

Preparation for Testing a Multi-Bay Box Subjected to Combined Loads

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ABSTRACT

The COmbined Loads Test System (COLTS) facility at NASA Langley Research Center provides a test capability to help develop validated structures technologies. The test machine was design to accommodate a range of fuselage structures and wing sections and subject them to both quasistatic and cyclic loading conditions. The COLTS facility is capable of testing fuselage barrels up to 4.6 m in diameter and 13.7 m long with combined mechanical, internal pressure, and thermal loads. The COLTS facility is currently being prepared to conduct a combined mechanical and pressure loading for a multi-bay pressure box to experimentally verify the structural performance of a composite structure which is 9.1 meters long and representative of a section of a hybrid wing body fuselage section in support of the Environmentally Responsible Aviation Project at NASA. This paper describes development of the multi-bay pressure box test using the COLTS facility. The multi-bay test article will be subjected to mechanical loads and internal pressure loads up to design ultimate load. Mechanical and pressure loads will be applied independently in some tests and simultaneously in others.

Key words: Composite, Combined Loading, Hybrid wing body, PRSEUS, Rod-stiffened

INTRODUCTION

The ability to subject aerospace structures to combined loads representative of actual operating conditions is an important aspect of aerospace structural design. The standard aerospace industry practice is to design a structure that supports the various loading conditions and to verify the design by structural testing. A test fixture is usually designed to subject the structure to a subset of the loading conditions. The test fixture is often limited to a particular design or single configuration. However, the development of structures technology to be used for future aerospace design requires that full-scale and sub-scale structural concepts be tested with combinations of mechanical and internal pressure loads. Combined loads testing requires a combined loads test machine with the flexibility to accommodate these structures. NASA Langley Research Center has developed a COmbined Loads Test System (COLTS) Facility that consists of a multi-actuator test machine capable of applying combined loads and internal pressure loading to validate structures technology [1]. Structural tests have been conducted using the COLTS facility to support airframe and space structures technology development.

The subject of this paper is the preparation for conducting a sequence of combined mechanical and pressure loadings to a large-scale multi-bay pressure box to experimentally verify the structural performance of a composite structure which is 9.1 m long. This test article is representative of a section of a Hybrid Wing Body (HWB) center fuselage section and supports NASA's Environmentally Responsible Aviation (ERA) Project. In this paper, first, the COLTS facility is described and the goals of the project are presented. Subsequently, preparations and plans for testing this structure are described.

COMBINED LOADS TEST SYSTEM

COLTS was designed to accommodate a range of fuselage structures and wing sections and subject them to both quasistatic and cyclic loading conditions. COLTS is capable of testing fuselage barrels up to 4.6 m in diameter and 13.7 m long with combined mechanical, internal pressure, and thermal loads. A schematic of COLTS configured with a cylindrical shell

mounted between the test machine platens is illustrated in Fig. 1a, and a photograph of the facility is shown in Fig. 1b. The loading platen is suspended from a gantry that can traverse forward or backward to accommodate test articles of different lengths. Compression and bending loads are applied to the test articles by six 2,001.7-kN hydraulic actuators located perpendicular to and between the loading and reacting platens along the x (longitudinal) axis. Torsion loads are applied to the test articles by two 1,334.5-kN hydraulic actuators located vertically and spaced 7.0 m apart. Shear loads are applied to the test articles by two 1,334.5-kN hydraulic actuators located horizontally and spaced 5.5 m apart. The test machine is located in a steel reinforced concrete pit that is approximately 9.8 m deep, 14.3 m wide, and 22.0 m long. This arrangement ensures that pressurized structural testing can be performed safely. The length of the axial actuators is extended by means of tubular extensions to connect the loading platen with the reacting platen so that test specimens that are longer than 3.05 m can be accommodated

For the development of tests to be conducted in COLTS, an approximately 10% -scale model of COLTS, called Mini-COLTS, is utilized. Compression, bending, shear, and torsion loads are applied to subscale test models by six 8,896-N hydraulic actuators located perpendicular to and between the loading and reacting platens along the x (longitudinal) axis. Torsion loads are applied to the test articles by two 8,896-N hydraulic actuators located vertically and spaced 81.6 cm inches apart. Shear loads are applied to the test articles by two 8,896-N hydraulic actuators located horizontally and spaced 57.15 cm apart. The length of the axial actuators is fixed with respect to the reacting platen so that test models that are 139.7 cm can be accommodated. A photograph of the Mini-COLTS is shown in Fig. 2. Using the COLTS control system, Mini-COLTS can be used to conduct operational checkout of the mechanical loading parameters before loading the actual test article. Once the Mini-COLTS loading has been verified, the controls can be switched back to the COLTS facility.

A 2048-channel data system is used to record data from the strain gages, thermocouples, transducers, and load cells during each test. Additional data systems to supplement this system can also be used. For example, fiber optic, digital video image correlations systems and acoustic emission systems have independent personal computer data systems to record their data but can be linked to the primary data system to acquire pressure and load from one load cell so that readings from the independent systems can be correlated.

GOALS OF THE MULTI-BAY TEST ARTICLE EXPERIMENT

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. [2]

Damage Arresting Composites

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 [5,6] that culminates in the test of a large 9.1-meter-long multi-bay pressure box that will be subjected to combined bending and internal pressure loadings.

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.

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. 3. 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-conductive 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.

Multi-Bay Pressure Box

The final step in the building block ground testing in applying the PRSEUS concept to the HWB centerbody is a 9.1-m-long multi-bay pressure box test article. [6] The test article is representative of a portion of the center section of a HWB vehicle and addresses the same construction, analysis, and pressurization issues that would be encountered on an airframe that has flat pressurized surfaces. These technologies include minimum-gauge design, post-buckled skins, crack arrestment, impact damage, manufacturing scale-up to larger structures, and joining technologies. The multi-bay test article contains 11 PRSEUS panels (crown, floor, two upper bulkheads, two lower bulkheads, two side ribs, two side keels, one center keel), four honeycomb inner rib panels, aluminum fittings, access doors, and titanium bolts and load introduction hardware. A photograph of a 9.1-m-long panel 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 and a photograph of the multi-bay pressure box in its holding fixture while being prepared for testing is shown in Fig. 6.

The multi-bay box test article will be subjected to mechanical loads, but it will also be subjected to internal pressure loads. Mechanical and internal pressure loads will be applied simultaneously. The loading conditions will simulate the critical load cases of 2.5g up-bending, 2.5g up-bending plus 63.4 kPa pressure, -1.0g down-bending, and -1.0g down-bending plus 63.4 kPa internal pressure maneuver conditions, as well as the static internal pressure loads of 126.9 kPa. These loading conditions were used to size the overall test article structure.

PREPARATION FOR THE MULTI-BAY BOX TEST

Preparation of the COLTS facility and the test article had to be conducted in preparation for the tests described above. These preparations included examination of the COLTS systems such as controls, pneumatics, and hydraulics and instrumentation of the test article to record point-data such as strains and displacements, and full-field images from cameras.

Control System

An MTS control system is used to control the ten COLTS actuators. In the multi-bay pressure box test, only four actuators are used. A combination of load-control, stroke control, and a mix mode will be used during the sequence of tests. The pressure loading commands can be input directly to the pressure controller or by discrete input from the MTS Control system. Air pressure loading is controlled by a separate Fisher controller that receives a discrete digital command from the MTS Control system. Internal pressure loading of the multi-bay box is achieved varying the opening of an inlet valve and an outlet valve.

Control System Checkout

A 9.1-m-long checkout beam was used to develop the test operations and procedures for the multi-bay test article evaluation. The multi-bay test article will be subjected to mechanical loading conditions to simulate flight conditions of the 2.5g and -1.0g bending maneuver conditions by applying loads on the platens of combined loads test machine. In order to achieve the critical 2.5g up-bending maneuver load, the center bay of the crown panel will be loaded to an average compressive running load of 875,634 kN/m across its width. The loading methodology to be used for the multi-bay box test was verified using the 9.1-meter checkout beam.

The checkout beam is a W36 X 256, A992 steel I-beam structure reinforced at each end with steel plates to allow load introduction. The checkout beam was subject to a maximum applied bending moment 1,346,594 m-N in COLTS in order to verify loading methodologies for the multi-bay box test. A photograph of checkout beam installed in COLTS is presented in Fig. 7. The series of tests on this checkout structure placed the beam in pure bending. Strain gages on the I-beam flanges were monitored to develop confidence that the MBB would be loaded in pure bending as planned. [7]

Instrumentation

Several types of instrumentation will be used to monitor and record data during each test. 262 linear and 36 conventional strain gages, 15 linear variable displacement transducers (LVDT), two pressure transducers, three fiber optic wires, up to 5 video digital image correlation systems, 26 acoustic emission sensors and 14 video cameras will be used to record the

behavior of the test article and the COLTS system. Strain gages are located on each PRSEUS panel and several metal fittings. The location of the LVDT's and fiber optic wires are shown in Fig. 8.

A speckle pattern, consisting of black paint dots on a white paint background was applied to a portion of the aft bulkhead, the crown and the center keel. Approximate locations of areas to be monitored using the video digital image correlation systems is shown in Fig. 8.

Video cameras will be placed inside each of the six bays of the test article to record cracks and deformations in the bulkheads, floor, crown and keel. Additional cameras will be placed outside the test article to see a more global view of the structure. These video images will be monitored during each test. Time will be used to correlate video images with strain gage and other data post-test.

Installation between platens

To ensure the fit of proper fit and alignment of the multi-bay pressure box test article between the platens in the COLTS facility, the bolt holes in the load introduction fixtures were not drilled during the assembly of the test article. Instead, these four fittings were attached to the test article and milled to be flat and parallel to each other. These fittings in the undrilled state are shown in Fig. 6.

The multi-bay pressure box was initially lowered into the test chamber and positioned between the platens so that the bolt hole locations where the COLTS platens would interface with the test article load introduction fixtures could be marked. Using the 222 kN capacity crane in the COLTS facility, the test article was lifted out of its holding fixture, lifted over the wall between the test preparation area, and lowered between the platens in the test chamber. The test article was placed on the cleat plates on each platen and held in place by the crane for marking. Moving the test article from its holding fixture to place between the platens for marking is shown in Fig. 9. The test article was then lifted back out of the test chamber and placed back in its holding fixture so that the holes could be drilled in the load introduction fixtures. After all drilling was completed, the test article was again placed between the platens. Bolts were installed to hold the test article against the platens. A photograph of the test article fully attached to the platens is shown in Fig. 10.

TESTING

Data from the strain gages, transducers, and load cells will be recorded at a rate of 1 scans per second. Plots of strain gages and LVDT's will be monitored during each test to track the structural behavior real time to compare to predictions and evaluate the operation of the loading system. Two still cameras will be positioned to view each speckled region to simultaneously photograph the pattern every 2 seconds during each test. These images will be compared using the Correlated Solutions software [8] to determine the displacements in the x, y and z directions and the in-plane strains. These systems will provide real-time full-field imaging of displacements and strains. Data from the fiber optic and acoustic emission systems will be used in post-test test-analysis correlation.

Video cameras will be placed inside each bay of the test article to record cracks and deformations in the bulkheads, floor, crown and keel panels. Additional cameras will be placed outside the test article to see a more global view of the structure. These video images will be monitored during each test. Time will be used to correlate video images with strain gage and other data post-test.

Pristine Structure Testing

After all instrumentation and other systems are in place, a pressure test to 13.8 kPa and a checkout mechanical loading test to 50% of design limit load (DLL) will be conducted to verify that all systems are functioning as expected. A series of ten tests are planned to evaluate the pristine test article's response to critical load conditions. Loading will be conducted starting with the least critical load condition to minimize the possibility of premature damage to the test article. The test article will be loaded to DLL in down-bending alone, down-bending with pressure, pressure only, up-bending alone, and up-bending with pressure conditions. In each case, load will be quasistatic with pause points in the loading to make sure the actuators are staying in sync with each other and with the pressure load. The four active actuators will be slaved together so that all ramp to the maximum load at the same time. When pressure is simultaneously applied, mechanical load and pressure will ramp such that the maximum pressure is achieved at the same time as the maximum mechanical load. The loading will be paused briefly at the maximum load then the load will be slowly reduced to zero. If anomalies are seen in the test data, ultrasonic scans may be conducted between tests to quantify possible damage. After all DLL tests are complete, the series of loadings will be repeated with load to design ultimate load (DUL). DUL for each load condition is given in Table 1.

Barely Visible Impact Damage Testing

After the completion of the pristine structure tests, barely visible impact damage (BVID) will be inflicted to the forward upper bulkhead panel. Three impacts to the interior of the structure and three impacts to the exterior if the structure will be inflicted. Interior impact energies will be 20 J in a skin area, 27 J on the top of a stringer, and 27 J on the top of a frame, as shown in Fig. 11. These impacts will be inflicted using a spring-loaded mechanism with an impactor tup diameter of 2.54 cm. Three exterior impacts will be imparted to the center keel panel. Exterior impact will be in a skin area with no interior support with an energy of 20 J, an area where the skin is reinforced by the frame flange with an impact energy of 81 J, and an area where the skin is reinforced by the stringer flange with an impact energy of 68 J, as shown in Fig. 12. These impacts will be inflicted using a gravity fed impactor with a 2.54 cm diameter tup. Immediately before and immediately after the impacts, ultrasonic scans will be conducted so that the extent of damage caused by the impacts can be quantified. After all NDI is complete and verification that all instrumentation is fully functional, the series of tests conducted for the pristine structure will be repeated for the damaged structure. The final test is in the load condition of 2.5g up-bending with pressure. However, if catastrophic failure has not resulted by DUL, this test will be modified such that after achieving DUL, pressure will be held constant and mechanical load will increase by an additional 10%. If catastrophic failure has still not occurred, mechanical loading will be reduced back to DUL, then pressure will be slowly removed while mechanical loading is held constant at DUL and then mechanical load will be increased to 200% of DLL. If catastrophic failure has still not occurred, loading will be removed, and NDI will be conducted. An additional loading with more severe damage to the structure is being considered.

CONCLUDING REMARKS

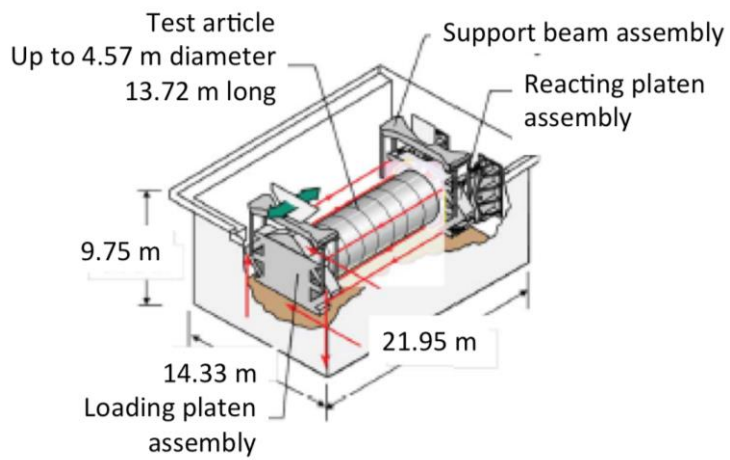
The COmbined Loads Test System facility at NASA Langley Research Center provides a test capability to help develop validated structures technologies. Preparations are almost complete for the testing of a large-scale composite multi-bay pressure box test article in the COLTS facility. The 9.1-meter-long test article will be subjected to a series of critical loadings in pristine and damaged conditions. Combined mechanical and pressure loading applied to the multi-bay pressure box will be used to experimentally verify the structural performance of a composite structure which is representative of a section of a hybrid wing body fuselage section.

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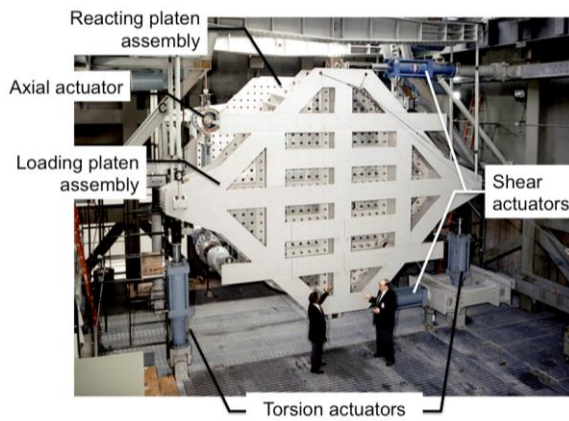
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Table 1: Load at DUL

Load condition	Pressure, kPa	Actuator load, kN
Pressure only	127	0
Down-bending	0	424
Up-bending	0	1,059
Down-bending with pressure	95	424
Up-bending with pressure	95	1,059



a COLTS test chamber



b COLTS facility with platen at 3-meter position

Fig. 1 Description of COMBINED Loads Test System



Fig. 2 Mini-COLTS

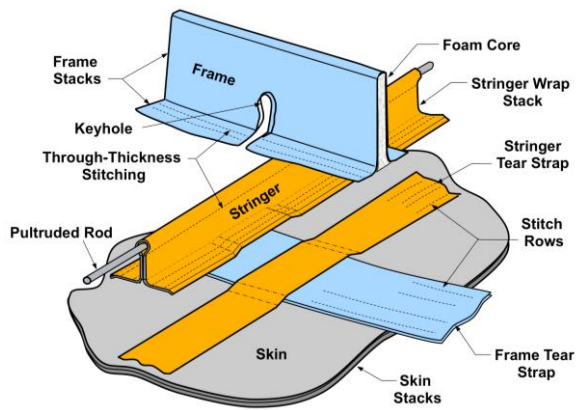


Fig. 3 Exploded view of Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) concept

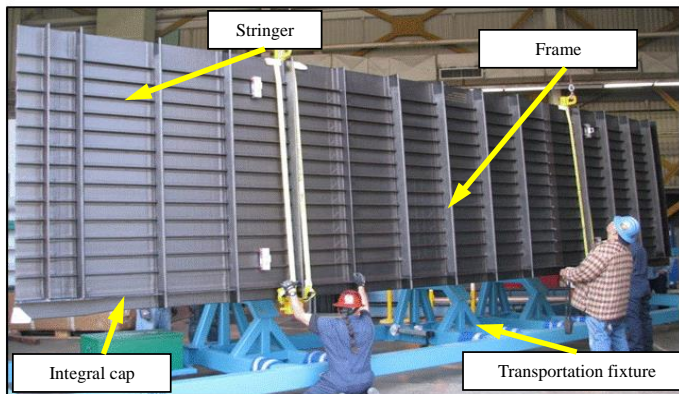


Fig. 4 PRSEUS 9.1-meter-long bulkhead panel

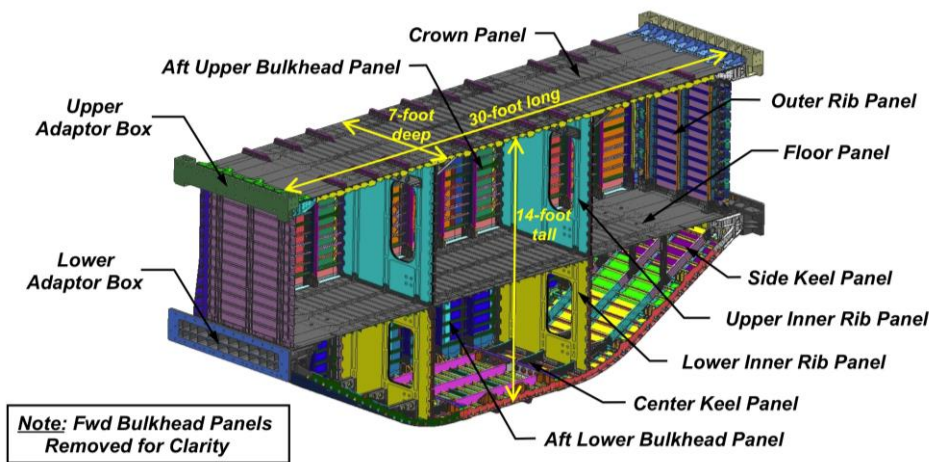


Fig. 5 Multi-bay pressure box

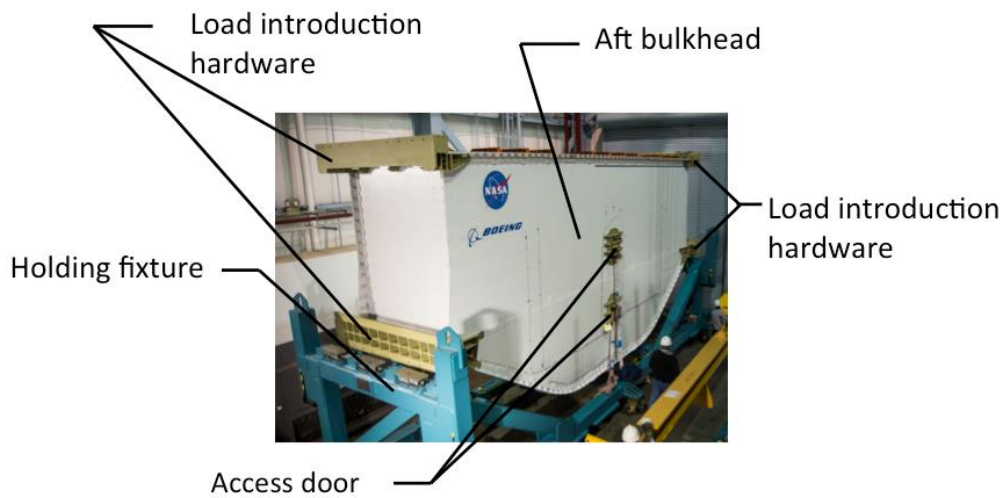


Fig. 6 Multi-bay pressure box in its holding fixture before moving into test chamber

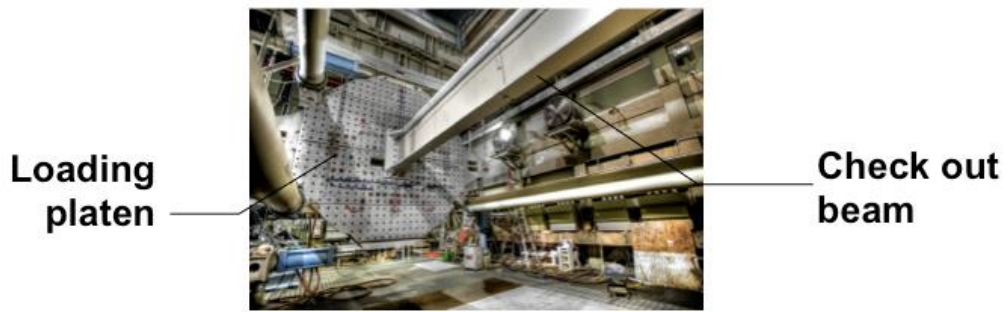


Fig. 7 Checkout beam between the COLTS platens

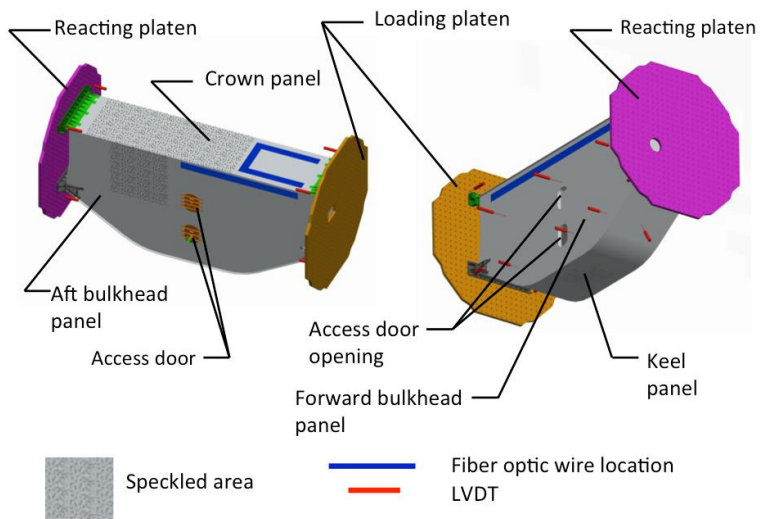
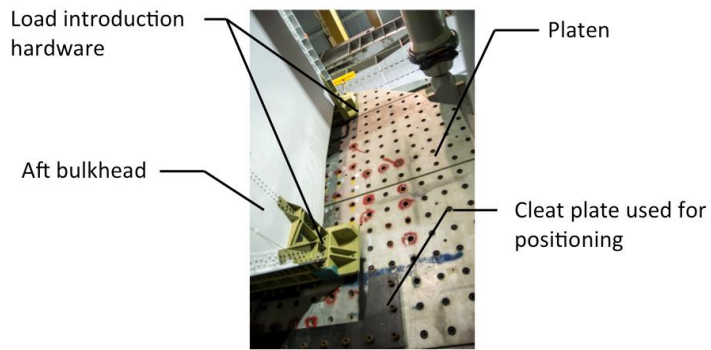


Fig. 8 Locations of LVDT's, fiber optic wires and speckle paint regions.



a Multi-bay pressure box suspended from crane above test chamber



b Multi-bay box load introduction fitting being placed against platen

Fig. 9 Moving Multi-bay box test article into test chamber

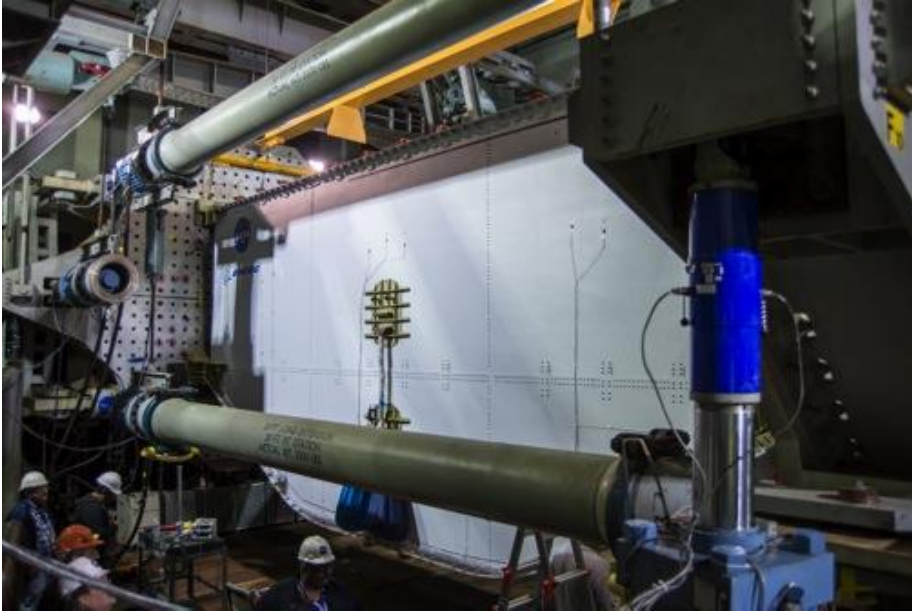


Fig. 10 Multi-bay box located between platens

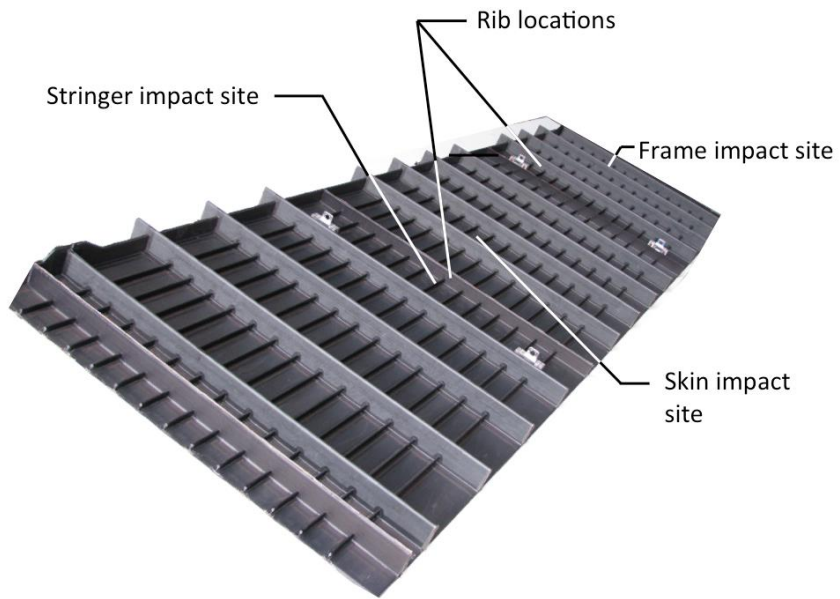


Fig. 11 Planned interior impact damage sites shown on bulkhead panel prior to test article assembly

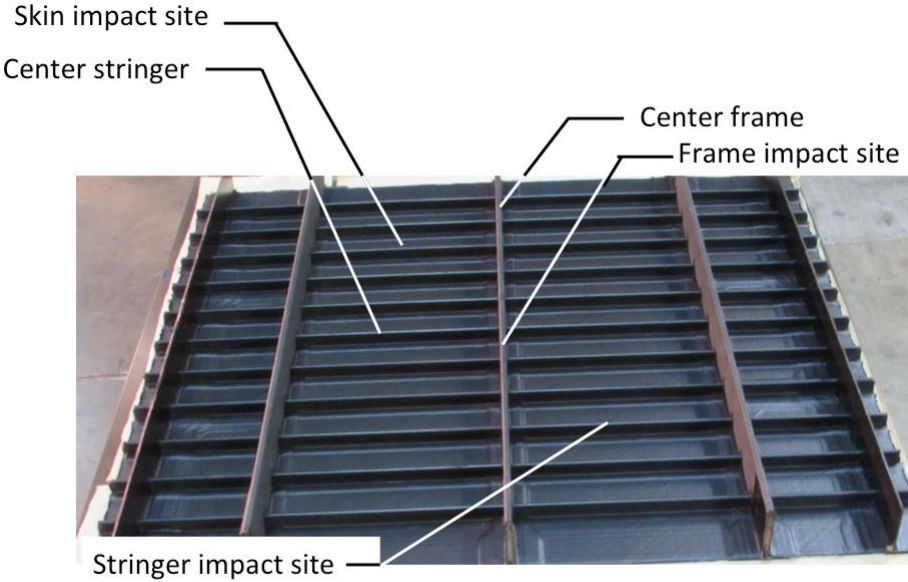


Fig. 12 Planned exterior impact damage sites shown on center keel panel prior to test article assembly