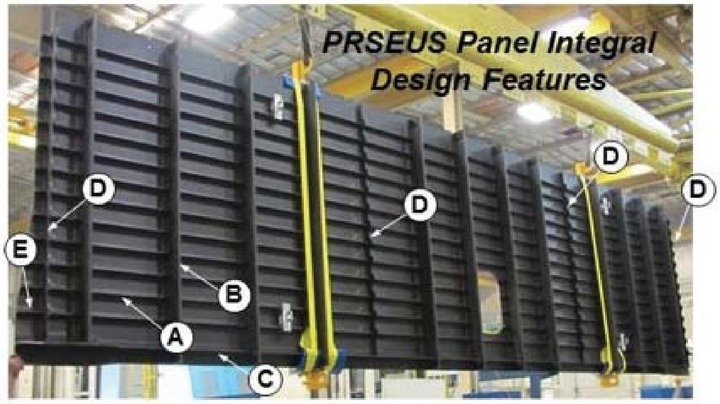


Figure 10. Key fabrication steps to build a PRSEUS panel.

The multi-bay pressure box was assembled at Boeing's 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 metal fittings, and eliminate fasteners through the exterior surface of the panels. This methodology is enabled by the integral design features of the stitched panel that results in fewer parts, less drilling, less lightning-strike protection materials, and ultimately, lower recurring assembly costs.

Even though the inclusion of the stringer and frame elements into the unitized panel design represented a major breakthrough in structural integration, further levels of integration were also achieved by incorporating the afore-mentioned integral cap feature that is used to complete the panel-to-panel connection at the perpendicular interfaces that occur at all rib and bulkhead locations. The high level of panel integration is clearly evident on the upper bulkhead panel shown in Fig. 11 where stringer and frame elements are labeled as items A and B, respectively. Integral cap features, labeled items C and D, are composed of solid laminates and create the cap detail for the adjacent joining panel. The integral cap labeled C attaches to the floor and the integral caps labeled D attach to the ribs. The resulting joint design permits the stringers to be continuous through the cap, as indicated at item E, and is highly effective in reacting the bending loads induced by the perpendicularly joined rib or bulkhead panels. Such an efficient method of transferring load along the square edges of the HWB pressure cabin is one of the key attributes needed to successfully implement the non-circular pressure cabin. The square corner problem in the pressurized section where concentrated stresses are applied during each pressurization is solved by taking advantage of the fatigue insensitivity of laminated composites and the through-thickness reinforcement which suppresses delaminations. The resulting structure is a highly tailored 3-dimensional composite panel joint where the primary loads move through layers of carbon material rather than through transition fittings and fasteners.

The use of these integral design and assembly techniques is enabled by the stitched interface and was first pioneered on the NASA Advanced Composites Technology Wing Program.[26] Based on that initial work, further refinements were made using the PRSEUS panel design to improve the laminate continuity and stitching patterns across critical structural interfaces that led to large improvements in damage arrestment that increased the overall panel residual strength, and ultimately enabled the use of more favorable fail-safe design criterion that are more closely associated with conventional metallic design methods. Although these panel-to-panel joining techniques were validated on the 4-ft wide cube test article,[12] there were still many questions as to whether the caps could be accurately molded to achieve suitable assembly tolerances that would facilitate the determinant assembly methods planned for the 30-ft long panels. The ability to accurately net-mold the integral cap features over a 30-foot span would not really be fully understood or appreciated until the first panels were actually brought together in the assembly jig.



ID	Feature	Resulting Design Feature	Advantage Derived
A	Stringer	Highly tailored, rod stiffened	Axial load efficiency
B	Frame	Full height frame w/o shear clip	Bending efficiency
C	Floor Cap	Integral design to reduce fittings	Panel joining efficiency
D	Rib Cap	Integral design to reduce fittings	Panel joining efficiency
E	Runout	Continuous stringer through cap	Corner joint efficiency

Figure 11. Summary of structural integration benefits.

As those initial panels were positioned to build the upper section of the specimen, the results were encouraging and the basic approach of net-molding a rigid interface to locate the adjacent panel worked well; although at some locations metallic shims were added to compensate for the out-of-perpendicularity that occurred in the rib and floor caps compared to the skin during the panel cure cycle. Once these effects were better understood, simple adjustments were made to the cure tools used on subsequent panels which resulted in more uniform flat surfaces so shimming was not required during assembly. These features are shown in Fig. 12.

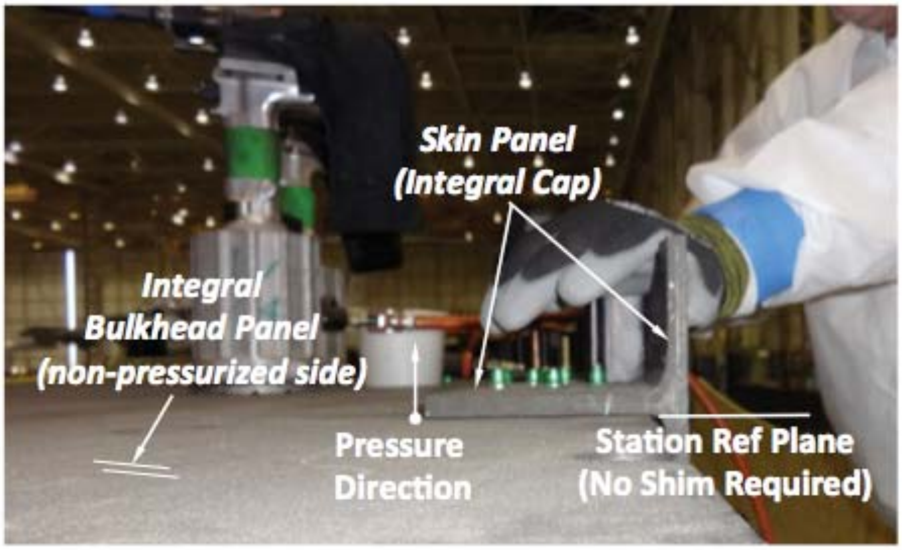


Figure 12. Molded integral cap station plane surface is used to locate panels.

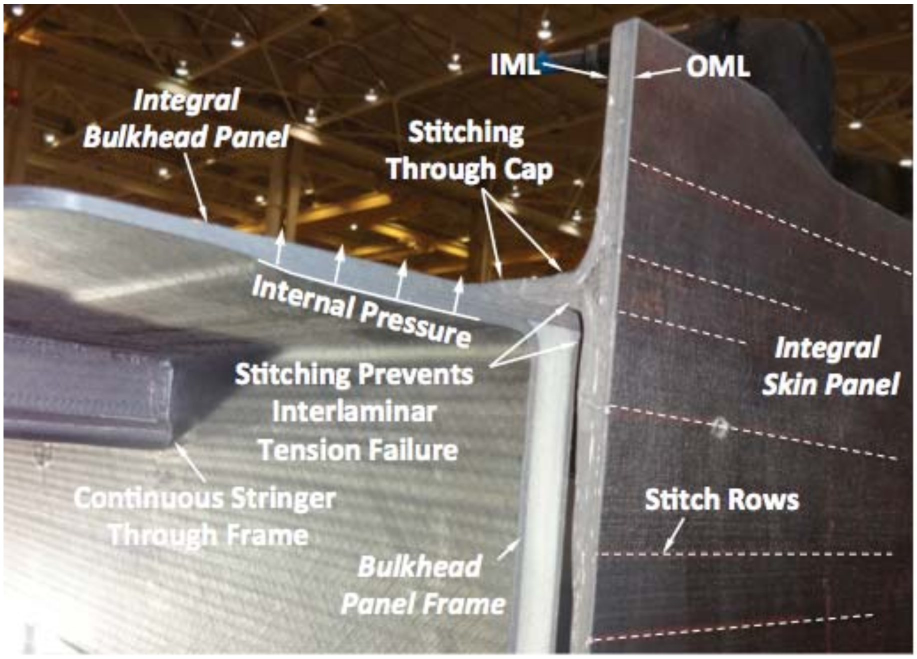


Figure 13. Unique panel-to-panel design reduces assembly weight and cost.

The high level of panel assembly integration is evident in the photograph shown in Fig. 13, where the integral bulkhead panel is positioned to bear up against the integral cap feature on the skin panel as the internal pressure pushes the panel outward. The basic shear connection between the panels is accomplished with mechanical attachments. Such an approach is critical for the HWB design because it permits these large integral panels to be efficiently assembled without placing countersunk fasteners through the outer moldline of the skin panel, which would be problematic for composite laminates subjected to the severe pull-off loading generated by the flat-sided pressure cabin. The basic drill out step and the installed fasteners are shown along a representative panel-to-panel connection in Fig. 14. The final phase of assembly is shown in Fig. 15 where all the panels are in place except the center keel.

Even with these advanced composite joining techniques, the inherent complexity of attaching discretely stiffened panels together dictated that hundreds of metallic fittings would still be required to close out the final assembly. The load introduction hardware was added and machined to fit properly in the test facility to complete the test article. The test article was then rotated upright, as shown in Fig. 15, and placed in a holding fixture. The entire test article assembly in its holding fixture is being transported to the NASA Langley Research Center where the combined-loads testing will be conducted in a series of loadings within the NASA Langley Combined Loads Test System (COLTS) in 2015.[27]

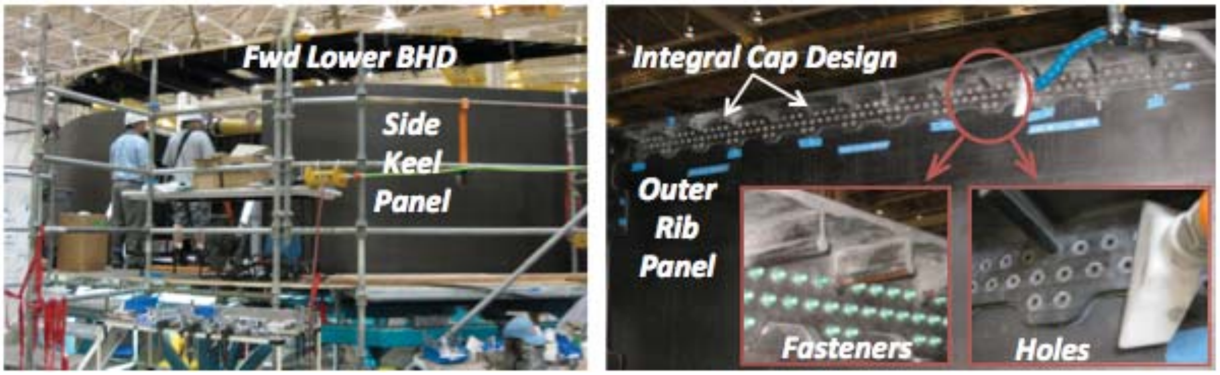


Figure 14. Integral panel-to-panel joining techniques are used to reduce joint weight and assembly cost.

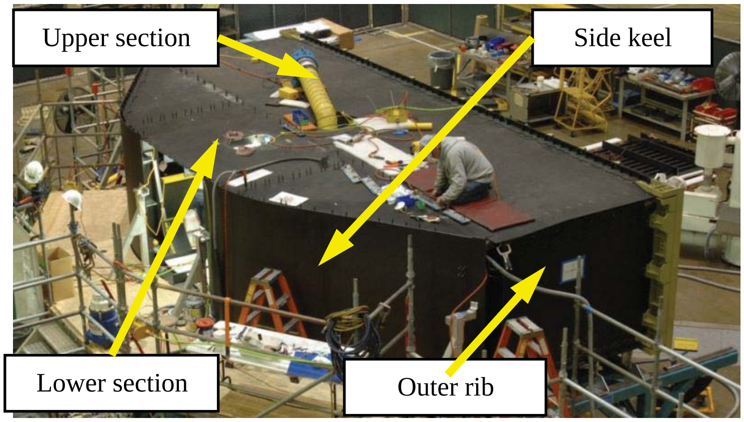


Figure 15. Mid-2014 assembly of multi-bay pressure box.

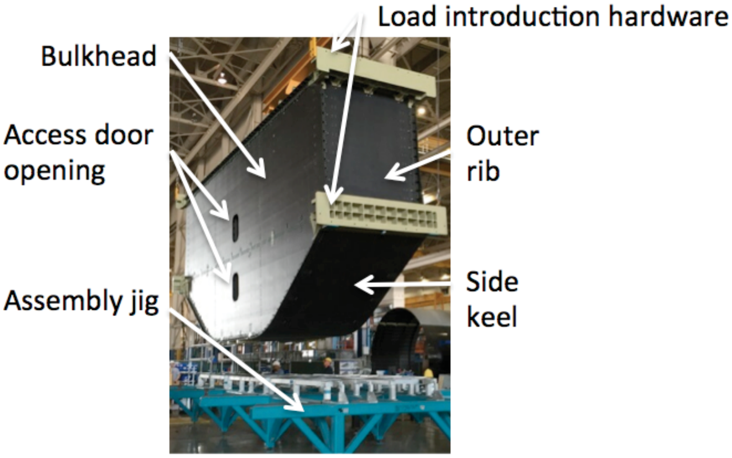


Figure 16. Multi-bay pressure box prepared for installation into the holding fixture.

VI. Multi-Bay Pressure Box Experiment

The multi-bay pressure box will be shipped to NASA LaRC in Dec. 2014. It will be mounted between the platens of the NASA Langley COLTS facility. The load introduction hardware where the test article will attach to the platens as shown in Fig. 16. The test article will then be subjected to a series of loadings in 2015. A sketch of the test article between the platens in the COLTS facility is shown in Fig. 17. The platens will be rotated to apply mechanical loads to the test article. Four actuators are located at symmetric locations connected to the platens. These actuators are not shown in the figure since they would obscure the view of the platen-test article arrangement. During testing in the up-bending conditions, the top two actuators will pull the platens together while the lower two actuators will push the platens apart, putting the crown in compression and the keel in tension. The opposite loading will be applied for the down-bending conditions. In the pressure-only and combined load cases, pressure will be pumped into the test article through an access door. Approximately 15 displacement transducers, 460 channels of strain gage data, two pressure transducers and loads from each actuator will be

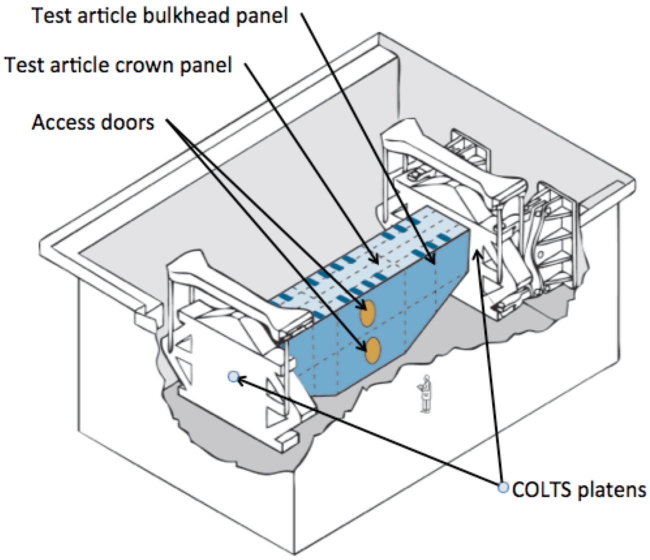


Figure 17. Testing arrangement in the NASA COLTS facility.

monitored and recorded for each loading. Digital image correlation systems will be used to monitor displacements and strains to the exterior crown, bulkhead and center keel panels. Additionally, fiber optics and acoustic emissions data will be acquired for post-test evaluation.

Five loading conditions will be applied to the pristine multi-bay pressure box in a series of experiments under DLL and then DUL load levels. These loading conditions are 1) an internal pressure load alone 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 -1-g bending condition which subjects the crown panel to tensile loads; 4) a combination of pressure and -1-g bending; and 5) a combination of pressure and 2.5-g bending. After all five conditions have been applied at the DLL and DUL levels, barely visible impact damage (BVID) will be inflicted to three locations on the interior of the test article and three locations on the exterior of the test article. The interior impact sites will be on one bulkhead on the top of one stringer, on the top of one frame, and to the skin mid-bay. For interior impacts, a spring-loaded impactor will be used. BVID for the interior sites corresponds to 20 ft-lb for the stiffeners, which causes little damage but is the maximum energy required for internal impacts for commercial aircraft, and 15 ft-lb for the skin mid-bay location, where clearly visible damage will be seen. A one-inch-diameter tup will be used for all impacts. Then BVID will be inflicted to the exterior of the test article. The exterior impact sites will be on the center keel panel to the skin where a frame flange terminates, where a stringer flange terminates, and to the skin mid-bay. For exterior impacts a gravity-fed impactor will be used. BVID for the exterior sites corresponds to energy levels of 60 ft-lb, 50 ft-lb and 15 ft-lb for the frame flange, the stringer flange and the mid-bay locations, respectively. A sketch showing the locations of the keel impacts near the flanges is shown in Fig. 18. After all BVID impacts are inflicted and ultrasonic inspection of each site is completed, the series of DLL and DUL tests will be repeated. The final test will be in the up-bending condition to loading above DUL until enough damage occurs in the test article that it can no longer support increased loading.

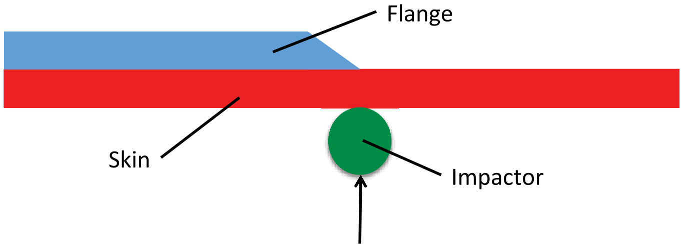


Figure 18. Exterior impact site near flange.

VII. Concluding Remarks

The PRSEUS panel architecture was conceived to address the weight and cost shortcomings inherent in conventional layered material systems. By replacing prepreg with dry fabric, and fasteners with stitching, a highly engineered structural solution is possible that moves beyond traditional composite design practices to offer a highly integrated structural solution with better load paths and the ability to stop damage progression. A building-block test program has been successfully executed leading up to the final large-scale test to demonstrate the viability of a PRSEUS fuselage for the HWB transport aircraft.

This final step in in the building-block process will take place at the NASA-LaRC COLTS test facility in mid-2015. The multi-bay pressure box has been fabricated from PRSEUS panels and is being prepared for testing under combined load conditions. This test article will be subjected to critical flight maneuver load conditions and pressurization in a ground test program that will demonstrate the technology is capable of meeting the structural weight goals established for the HWB airframe. These loadings include combinations of up-bending, down-bending and internal pressure, with loading to DUL. The test article is designed to withstand BVID to DUL and is expected to demonstrate post-buckling behavior and damage arrestment prior to failure at loading in the up-bending condition at load greater than DUL. These test results will demonstrate the viability of the PRSEUS concept for HWB center section type structure.

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