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APPLICATION OF ADVANCED GRID-STIFFENED STRUCTURES TECHNOLOGY TO THE MINOTAUR PAYLOAD FAIRING

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ABSTRACT

The Air Force Research Laboratory Space Vehicles Directorate (AFRL/VS) is exploring new structural configurations and corresponding methods for fabricating launch vehicle fairings. The goal of this research is to reduce the cost of these components while also enabling large structures to be fabricated. Processes for fabricating Advanced Grid Stiffened (AGS) composite structures have been developed that show promise to help achieve these goals. These procedures were successfully demonstrated in an AGS fairing for the Ballistic Missile Defense Organization's (BMDO) Combined Experiments Program. Currently, AFRL/VS has joined with Boeing's Phantom Works and Orbital Sciences Corp (OSC) to develop an extended fairing for the Orbital Suborbital Program's Minotaur launch vehicle. The design methods, fabrication procedures, and testing plans used to develop this fairing will be discussed.

INTRODUCTION

The Integrated Structural Systems Team (ISST) of the Air Force Research Laboratory Space Vehicles Directorate (AFRL/VSSV) is exploring new structural configurations and fabrication methods to allow large composite structures to be fabricated using low cost techniques. One step in this direction is the development of Advanced Grid Stiffened (AGS) Structures. AGS structures consist of a thin Carbon Fiber Reinforced Polymer (CFRP) composite skin integrally connected to a series of helical and longitudinal CFRP ribs. These ribs typically form a pattern of repeating triangles as shown in Figure 1. AGS structures take advantage of the high specific stiffness and strength of carbon fiber materials by orienting the fibers along the rib direction. This results in a structure that has high geometric efficiency due to the skin-stiffened configuration and makes the optimal use of the material efficiency. Thus, these structures compete well with optimized honeycomb sandwich structures in terms of structural efficiency, i.e. stiffness-to-weight and strength-to-weight ratios.

Figure 1. Advanced Grid Stiffened (AGS) Structure Configuration

These AGS structures have the potential to eliminate many of the problems associated with honeycomb sandwich structures. Specifically, moisture uptake is a well-known problem for honeycomb panels since the water gets trapped in the hexagonal cells of the honeycomb and causes corrosion and softening of the composite face-sheets. A second critical problem with launch vehicle payload shrouds made of honeycomb sandwich panels is that a large amount of time is required to cut and splice the honeycomb core to fit on the complex shape of the shroud. This results in a high cost and long lead-time for the payload shroud. In contrast, AGS panels do not trap water since the panel has skin on one side only, and moreover AGS panels can be manufactured using an almost entirely automated process. This has been shown to result in a cost savings of nearly 20% over comparable honeycomb sandwich payload fairings (Van West, 2001).

History of Grid-Stiffened Structures Research at AFRL/VS

For nearly a decade the Air Force Research Laboratory's Space Vehicles Directorate has been conducting research on AGS structures (Huybrechts, 1997, and Wegner, 2000). This has resulted in the development of patented analysis techniques as well as fabrication techniques for these structures. In 1997 the Air Force Research Laboratory successfully designed, fabricated, and flight-tested an AGS sounding rocket payload fairing under the Ballistic Missile Defense Organization's (BMDO) Combined Experiments Program (CEP). This fairing was 60% lighter than the existing aluminum fairing, and over 40% lighter than a conventional skin-stiffener composite fairing. Furthermore, the filament winding fabrication technique developed by the AFRL is nearly entirely automated. This advancement has been demonstrated to decrease manufacturing cost by an estimated 20% over conventional honeycomb sandwich fairings. A picture of this fairing with a close up of the rib sections is shown in Figure 2.

Figure 2. AFRL's AGS Fairing for BMDO's Combined Experiments Program (CEP), Side-View and End-View

OSP/Minotaur Fairing Development Program

The next step in the development of this technology is to design, fabricate and flight qualify an AGS composite payload fairing for the OSP launch vehicle. The Orbital-Suborbital Program launch vehicle is being developed by Orbital Science Corp. (OSC) under contract to the Rocket Systems Launch Program of SMC Det12. This vehicle is comprised of Minuteman II first and second stages mated with OSC's Pegasus motors for the third and fourth stages. The baseline configuration of this vehicle uses the standard Pegasus payload fairing, however, the vehicle has the launch capacity that will allow a larger fairing to be utilized. A larger fairing could enable dual manifest missions on this vehicle. Consequently, AFRL/VSSV teamed with Boeing's Phantom Works to build a 1.55 m (61") diameter fairing for the OSP vehicle; utilizing Boeing's state-of-the-art fiber placement machine.

The successful completion of this program will result in the flight qualification of a 1.55 m (61") diameter payload fairing. In the process, the manufacturing methods developed by the AFRL/VS will be scaled up to the sizes required for use in commercial launch vehicles, the first high quality AGS structure having complex cutouts will be fabricated and tested, and the technology necessary to design and fabricate AGS structures will be transferred from the AFRL/VS to industry. This will lead to lighter weight and less expensive payload fairings throughout the industry. Before these goals can be met, a number of technical issues remain to be solved. These include scaling up of the tooling and of the part geometry, transitioning from filament winding manufacturing to fiber placement manufacturing, and validation of the analysis tools with test results.

DESIGN REQUIREMENTS FOR THE MINOTAUR PAYLOAD FAIRING

The most significant loads on the fairing during operation are compression and bending due to the aerodynamic pressure and inertia of the accelerating structure. The drag produces a fairly uniform compression load throughout the shell whereas the bending loads produce tension, compression and shear in different parts of the shell. These forces were predicted using a variety of complex numerical models of the entire launch vehicle and were validated through wind tunnel testing on sub-scale models. The aerodynamic loads are translated into a series of pressure coefficients over the surface of the payload fairing. These pressure coefficients are then integrated over the surface and multiplied by the Max alpha-Q (i.e., the maximum dynamic pressure at the worst case altitude and launch vehicle angle of attack) to resolve these pressures into forces. These forces are added to the inertial forces to result in a group of loads on the fairing as shown in figure 3 (the magnitudes of the loads are proprietary to Orbital Sciences Corp, Inc.). The inertial loads include the weight of the fairing, all hardware attached to the fairing, as well as the weight of thermal protection cork on the exterior of the fairing.

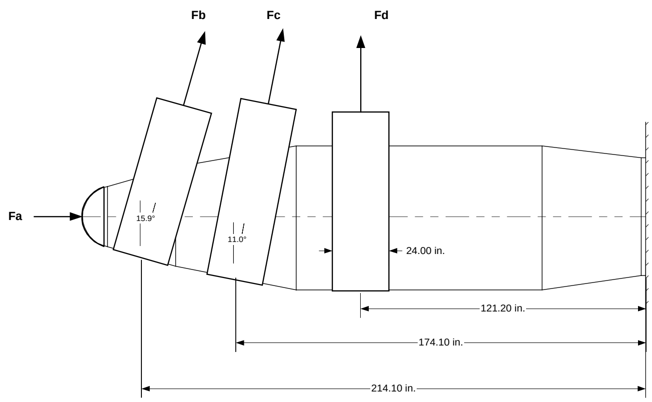


Figure 3. Reaction Forces on the Minotaur Fairing Due to Aerodynamic and Inertial Loads

In addition to these aerodynamic and inertial loads, an internal pressure is applied to the fairing. This is caused by the differential pressure on the inside and outside of the fairing. During launch, a low pressure region is present in the boat-tail section of the fairing. This is equivalent to a positive pressure on the inside of the fairing.

A safety factor of 1.25 is applied to all aerodynamic as well as inertial loads. With this safety factor, these loads become the qualification test loads for the fairing and thus are the loads that the fairing is designed to withstand. There are two important structural requirements for the fairing when these loads are applied. First, the fairing cannot experience a catastrophic structural or material failure. Second, the fairing cannot deflect such that the fairing comes into contact with the internal payload. This "stiffness" requirement is often the most stressing case for the design of rocket payload fairings.

In addition to these loads, the payload fairing must be able to withstand acoustic loads, thermal loads, jettison loads and ground handling loads. These loads are secondary to the strength and stiffness requirements imposed by the aerodynamic and inertial loads and are therefore verified via analysis and secondary testing.

A final design requirement that is difficult to characterize via test or analysis, is a "cleanliness" requirement. The surface must be visibly-clean of all contaminants when inspected with normal vision from 6-8 inches from the surface.

ANALYSIS PROCEDURES USED FOR MINOTAUR FAIRING

The design methodology used in this program consists of structural optimization using a "smeared-stiffener" model developed by Hypersizer, Inc, linked to a finite element model of the fairing as shown in Figure 4 (Collier, 2002). In the Hypersizer optimization the skin and stiffener combination is replaced with a single laminate having the equivalent bending stiffness. This stiffness is then used to predict the deflected shape and load distribution throughout the fairing. The Hypersizer software then uses this information to calculate strength and stability margins for both the ribs and the skin throughout the structure. For example, the structure is analyzed for the three most common stability failure modes, rib crippling, skin pocket buckling, and global Euler buckling. If any of the regions on the structure are found to be deficient, the grid spacing is changed or the ribs or skin is strengthened.

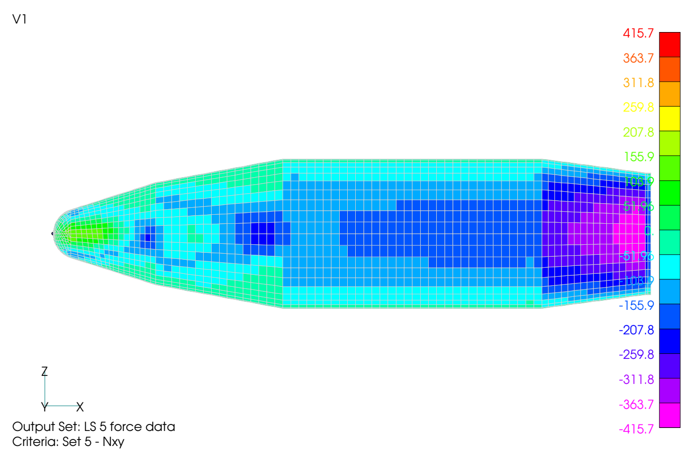


Figure 4. Hypersizer Model of Minotaur Fairing (Collier, 2002)

This analysis tool provides an overall geometry for the fairing. However, it does not account for design details such as the base ring that interfaces with the launch vehicle, access ports and doors, external connection points, deployment hinges and cams, separation joints, nose cap and internal equipment attachment points. Thus, using this optimized configuration, a detailed finite element model of the fairing is developed to design local pad-ups for hardware attachments and for local strengthening. An example of this model is shown in Figure 5 (Van West, 2001).

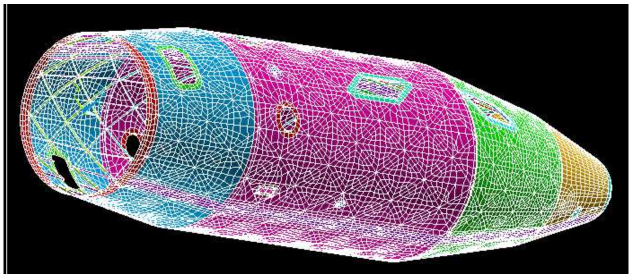


Figure 5. Detailed Finite Element Model of Minotaur Payload Fairing

One very important design consideration to note for this fairing is the Hypersizer optimization determined the lightest possible configuration resulted when the skin was as thin as possible. Consequently the majority of the applied load is carried by the ribs and the skin acts simply to stabilize the ribs against buckling. However, because the skin has very little stiffness, it pocket-buckles very early. Thus a non-linear post-buckling analysis must be utilized to predict the failure of this structure (Higgins, 2002). The structure is assumed to fail in this post-buckling analysis when the model becomes numerically unstable and can no longer support additional load. Initial test results have shown extremely good correlation between test results and these numerical predictions.

A secondary failure could occur when the strength of the epoxy bond between the rib and the skin is exceeded. At this point, the rib would separate from the skin and could buckle since it no longer has the stability afforded by the skin. Therefore, a detailed finite element model of this rib-skin joint was developed, see Figure 6.

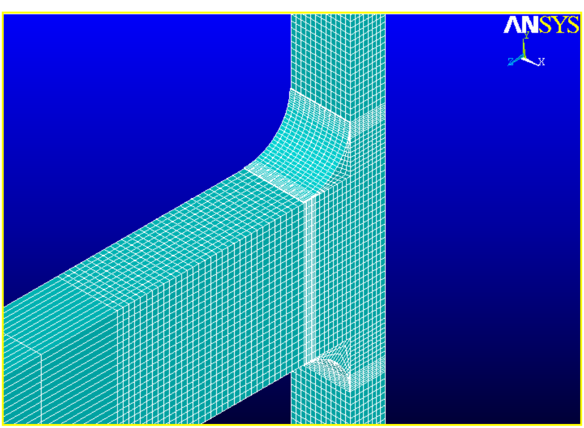


Figure 6. Finite Element Model of Rib-Skin Joint

Initial results utilizing a strain invariant based failure theory show good correlation between predicted and measured failure loads. This will be used a basis for a mapping scheme between the shell based finite element model shown in Figure 5 and the detailed rib-skin joint model shown in Figure 6. This will enable the possible failure of the rib-skin joint to be accounted for in the structural design. Therefore, the fairing will be analyzed for a stability failure as well as for a material failure between the rib and the skin that could result in a lower stability failure load.

TEST VERIFICATION

A comprehensive test program is being used to validate the grid-stiffened fairing design. At the most basic level, a full set of material characterization tests were performed at AFRL/VS to quantify the fundamental properties of the IM7/8552 carbon/epoxy composite being utilized in this fairing. These tests were performed on coupons that were machined from an 8-ply unidirectional panel that had been fiber-placed, vacuum bagged, and autoclave cured in the same manner as the full grid-stiffened fairing. This was done to ensure that any manufacturing defects would be represented in the test coupons. The principle moduli (E_{11}, E_{22}, G_{12}), the major poissions ratio (ν_{12}), and the tensile and compressive strength of the material in the principle material directions (F^{1t}, F^{1c}, F^{2t}, F^{2c}, and F^{s}) were measured using ASTM standardized test procedures. These tests resulted in the following properties for this material.

Table 1 Baseline Material Properties

IM7/8552 Carbon/epoxy V_f=59.8%	Manuf Data	AFRL Test
0-deg tension (ksi)	338.11	337.40
0-deg comp (ksi)	224.83	185.75
90-deg tens (ksi)	13.81	5.34
90-deg comp (ksi)	37.76	31.30
Shear (ksi)	15.18	14.40
0-deg Modulus (Msi)	20.60	21.90
90-deg Modulus (Msi)	1.56	1.22
Shear Modulus (Msi)	0.66	0.66

Following these tests, a set of coupons was fabricated from the ribs of a fiber placed flat panel. These coupons were tested in compression, tension, and shear to compare the strength and stiffness of the coupon specimens to the strength and stiffness of the ribs. These results are shown in Table 2. Acid digest void volume and fiber volume measurements were performed according to ASTM specifications. These ribs had an average fiber volume fraction of 59.% and and average void volume of 0.89%. These are well within the design guidelines of 61% fiber volume fraction and less than 3% void volume fraction. These tests showed that the manufacturing process for the ribs and skin are generating adequate strength and stiffness.

Table 2 Properties of Rib Stiffeners

IM7/8552 Carbon/epoxy V_f=59.8%	Rib Specimen	AFRL Coupon Tests
0-deg tension (ksi)	337.45	337.40
0-deg comp (ksi)	173.4	185.75
90-deg tens (ksi)	6.63	5.34
90-deg comp (ksi)	31.35	31.30
Shear (ksi)	14.37	14.40
0-deg Modulus (Msi)	21.9	21.90
90-deg Modulus (Msi)	1.16	1.22
Shear Modulus (Msi)	0.66	0.66

Next, a series of tests were conducted to determine the bolt-bearing allowable strength for this material (Wegner, 2001). These tests were performed using three different test methods: (1) a single lap-shear test (ASTM D 5961 method A), (2) a double lap-shear test (ASTM D 5961 Method b), and (4) the Boeing stabilized single lap-shear test. A schematic of the Boeing Stabilized Single lap-shear test is shown in figure 7. The test coupons were fabricated from a panel having the $[(0/45/90/-45)_s]_4$ layup. The tests showed that the Boeing stabilized single lap-shear test was less conservative than the single lap shear test but more conservative than the double lap-shear tests. Since this is the actual configuration of the bolted joint on the payload fairing, the results from this test were utilized in the design of the bolted interface joint. The maximum bolt bearing strength of this material and laminate configuration was determined to be 3097 lb/in. This is much more than the allowable shear load (1637 lb/in) on the bolts for the required bolt configuration so in the final design the laminate in this region is thinner.

A series of tests have been conducted on large curved panels (Van West, 2001, Van West, 2002, and Higgins 2002). These test panels consist of a baseline panel, a window panel, and a bolted joint panel. The configuration of these three panels are shown in Figure 8.

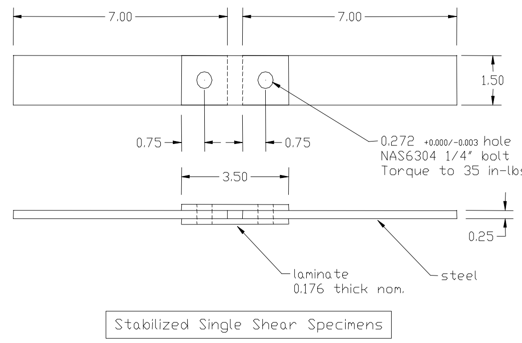


Figure 7. Boeing Stabilized Single Lap-Shear Test

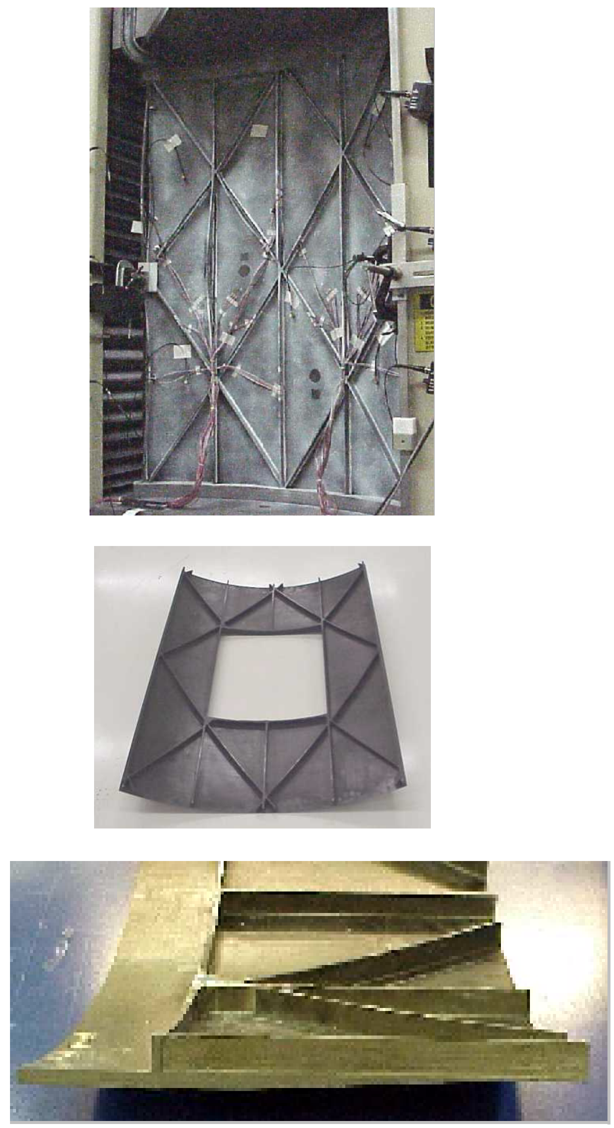


Figure 8 Baseline Panel, Window Panel, and Bolted Joint Test Panels

These tests have been used to validate the design procedures used for this fairing. Initial results have been very good. As can be seen in Figure 9, the predicted deflections match the measured deflections very closely, and the predicted failure load was very close to the measured failure load.

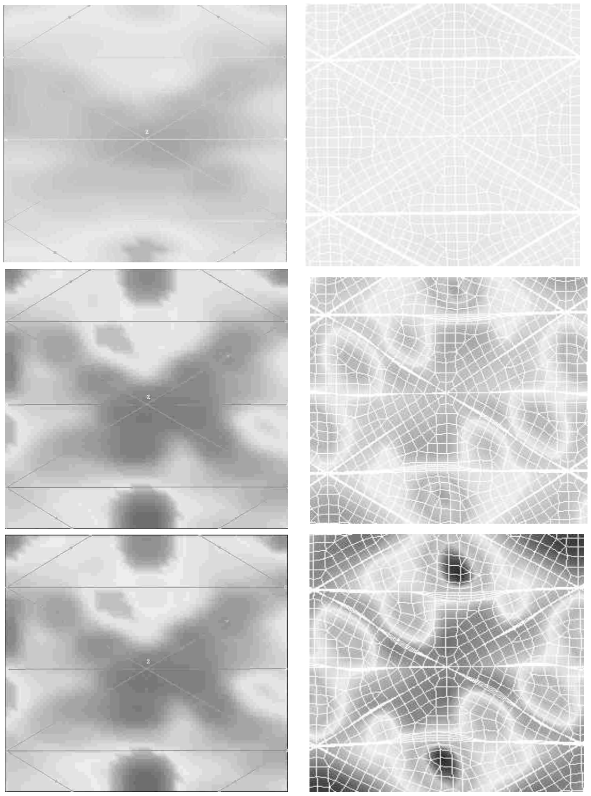
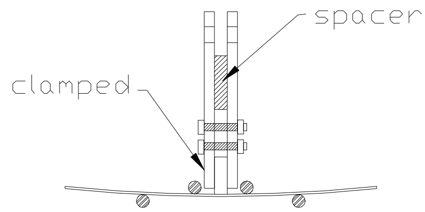


Figure 9. Skin Displacement Patterns at Compressive Loads of 44,443 N. 111,122 N, and 177,801 N from Experimental Data (left) and AFRL Analysis (right) (Higgins, 2002).

These series of tests have also served to highlight the failure mode of these panels. It has been observed that in the configurations tested, the skin simply restricts the ribs from buckling and thus, the majority of the applied compressive load is taken up by the rib stiffeners. The failure of the panel emanates from a fracture or disbond in this rib-skin interface. Essentially, when the rib disbonds from the skin, it no longer is supported laterally against column buckling. The rib then buckles and fails. Therefore a series of tests have been conducted to characterize the strength of this rib-skin interface that can then be used to validate failure models of this joint. An example of these rib pull-off specimens is shown in Figure 10. Initial modeling of this rib-skin interface combined with a strain invariant failure theory have resulted in very good correlation between the measured and predicted strength of this rib-skin interface.



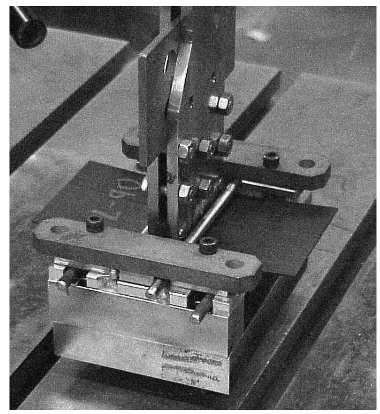


Figure 10. Rib-skin Pull-Off Test

To test the ability of the skin-stiffened panels to withstand internal and external pressure loading, a series of flat panels were fabricated and tested under a variety of pressure conditions. A metal frame and base was fabricated around the perimeter and underneath of the grid-stiffened panels. Then vacuum pressure was pulled on the space between the panel and the bottom of the frame. Simply turning the panel over such that atmospheric pressure was pushing on the desired surface of the panel could simulate an internal or external pressure. This test setup is shown in Figure 11. The most stressing pressure load requirement on the panels was 6.58 psi on the interior of the fairing. These test panels are being used to evaluate a variety of skin thickness and rib attachment schemes

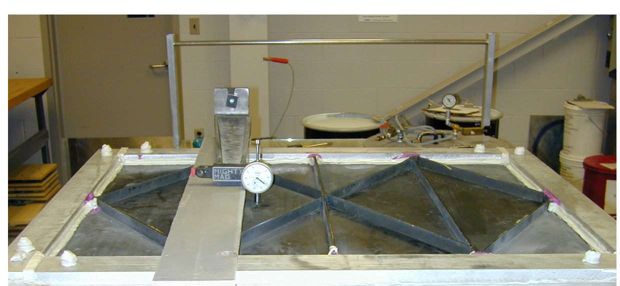


Figure 11. Pressure Tests on Grid-Stiffened Panels

The final test in the verification of the fairing design will be a full-scale test of an engineering demonstration unit (EDU) as shown in Figure 12. This test will be conducted at AFRL/VS in a reaction structure that has recently been developed. Hydraulic actuators will be used to apply the loads to the fairing through straps around the fairing as shown in Figure 3. Stiffness simulators will be used at both the base of the fairing to simulate the stiffness of the launch vehicle interface and at the longitudinal separation rail to simulate the stiffness of this separation system. In this test, the EDU will be tested at qualification level loads, i.e. 1.25 times the flight loads. The fairing must withstand these loads without experiencing any material failure, structural instability, or deflections larger than allowed by the dynamic envelope of the fairing.

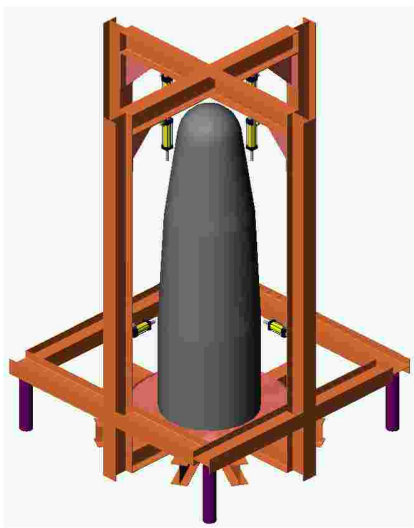


Figure 12. Qualification Level Test of the Full-Scale Engineering Development Unit

CONCLUSIONS

The grid-stiffened fairing for the Minotaur Launch Vehicle that is being developed jointly by AFRL and Boeing's Phantom Works will enable dual manifest missions to be flown on the OSP Launch Vehicle; which would provide cost savings to the Air Force of nearly $6M per launch. The fabrication of this fairing will be almost entirely automated, which may result in cost savings of nearly 20% over a comparable honeycomb sandwich fairing. Further, the design of this fairing will be based upon robust design procedures that have been validated with a great deal of experimental data. The successful design, fabrication, and flight qualification of a grid-stiffened fairing for the OSP Launch Vehicle will provide a clear path for other development programs to follow when an efficient and cost effective structure is needed. This will allow other launch vehicle developers to utilize grid-stiffened structures in their fairings, interstage adapter rings, and payload attach fittings. Grid-stiffened structures may also find their way into aircraft structures, spacecraft structures and civil structures.

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TRADEMARKS

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