Design, Analysis and Testing of a High-g Composite Fuselage Structure

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ABSTRACT

The Wide Area Surveillance Projectile (WASP), is a small autonomous flyer that is launched contained in an artillery shell, and then deployed over a battlefield to capture images. The focus of this paper is the structural design and testing of the aft section of this vehicle. The aft section is not only subjected to high impulsive inertial loads, but its weight has a substantial effect on the controllability of the vehicle; therefore it is manufactured in advanced composite materials to save weight without incurring a strength penalty. Finite element models of this section as well as hand lay-up test specimens were produced to optimize the design. These specimens were tested statically as well as in a dynamic environment. Using the analytical procedure presented in this paper, a high-g survival part could be designed with much less time and at a lower cost than with previous techniques.

BACKGROUND

The WASP project was commenced as a cooperative venture between the Massachusetts Institute of Technology and Draper Laboratories in 1997. The goal was to develop an unmanned aerial vehicle that would reduce the risk associated with obtaining time-critical battlefield reconnaissance data. The mission profile required a g-hardened vehicle that was extremely light and sufficiently maneuverable to achieve an acceptable mission endurance; the current design can be seen in **Figure 1**. A key modification from the original design was the introduction of composites as the principal structural material. A finite element model was created to evaluate the advantages of utilizing composite materials over aluminum in the design of the tail section. It was found that a significant saving in weight and a slight increase in strength could be achieved by this material substitution. While the high values of specific strength and stiffness lead composites to be a good selection for this vehicle, these performance advantages are incurred at the expense of increased cost and complexity of design, analysis and manufacturing. The rationale for the work presented in this paper was to mitigate the risk of using composites in WASP by providing a validated design tool and

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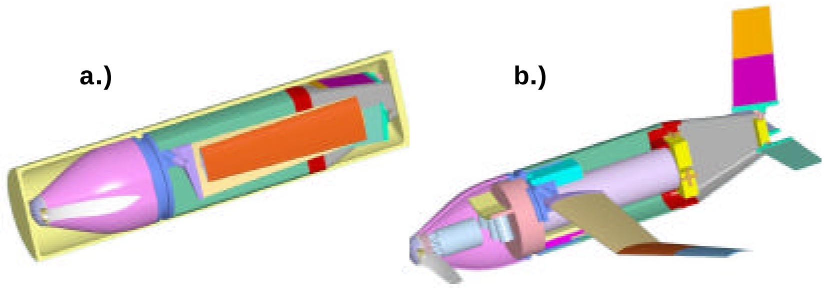

Figure 1: CAD representation of WASP II flyer in a) stowed and b) deployed configurations

developing manufacturing processes [1]. While no previous studies were found in the literature directly relating to the design of high-g composite fuselage sections, several have identified design procedures utilized for cylindrical structures similar to those used in WASP [2][3][4][5][6].

AFT SECTION REQUIREMENTS

The most critical area for detailed analysis and testing was the aft section. This section has significant influence on the control stability of the vehicle and experiences the highest launch loads due to its location. The specifications for the aft section of the WASP vehicle were dictated by the MK64 5" Navy gun shell that it was designed to be contained within. It housed the tail servos, much of the electronic components and was where the tail fins stowed. The geometrical requirements for this section were to maximize the internal volume while not exceeding the maximum internal diameter of the shell, and to provide appropriate cutouts for the fins and inserts. There were two distinct configurations investigated; one with two long slots where the V-tail was stowed, and the other with two short slots where electronic inserts were placed. For the work presented in this paper, the

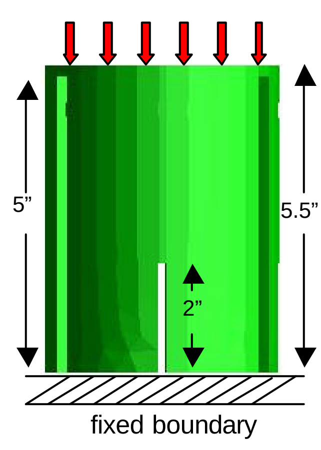

Figure 2: Model geometry, side view

aft section was represented by a cylinder 3.5” in diameter and 5.5” in length, with a pair of ¼” rounded slots cut to lengths of either 2” or 5”. The major design load was the set-back inertial launch load of 16,000 g’s (160 km/s^2) pushing the entire mass of the vehicle against the tail section, distributed evenly across the upper cross-sectional face of the tail section. At either end of the aft section, a metallic bulkhead constrains the composite cylinder from displacing radially. A representation of this geometry can be found in **Figure 2**.

ANALYSIS

General Procedure

The procedure for analyzing the composite sections is shown in **Figure 3**. First candidate laminates were examined using a classical laminated plate theory (CLPT) code written in Matlab™, to predict first ply failure as determined by the Tsai-Wu failure criterion. The next step was to use I-DEAS™ as a pre-processor and mesh generator. The geometry of the section was modeled and meshed with 9-node S8R5 shell elements, and then sets of boundary elements and nodes were exported together into ABAQUS™. Once in ABAQUS™, material properties, boundary conditions and a nominal 1000 lbs distributed axial compressive load were imposed. Both a static and dynamic analysis was performed for each model.

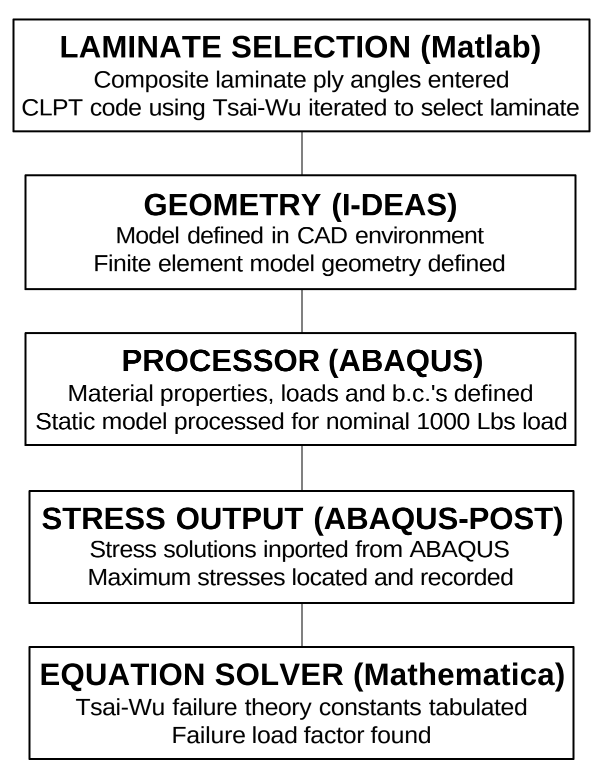

Figure 3: Analysis procedure flow chart

Static Model

The three primary stress components—axial, circumferential and shear—were extracted in ABAQUS™ static models from the elements with the highest stress state near the slot tip. These stresses along with the tabulated Tsai-Wu failure constants were then entered into an equation solver in Mathematica™. Since the laminate was assumed to behave linearly until first ply failure, the stresses in the cylinder would scale linearly with the load applied. The solver was used to determine the critical load factor to be multiplied by the nominal load entered in ABAQUS™, to cause first ply failure as determined by the Tsai-Wu criterion.

Dynamic Model

Since slots were relatively long, it was uncertain whether the tubes would fail by fracture or buckling; therefore a dynamic model was also analyzed in ABAQUS™. The dynamic model was created similarly to the static model, using identical geometry, materials, loads and boundary conditions. The only difference occurred in the solution section of the input file, where linear buckling (eigenvalue buckling) was specified instead of a static solution. The subspace iteration method was used to find the buckling load factor, using 3 vectors and 30 iterations.

EXPERIMENTAL PROCEDURES

Manufacturing Specimens

The experiments were performed using a $[0/\pm45]_{3s}$ layup of AS4/3501-6 graphite epoxy pre-preg, with the 0° direction of fibers defined as axial. The samples were cured following the manufacturer's standard autoclave cycle on a 3.5" diameter aluminum mandrel. Since each layer added to the laminate increases the circumference of the part around the mandrel, each ply had to be carefully cut to the correct individual width, which presented the greatest manufacturing challenge. Then, after being post-cured, the specimens were machined to a total length of 5½" using a continuous carbide grit band-saw blade. Finally, the appropriate slot formations would be milled into the tubes with a ¼" 2-flute carbide endmill. A two-pass method was developed which alleviated much of the torque transmitted to the specimen, thus reducing the amount of delamination of the edge fibers.

Test Fixtures

To simulate the appropriate boundary conditions during testing, two sets of test fixtures were manufactured. The first, a proof mass, was placed on the top rim of the specimens, which served the dual purpose of restraining the samples from compressing in the radial direction and provided a uniform load along the upper surface for both mechanical and air-gun testing. The part weighed 4.0 lbs, to obtain appropriate stress levels at a feasible g-level during air-gun testing. The second fixture was a clamp simulator, which was also machined out of aluminum. The bottom ½" of each sample was held into this fixture by a crystalline wax.

Mechanical Compression Tests

Six axial compression tests were performed in displacement control on a servo-hydraulic testing machines until failure, at a rate of .025” per minute. The load-displacement data was recorded using LabView5™. Compression platens were placed on both heads of the load frame, and each specimen was loaded with proof mass and clamp fixtures in place.

Air-Gun Tests

Air-Gun testing was conducted in order to simulate the actual launch conditions the vehicle would experience in service. Testing was performed at Picatinny Arsenal, NJ using a 155mm air-gun. Specimens were loaded into canisters and then placed in the air-gun with an O-ring on either end. Pressure was built up in the breech, to obtain the desired acceleration. Four shots were successfully completed using this gun.

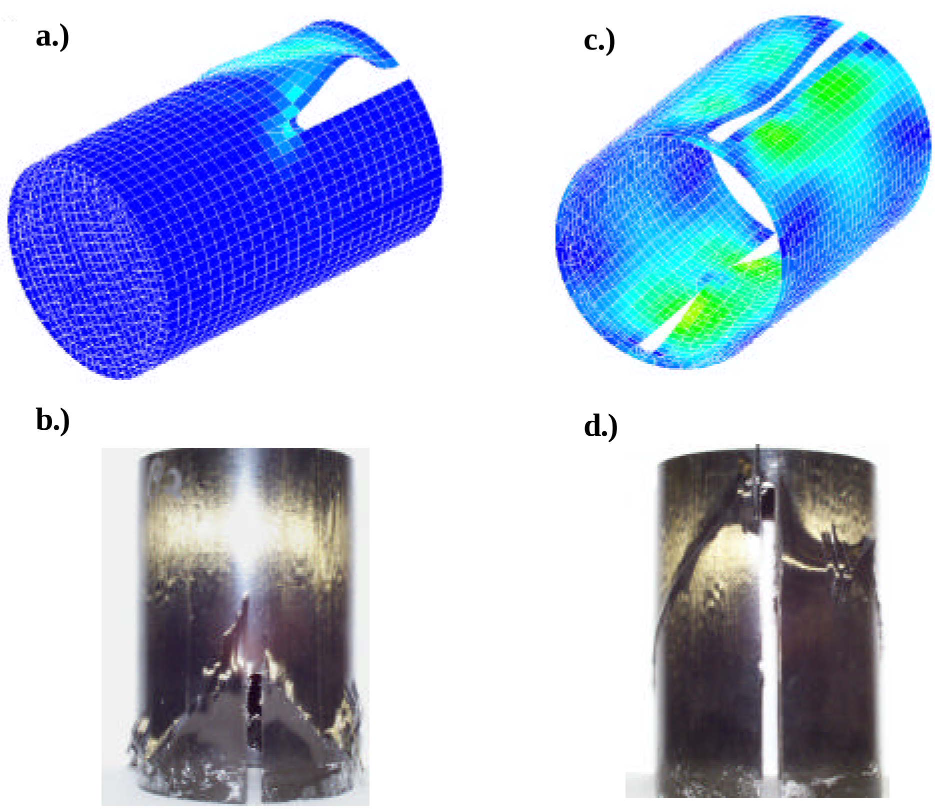

Figure 4: a.) Finite element model of short slotted specimen predicting first buckling mode at 92,700 lbs and fracture load of 51,900 lbs. **b.)** Photograph of short slotted specimen fractured under compressive load averaging 45,000 lbs. **c.)** Finite element model of long slotted specimen in first buckling mode at 56,400 lbs and predicted fracture load of 64,100 lbs. **d.)** Photograph of buckled long slotted specimen from a compressive load averaging 56,000 lbs.

RESULTS

Comparison of FEA to Compression Tests

There was reasonable correlation between the failure predicted—based on FEA together the Tsai-Wu failure theory—and the compression tests results as seen in **Figure 4**. The most consistent result was the correct selection of dominant failure mode, which was predicted by comparing the results of the dynamic and static models. For the short-slotted case the static failure load was predicted to be 51,900 lbs with failure of the outermost 45° ply in the laminate, while the buckling load was 92,700 lbs, clearly indicating that this cylinder would fail in fracture. Similarly, the static fracture load calculated for the long-slotted tube was 64,100 lbs and the buckling load was predicted to be 56,400 lbs initiating near the upper slot tip. Both of these predicted failure modes corresponded with the test results.

The quantitative comparison of prediction and experiment was reasonable. For the short slotted cylinder, the predicted fracture load was 51,900 lbs while the average failure load in experiments was 44,710 lbs, a difference of 16%. The long slotted cylinders were predicted to buckle at 56,400 lbs, whereas the actual average buckling load was 55,870 lbs, a difference of 9%. While not sufficiently accurate to permit detailed design without testing, these codes do provide insight to help design which specimens to test, and to specify the required range of test conditions.

Comparison of Compression to Air-Gun Tests

Since air-gun tests are expensive and time consuming, a key goal of this project was to prove that compression tests could serve as an accurate substitute for some phases of the design process. The air-gun tests performed for this project only sufficed to provide a bound for the failure acceleration; both cylinders which were tested survived a launch load of 40,000 lbs without measurable or visible damage, and both failed catastrophically at a load of over 60,000 lbs. These results do indicate however that the failure experienced during the compression tests was in the same range as would be seen in a gun launch. Analysis shows that for this composite section, the air-gun testing environment was "quasi-static," i.e. the resonant frequency of the system was much higher than the gun-shot frequency, so it was not excited. While this does not eliminate the necessity for final air-gun testing to prove g-hardness, it does provide evidence that quasi-static compression tests may provide a quick and cheap experimental design tool. Compression tests can also be used to compare the survivability of competing configurations, thereby drastically reducing the number of air-gun tests need.

Influence of Variables on Failure

Several variables were analyzed to provide a rubric to predict the effect of potential design changes on the failure load. The first variable investigated was the effect of changing the slot length on the failure load. Since this is a geometric change, it could be assumed to alter both the static failure due to a new stress concentration at the slot tip and the buckling load. Somewhat contrary to expectation, the resulting stresses indicated that lengthening the slot did not have much of an effect on the fracture strength of the cylinder, and in fact somewhat relieved the stress concentration. The long-slotted cylinder was predicted to fail at a lower stress level than the short slotted cylinder by the design tool however, because the buckling load was significantly reduced by the slot length, causing the change in dominant failure modes. This reduction in buckling load can be explained through the Euler buckling equation, where the length here would be the local length of the slot, which accounts for the large reduction in failure load. It was discovered that increasing the tube diameter by 1" would decrease the buckling load factor by 33%; however, increasing the overall tube length had virtually no effect as long as the slot lengths remained constant. Next, the material properties of the composite were altered to explore the significance of the cylinder's stiffness to its final buckling load. The response was found to follow standard buckling theory, with a 10% reduction in modulus lowering the load factor by 10%.

Design Tools for High-g Fuselage Sections

A fundamental goal of this project was to prepare a design tool for high-g fuselage sections, which can be followed in the flow chart in **Figure 5**. First of all, using the trade-studies discussed above, one could design a reasonably survivable part, which could then be verified using the static and dynamic modeling tools presented in this paper. Then, iteratively using the results from the failure prediction procedure outlined, the design could be further refined using the trade-studies until an acceptable failure strength prediction is generated. From this point specimens would be manufactured to verify those results in a compression test, where again it could be redesigned slightly if necessary. Finally, once the desired configuration is obtained, the updated fuselage section design would only need to be fired out of an air-gun a few times to verify its g-hardness. Using the analysis procedure presented in this paper, it is anticipated that a high-g survival part could be designed with much less time and effort than with previous techniques.

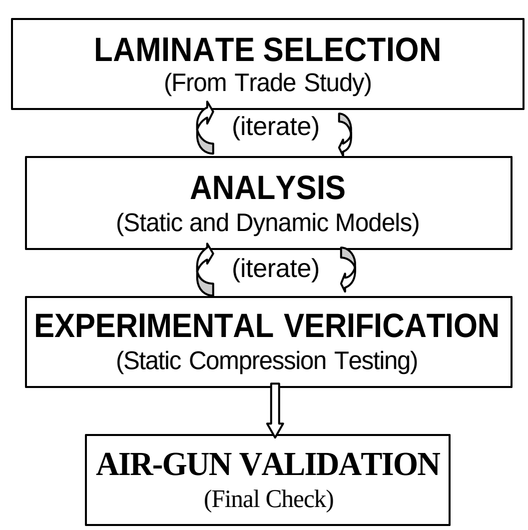

Figure 5: High-g design tool flow chart

CONCLUSIONS

Finite element models were developed to investigate the static and dynamic effects of high-g loading on composite fuselage sections. Static compression and air-gun tests were then performed to validate these models. From these models and tests, a "building-block" procedure for the design of high-g composite components was proposed utilizing CLPT, a finite element model, the Tsai-Wu failure criterion and a few tests. Also, the correlation between the static and air-gun tests provided an indication that it may be possible to save time and money in the design process for high-g survivable composite structures.

RECOMMENDATIONS FOR FUTURE WORK

This work offers insight into the preliminary design of a high-g composite structure, however further work is necessary to fully qualify a protocol for designing a g-hardened vehicle. Further refinement is needed in the ABAQUS™ code presented to more accurately predict the failure load observed during testing, and the failure code could be integrated as a embedded subroutine to make this procedure more compact. Other composite materials utilizing higher strength fibers and tougher matrices should be investigated to further validate this procedure, as well as specimens manufactured with alternate techniques. To fully design a survivable high-g vehicle however, a more advanced procedure or tool will have to be developed to analyze details such as joints, hinges and attachments.

ACKNOWLEDGMENTS

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REFERENCES

1) Kessler, S. S. December 1999. "Design, Analysis and Testing of High-g Unmanned Aerial Vehicle," Massachusetts Institute of Technology, Cambridge.

2) Jenkins, S. N. June 1999. "Investigation of Curved Composite Panels Under High-g Loading," Massachusetts Institute of Technology, Cambridge.

3) Hilburger, M.W. June 1998. "Numerical and Experimental Study of the Compression Response of Composite Cylindrical Shells with Cutouts," University of Michigan, Ann Arbor.

4) Hu, H.T., and S.S. Wang. 1992. "Optimization for Buckling Resistance of Fiber-Composite Laminate Shells With and Without Cutouts," *Composite Structures*, 22: 3-13.

5) Tong, L.1999. "Buckling of Filament Wound Composite Conical Shells Under Axial Compression," *AIAA Journal*, 37: 778-781.

6) Tennyson, R.C. 1975. "Buckling of Laminated Composite Cylinders," *Composites*, 1: 17-25.