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Test and Analysis of a Hyper-X Carbon-Carbon Leading Edge Chine

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Abstract

During parts production for the X43A Mach 10 hypersonic vehicle nondestructive evaluation (NDE) of a leading edge chine detected an imbedded delamination near the lower surface of the part. An ultimate proof test was conducted to verify the ultimate strength of this leading edge chine part. The ultimate proof test setup used a pressure bladder design to impose a uniform distributed pressure field over the bi-planar surface of the chine test article. A detailed description of the chine test article and experimental test set-up is presented. Analysis results from a linear static model of the test article are also presented and discussed. Post test inspection of the specimen revealed no visible failures or areas of delamination.

Introduction

The Hyper-X flight demonstrator program represents NASA's state of the art in hypersonic flight vehicles and technology. In addition to having SCRAM type engines (ref. 1) versus the more traditional RAM engines in a Mach regime of 7-10, the X43A also has Carbon-Carbon (C-C) leading edge sections to withstand peak heating conditions and flight pressure loads. Due to concerns over subsurface density variations, evidenced in a prototype leading edge chine that had delaminated near the surface, it was decided that an ultimate proof test was warranted to further evaluate the load carrying capability of the part. Additionally, due to the tight schedule required to accomplish the ultimate proof test, the concept of a pressurized bladder for load introduction was designed and implemented. This paper discusses the leading edge chine design and mission profile, the test article and test set-up, as well as the analytical and experimental results.

Mission Profile and Thermo-mechanical Loading

An artist's conceptual portrayal of the X43A vehicle in flight with the vehicle's projected flight profile is shown in Figure 1. During the ascent portion of the flight at Mach 2.8 and near maximum dynamic pressure (max-q) flight loads, an average worst case calculated flight load pressure of 1.13 psi over the leading edge chine section was determined. Figure 2 shows various views of the vehicle with the C-C leading edge area at the perimeter of the nose section (ref. 2). Peak heating flight data, for the second Mach 7 flight, indicated temperatures limited to the 1600°F-1800°F region (ref. 2). During the third and final Mach 10 flight, temperatures in the chine area were expected to be in the 2000°F range and above. The envisioned thermal environment in flight was not considered an issue for the cantilever chine section's structural response. Carbon-Carbon type materials tend to have increasing strength levels well into the 2000°F temperature range, and hence, a room temperature proof test was deemed conservative. The projected total limit load on the flight section was calculated to be 50 lb.; thus, with a Factor of Safety (FS) of 2.0 the total target ultimate load was determined to be 100 lb.

Test Specimen

The C-C chine test article section is shown in Figure 3 and consists of a bi-planar and curved contour surface that is 3 in. wide by 16 in. long and has a tapering thickness. The pressurized specimen area consists of a 3 in. wide flat at the thicker aft end of the specimen (Figure 3B), a nominal 16 in. length, and towards the thinned down forward section (Figure 3C) two planar areas with a combined planar dimension of approximately 3.25 in. Also shown in Figure 3 is a mounting flange area, 1 in. wide by 0.25 in. thick, that when attached to the flight vehicle forms a cantilever beam supported structure.

Load Introduction Pressure Bladder and Test Fixture Description

The concept behind the ultimate proof load test rig is that of a pressurized bladder or conformal pressure vessel. Since static pressurization within a cavity acts normal to the surface of the cavity the bladder concept allows for a simple, uniform distributed pressure load application. A sectional side view of the test fixture is shown in Figure 4 with the reactive/supportive test fixture wall sections. Also shown in Figure 4, is the 0.030 in. worst case gap offset which could result when the chine section is mounted to the supporting side walls of the X43A vehicle. Incorporating the gap offset allowed the chine test article to rotate in a manner representative of actual vehicle boundary conditions. The minimization of this gap would create an interface (with the supporting side-wall) which could serve to artificially stiffen the edge boundary conditions.

An isometric backside view of the aluminum test fixture is shown in Figure 5 with end sections and a spacer plate. Initially the pressure bladder was to be truncated by the end sections as shown in Figure 5, but during the test setup it was easier and more expedient, to have the end close out sections removed. This effectively eliminated all of the issues of how the bladder would deform onto the specimen in the close-out area, and the concern of possible perforation of the bladder. The spacer plate section, located at the rear of the fixture, allows for clamping of the fixture to the same thickness level as the C-C mounting flange preventing possible excessive compressive loads in the specimen flange area.

Test Sequence

During test set-up a reference load plate of 46 sq. in. was used to calibrate the desired final load based on the pressure input to the bladder (Figure 6). To achieve the 100 lb ultimate load, force would be equal to pressure multiplied by area (or F = PA). Therefore a pressure value of 2.2 psi based upon the reference load plate of 46 sq. in. would result in a load of 101 lb. However, due to the bi-planar contoured nature of the pressurized surface (Figure 3A), the actual pressurized area of the specimen was slightly larger than the 46 sq. in. used during the calibration process. Triangular and quadrilateral area calculations of the specimen top surface yielded a value of 48.9 sq. in., and two graphical area assessments yielded values of 48.6 sq. in. and 49.3 sq. in., respectively. An average of the three area measurements gives a value of 48.9 sq. in. Therefore, the final load applied to the cantilever section was equal to the ratio of the actual area divided by the reference area, which effectively becomes a scaling coefficient (or corrective coefficient) on the actual applied load. Therefore, the actual total load equals (48.9/46) x 100 lb = 106.3 lb total force applied to the specimen.

Figure 7 shows the X43A Carbon-Carbon chine specimen mounted in the test fixture for pressure testing. The required minimum load duration was determined to be 130 seconds (ref. 3). Shop air and a hand controlled pressure valve were used to implement the pressurization loads. The load sequence consisted of a 4 minute ramp to the target pressure, a 130 second hold period and then a subsequent rapid release of the pressure load over a 5 second interval.

Analysis

The finite element model (FEM) used for analysis of the X43A C-C chine section is shown in Figure 8. The model consists of 143,816 solid elements (8-noded brick and 6-noded wedge elements) utilizing the MSC NASTRAN (ref. 4) FEM code for analysis with MSC PATRAN (ref. 5) utilized as the pre, and post, processing software. The limit pressure load on the chine, from launch through the engine test, occurs during the ascent phase near the time of max q. A 1.13 psi uniform pressure distribution across the chine is a conservative approximation of the calculated aerodynamic pressure distribution. A 2.0 FS was applied to the limit pressure with the resulting load shown in Figure 8B.

As shown in Figure 9, stress contour plots for the chine section are given for two different imposed boundary conditions. Figure 9A shows the bending stress results due to the mounting flange (fig. 3) being fixed halfway across the width of the mounting flange tab resulting in a localized peak stress of 1260 psi. As shown in Figure 9B, a support condition fixed at a distance of 0.083 in. away from the thicker section shows peak stresses at the tab cross section of 583 psi. Hence, the stress result case, as shown in Figure 9A, is conservative, and stress values are reduced as the FEM boundary condition is fixed as close as possible to the chine/chine tab interface section. The C-C chine material has an expected failure strength in excess of 5000 psi. Therefore the part has an ample margin of safety (MS) during the ascent portion of the flight at Mach 2.8 and near max-q flight loads.

Post Test Inspection

After completion of the test sequence the specimen was visually inspected. Neither delaminations nor failure areas were evidenced. Additionally, there were no audible indications of specimen failure during the test as well.

Concluding Remarks

The pressure bladder load introduction concept performed very well. This approach provided a quick, simple, and efficient method of applying a uniform pressure field onto a bi-planar contoured specimen surface.

The potential of the pressure bladder load introduction concept for broad application in thermo-mechanical testing of structures would require experimentation in various thermal environments and on various test specimen geometries. Test specimen geometries could range from one such as that reported in this paper (a single bi-planar surface with no built up features) to geometries as complex as highly built-up integrated vehicle structures.

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Dr. Max Blosser and Dr. Steve Scotti of the Metals and Thermal Structures Branch (MTSB) for their insight into thermo-structural testing as well as the graphic designers at the Dryden Flight Research Center for their excellent web-site graphics which are reproduced herein.

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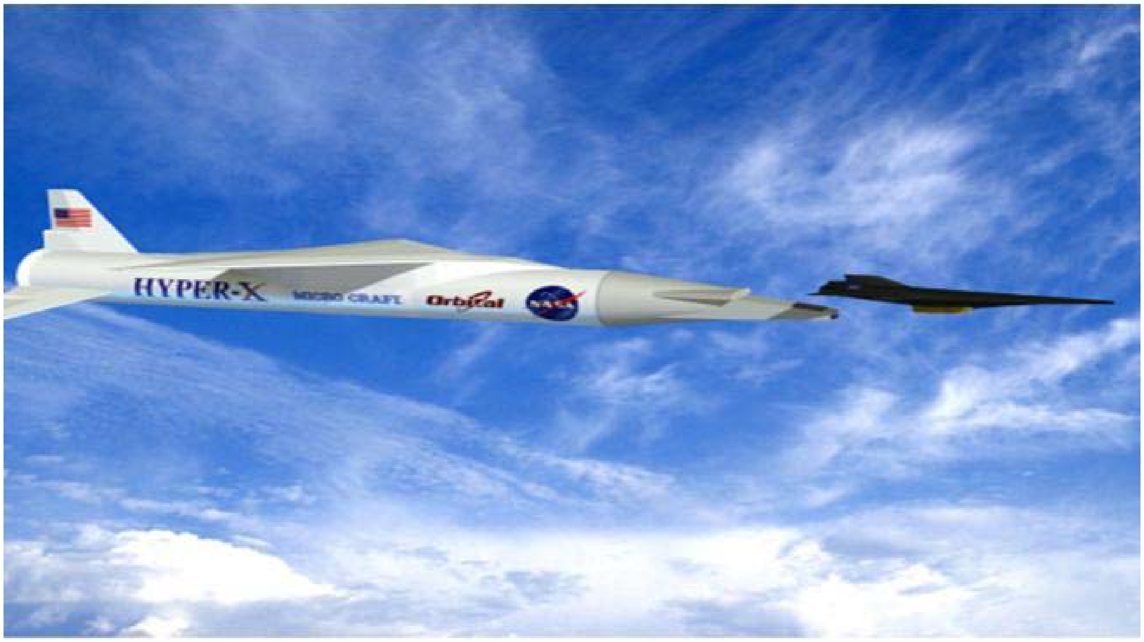

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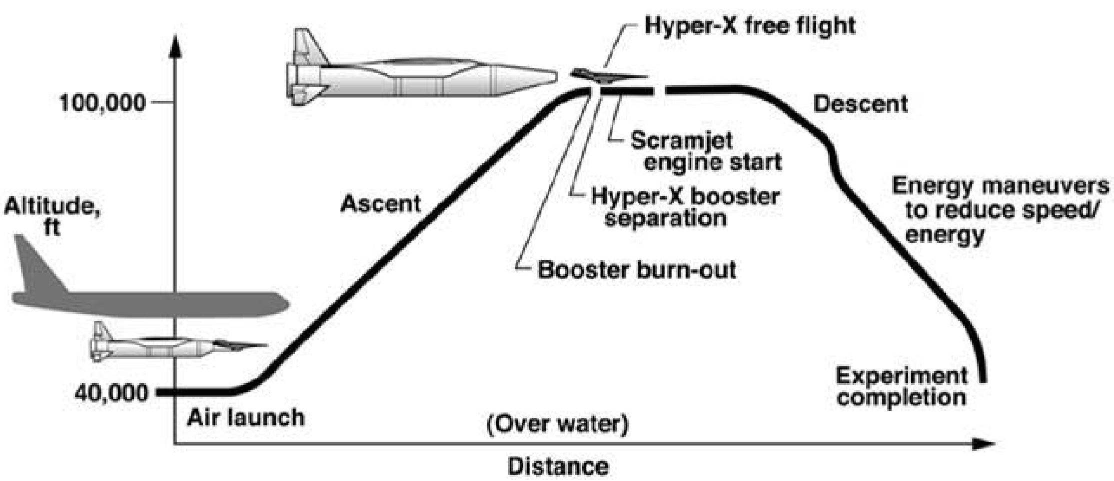


(B)

Figure 1: Hyper-X In-flight (artist's portrayal) and Flight Profile.
(http://www.dfrc.nasa.gov/gallery/graphics/index.html)

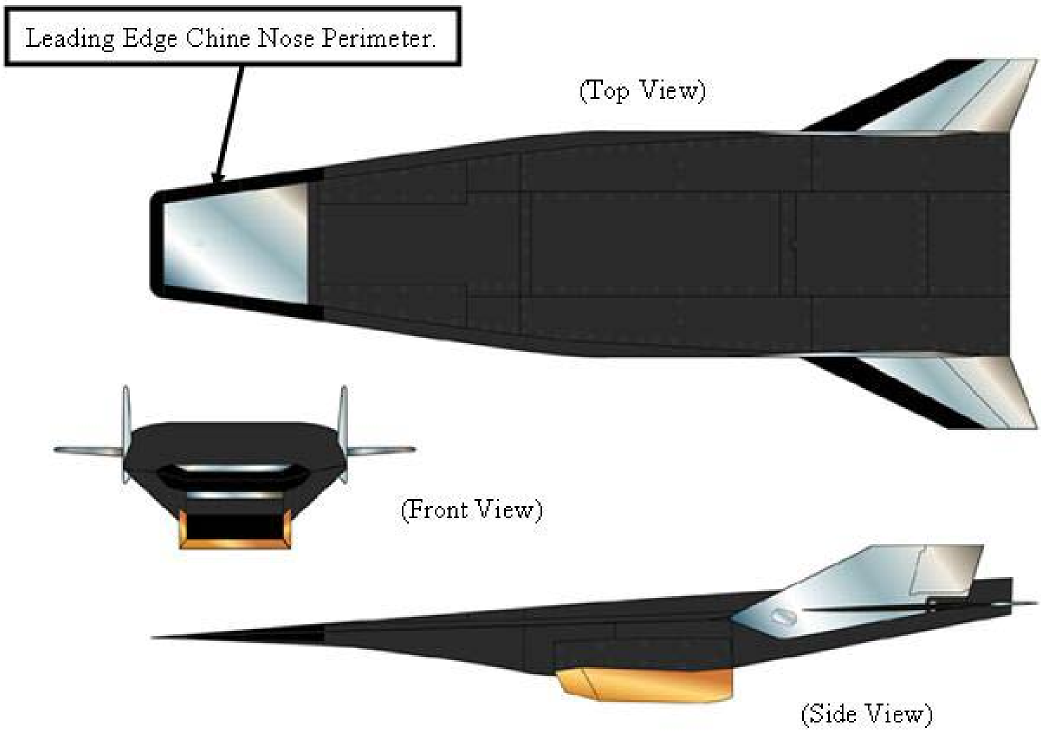


Figure 2: Various Views of X43A Flight Vehicle with Leading Edge Nose Perimeter.
(http://www.dfrc.nasa.gov/gallery/graphics/index.html)

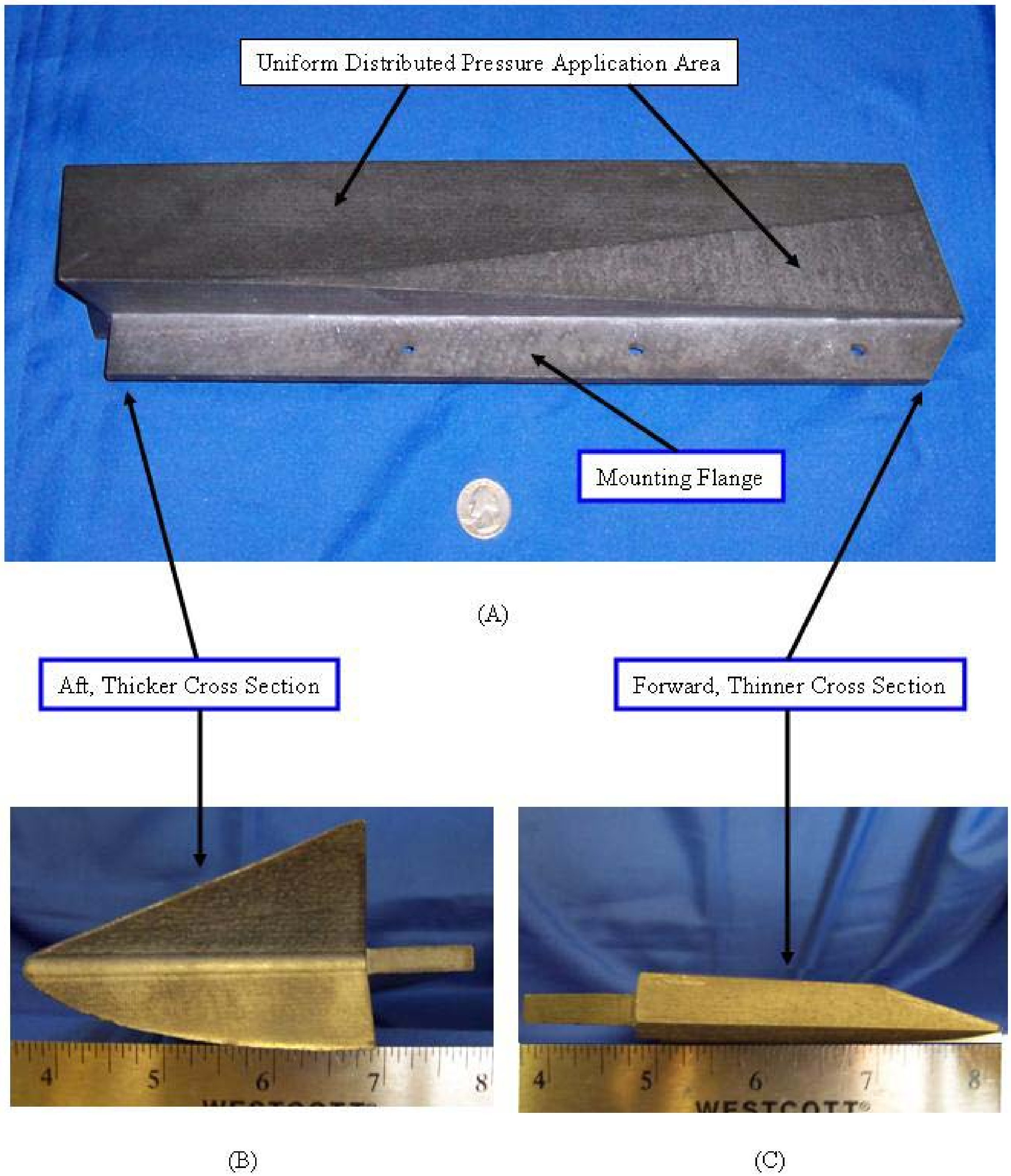


Figure 3: X43A Carbon-Caron Leading Edge Chine as Tested.

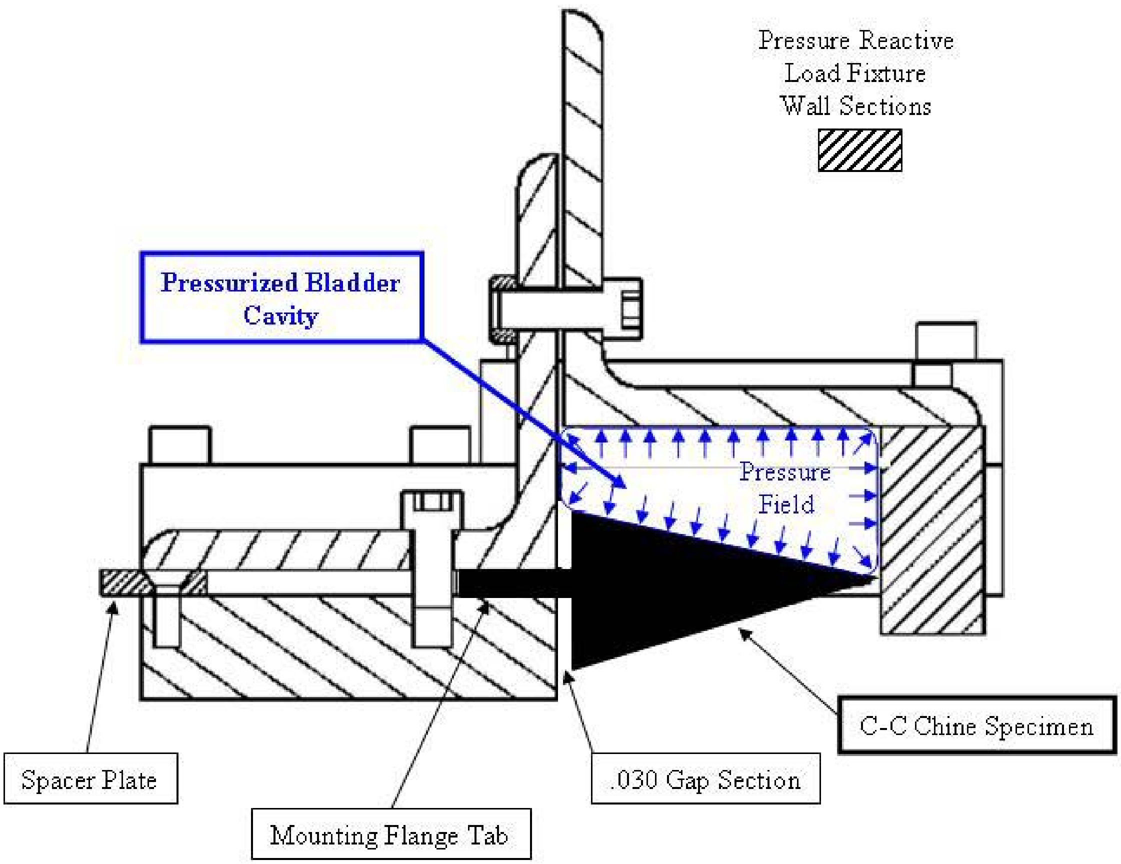


Figure 4: X43A Section Side View of Pressure Reactive Test Fixture.

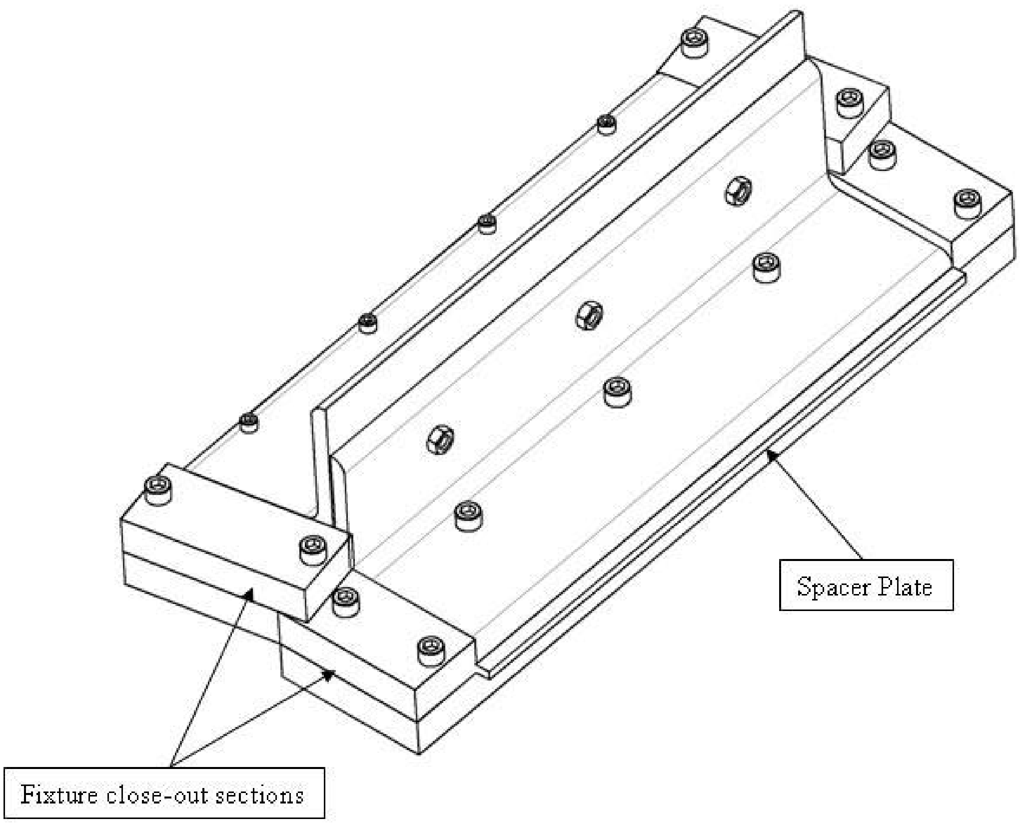


Figure 5: Isometric Backside View of Pressure Reactive Test Fixture.

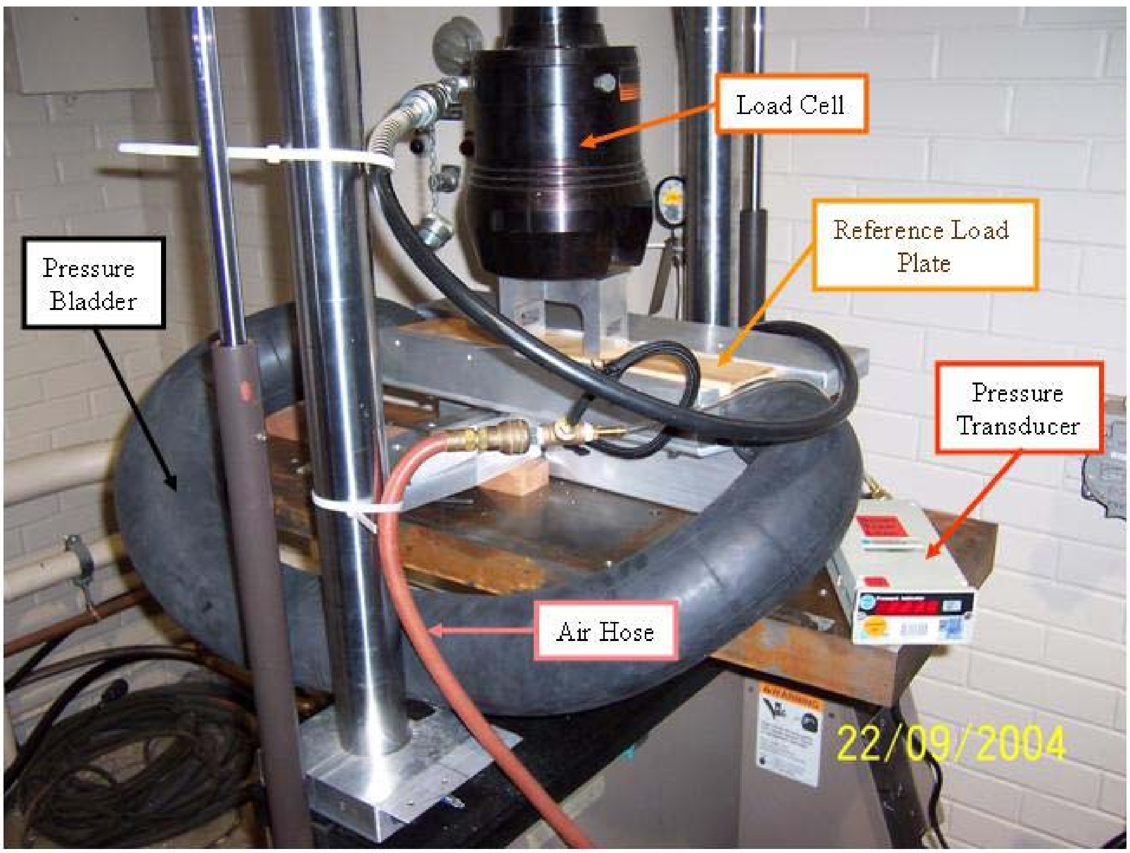


Figure 6: Calibration of Test Fixture Prior to Testing.

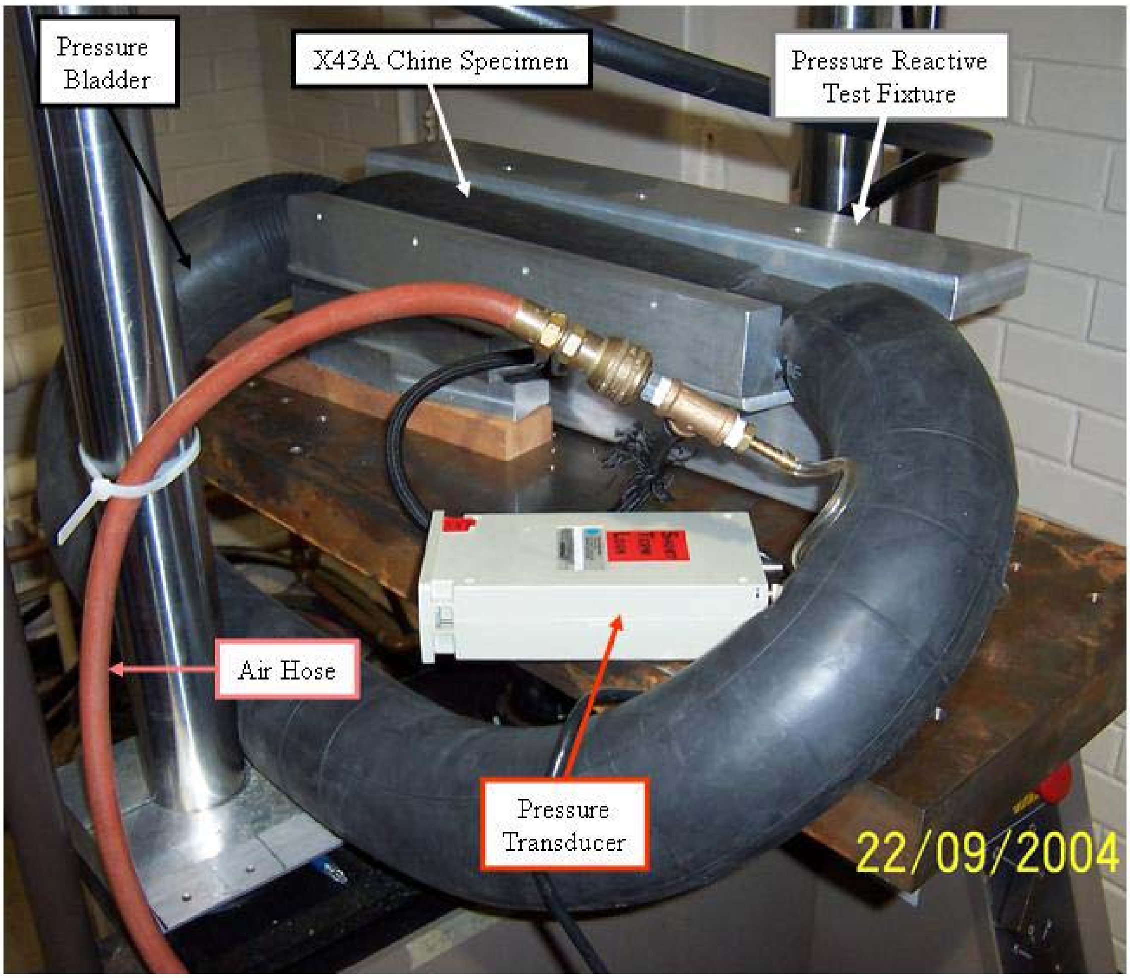
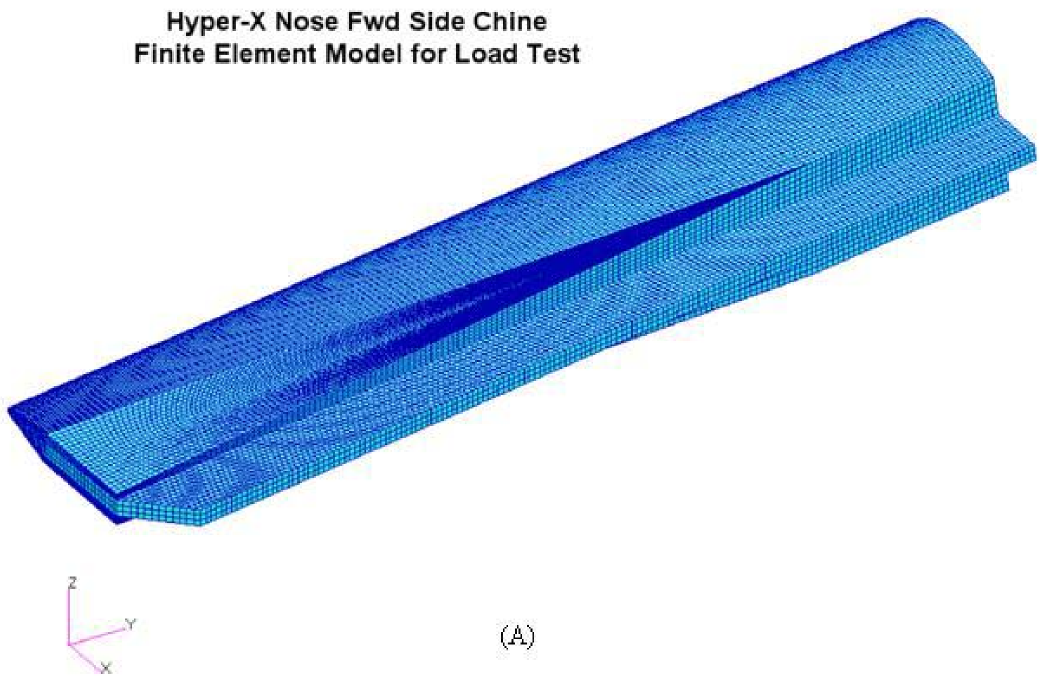


Figure 7: X43A Chine During Ultimate Proof Load Test.



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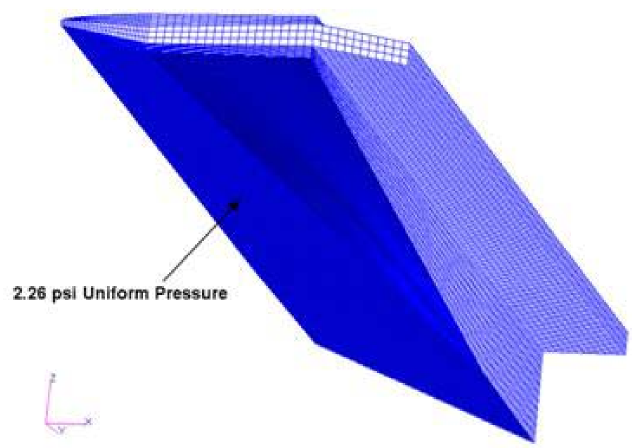
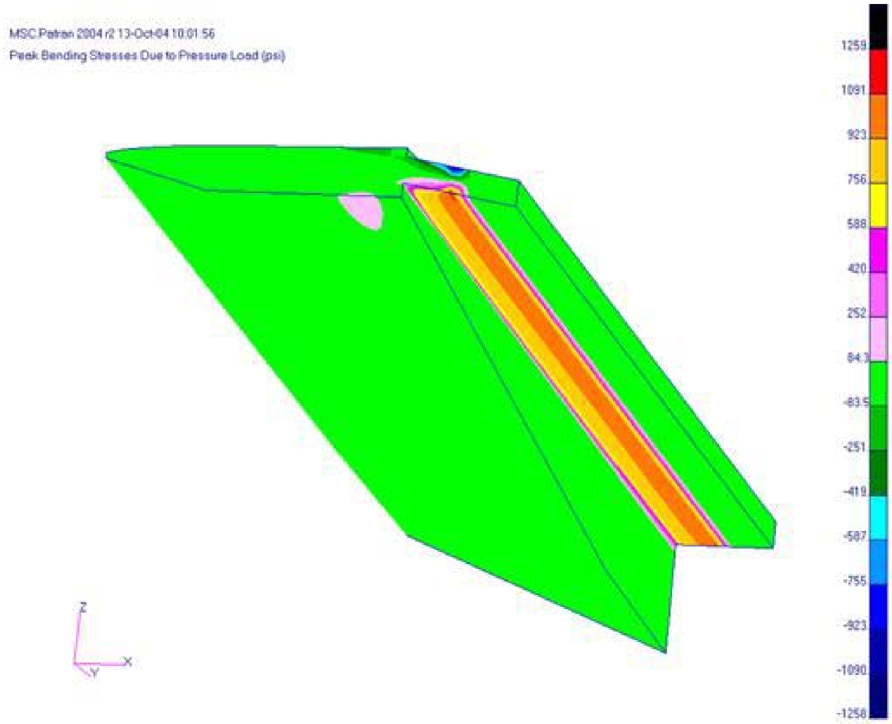


(B)

Figure 8: Finite Element Model of Carbon-Carbon Chine Showing Mesh & Elements.



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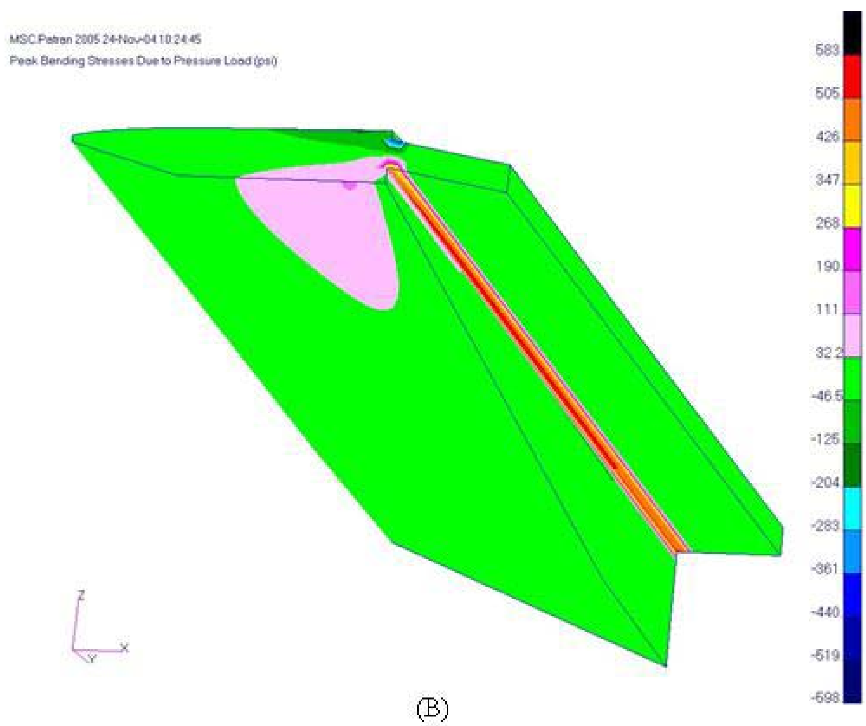

(B)

Figure 9: FEA Stress Contour Plots for C-C Chine.

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