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ENERGY ABSORBABILITY OF LARGE SCALE INFLATABLE COMPOSITE STRUCTURES

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ABSTRACT

Airbeams, inflatable composite structures, have traditionally been used solely as structural elements. Modeling and test procedures have been under development by academia, industry and governmental agencies to predict and evaluate an airbeam's structural properties. However, the pneumatic component that gives airbeams their strength and stiffness also provides airbeams the capability to absorb energy. Test procedures and scaling laws that can be used to evaluate the energy absorbing capacity of these structural elements will be described and evaluated. Test data will show that airbeams can reliably absorb sufficient energy for applications such as a pneumatic fender and meet other functional requirements. The paper will also describe textile considerations and other material properties that will enable this application to be successful.

INTRODUCTION

Airbeams are a category of load carrying composite structures. These tubular textile composites are formed by uniquely oriented, high strength fibers that, upon pressurization, expand into predetermined shapes. The pressurization tensions the fibers into a temporarily rigid composite with load carrying capabilities not previously achievable with other inflatable structures. A large airbeam arch (three feet in diameter, spanning 85 feet, pressurized to 85 psi) can support loads in excess of twenty thousand pounds. Airbeams are also rapidly deployable and compactly stored. Made from textiles, airbeams are inherently lightweight. When not in use, their textile construction allows them to be stored in a folded shape efficient for deployment. The airbeam can then be rapidly inflated when needed as a structural element. These unique capabilities make airbeams an ideal candidate for mobile and temporary structural applications. Typically, airbeams have been used to replace structural metal frames in military and commercial fabric shelters; in space applications like booms; and as inflatable wings on unmanned aircraft vehicles. In each of these applications, the airbeam acts as a structural element.

This paper considers a second application for airbeams, that of an energy absorbing element. As a structural textile that can readily deform and return to its original shape without damage, airbeams can repeatedly absorb energy created by the impact between two bodies. Assuming that the airbeam is compressed along its length, the stiffness of this deformed composite would also be able to maintain a separation distance between these two bodies. When not in use, the airbeam could be flattened for storage, minimizing stowage and weight. A specific application for an energy absorbing airbeam would be a rapidly deployable and lightweight pneumatic airbeam. This paper will describe modeling methods and test procedures that can be used to evaluate airbeam geometry and inflation pressure as an energy absorbing element. Test data and finite element analysis will demonstrate that an airbeam can absorb a

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sufficient amount of energy to serve as a pneumatic energy absorbing device.

NOMENCLATURE

Air inflated structures, airbeams, inflatable composites, energy absorption

GEOMETRY OF ENERGY ABSORBING ELEMENT

The geometry of the airbeam energy absorbing element is driven by three inter-related factors: energy absorption requirements, maximum pressure limits under compression, and the deflection at which these first two requirements are met. For an airbeam to act as an energy absorbing element, it must have sufficient volume to absorb the required impact energy. The second factor, the maximum inflation pressure, is equivalent to the contact pressure on the surface. This value must be sufficiently small to meet strength of material design specifications for the impacting surfaces. When the airbeam compresses, its volume decreases and its internal pressure increases due to isothermal expansion. While the increase in pressure allows the airbeam to absorb energy, the new internal pressure applies a rising contact force on the impacting surface. The deformed airbeam geometry and the rising internal pressure must work synergistically to meet energy absorption requirements without exceeding impacting surface pressure limits. The final factor is the separation distance that is maintained between the two impacting bodies. Energy absorption requirements must be met within the design constraints of the maximum allowable pressure on the two impacting surfaces and the minimum allowable separation distance between the two impacting bodies. For this study, the basic airbeam geometry was selected as a cylinder with hemispherical endcaps. Compared to flat cylindrical ends, this specific endcap shape has several benefits. These endcaps provide additional volume for energy absorption and cause the internal pressure to rise more slowly given an equivalent cylindrical length. Finally, this geometry can be easily fabricated from textiles.

Design principles and geometry were guided by the work of Bulson [1], who developed basic design equations for the compression of inflatable structures. While methods have been developed for the modeling and testing of air beam structures [2-5], computational techniques for analyzing the performance of airbeams as an energy absorbing device have not been developed or validated. Previous work evaluated airbeam structural behavior using beam theory [3,4] or as a pressurized membrane acting as a beam [2,3]. A primary difference between this structural behavior and that of an energy absorbing device lies in the importance of the airbeam material properties. As a beam, the material properties of the textile and its construction play a critical role in the stiffness of the beam and its ability to carry bending loads [2-4]. For energy absorbing devices, the ability to absorb volume is a function of the external work, which is not appreciably affected by the material properties of the textile.

Pneumatic full-scale energy absorbing devices can be as large as five meters in diameter and twelve meters long. For laboratory testing, it is much more practical to test and evaluate an energy absorbing element that is smaller in size. In this study, the geometry of the prototype was scaled to ¼ the size of the full-scale airbeam. It can easily be shown that the ratio of the volume of the quarter scale prototype to the full-scale device is 1/64. Integration of $\int PV$ yields

$$\int PV = P\int dV_{fs} + V_{fs}\int dP = 64\left(P\int dV_{qs} + V_{qs}\int dP\right) \qquad (1)$$

where V_{fs} represents the volume of the full-scale airbeam and V_{qs} the volume of the quarter scale airbeam. Eq. (1) assumes that, the inflation pressures of the full-scale and quarter-scale airbeams under compression are the same, expressed as the state conditions:

$$P_{qs_initial} = P_{fs_initial} \qquad (2)$$

$$P_{qs_final} = P_{fs_final} \qquad (3)$$

Here, $P_{fs_initial}$ and $P_{qs_initial}$ represent the inflation pressures prior to compression for the full-scale and quarter-scale, respectively, and P_{fs_final} and P_{qs_final} are the inflation pressures at the maximum amount of compression for the full-scale and the quarter-scale airbeams. When the airbeam is compressed, the external work is measured as the area under the load-displacement curve. Measuring energy absorption as the work performed assumes that the capacity of the airbeam to absorb energy, i.e. the external work performed by compressing the airbeam, is governed by the integration of $\int PV$ and that the strain energy is negligible. Based on Eq. (1), the amount of energy absorbed by the full-scale airbeam should be 64 times the amount absorbed by the quarter-scale prototype. Finite element analysis of the quarter-scale and full-scale geometries validated the use of Eq. (1). In addition, finite element analysis of the quarter-scale airbeam was compared to experimental test results.

FINITE ELEMENT MODELING

As an energy absorbing element, the volume of the airbeam will decrease under impact, causing its internal pressure to increase. The energy absorbed is the work done by isothermal expansion. Finite element analysis provides an efficient, physics-based design tool capable of predicting energy absorption, contact pressures on the impacting bodies and contact areas using a minimal number of prototype validation tests. The ABAQUS/Explicit FEA code captures pressure-volume behavior, geometric nonlinearities due to deformations and wrinkling, contact between the airbeam and the rigid surface during impact, and fluid-structure interactions when ballasted.

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To increase efficiency, pre-concept prototypes were tested to begin model validation. The development of modeling methods began with two preliminary airbeam designs, a quarter-scale design and a full-scale design. Both models were straight cylindrical sections with attached hemispherical caps. The full-scale model was 2.4 meters in diameter and 7.3 meters long; the quarter-scale model was sized accordingly. The fabric thickness was the same for both the full-scale and quarter-scale geometries. Since the fabric was incapable of developing bending strain energy, it was represented with membrane elements. A pressurized cavity was defined along the inside surface of the fabric material in order to model the internal fluid, structure, and air interaction. The cavity and its enclosed surface were used to apply the internal pressures directly to the membrane (fabric) elements, and define the volume of air contained by the cavity in the airbeam, coincident with the membrane elements. The internal air was modeled as a compressible (pneumatic) fluid that satisfied the ideal gas equation of state (EOS) shown in Eq. 4. This EOS assumes that air was compressed adiabatically, that is, no heat transfer was permitted across the boundaries between the cavity and the fabric.

$$P + P_A = \rho R\left(\theta - \theta^Z\right) \tag{4}$$

Here, P is the gauge pressure, P_a is the ambient pressure, ρ is the air density, R is the ideal gas constant, θ is the current absolute temperature, and θ^z is the absolute zero temperature. The ideal gas constant, R, is given by

$$R = \frac{\tilde{R}}{M_W} \tag{5}$$

Where $\tilde{R}$ is the universal gas constant and M_w is the molecular weight. The external work done on the airbeam during a quasi-static compression between upper (displacing) and lower (stationary) rigid surfaces was computed as the area under the impact force, F_{imp}, versus the impact displacement, δ_{imp}, curve. During impact, the external work is equal to the change in internal energy of the airbeam, ΔE_{int}. The energy balance is shown in Eq. (6).

$$\int F_{imp} d\,\delta_{imp} = \Delta E_{int} \tag{6}$$

where

$$\Delta E_{int} = \Delta E_{strain} + \Delta E_{kinetic} + \int PV + \Delta E_{dis} \tag{7}$$

given ΔE_{strain} is the fabric strain energy, $\Delta E_{kinetic}$ is the kinetic energy of the total system mass, $\int PV$ is the energy exerted by compressing the air, ΔE_{dis} is the viscous dissipation energy when damping is present.

Quarter-Scale Energy Absorbing Device

The fabric was considered isotropic and assigned a linear-elastic modulus of 6.9×10^5 kPa and thickness, t, of 0.127 cm. Two load steps were applied. The first step pressurized the airbeam from 0.0 kPa to the target inflation pressure in one second. The second load step was used to create an impact event between upper and lower rigid surfaces. For this model, these rigid surfaces were sized for full-length contact. The upper surface was displaced 0.3 meters (i.e.; 50% diameter) over a 10-second time interval, while the lower surface remained stationary. During impact, the air pressure increased from 17.2 kPa to 59.3 kPa and the air volume decreased from 0.47 cubic meters (m^3) to 0.35 m^3. Wrinkling began at the transition regions where the radii of curvature varied between the straight cylindrical geometry and the hemispherical end caps, shown in Figure 1. Within the wrinkled zones, the axial stresses due to impact opposed the axial pretension stresses due to inflation; therefore the fabric within these zones was unable to carry appreciable axial loads. Figure 1 shows the displacement contours for an airbeam compressed to 50% of its diameter. The wrinkling zones are labeled.

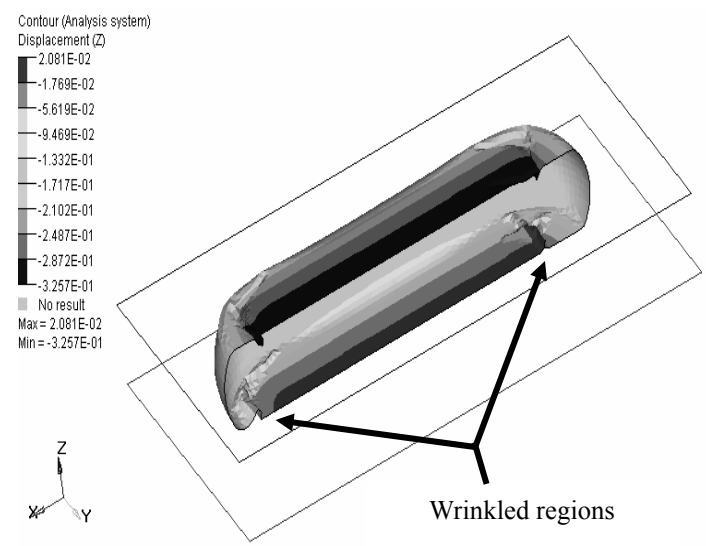

Fig. 1: Half-Symmetry Finite Element Displacement Contours for the Quarter-Scale Model. Wrinkled regions have self contact on the top and bottom surfaces.

Full-Scale Energy Absorbing Device

The full-scale model assumed the same fabric material properties and thickness as the quarter-scale prototype. The airbeam was inflated to 17.2 kPa in one second and was compressed to 50% of its diameter in over ten seconds. During the impact step, the air pressure increased from 17.2 kPa to 51.0 kPa while the corresponding volume decreased from 31.2 m^3 to 24.3 m^3 (a 22.2% reduction). Figure 2 shows the

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displacement contours for the half-symmetry full scale finite element model. The radii of curvature for the straight cylindrical section and hemispherical end caps are four times greater than those of the quarter-scale airbeam model. Therefore, wrinkling was not observed at 50% compression; however, wrinkling may occur beyond this point. The maximum energy absorbed at 50% compression was 300 kJ.

Model Scalability

The compressibility behavior of the air was governed by Eq. (4), with the additional adiabatic restriction of heat transfer across the air volume. The results of the finite element analyses were then evaluated for scalability. The analytical

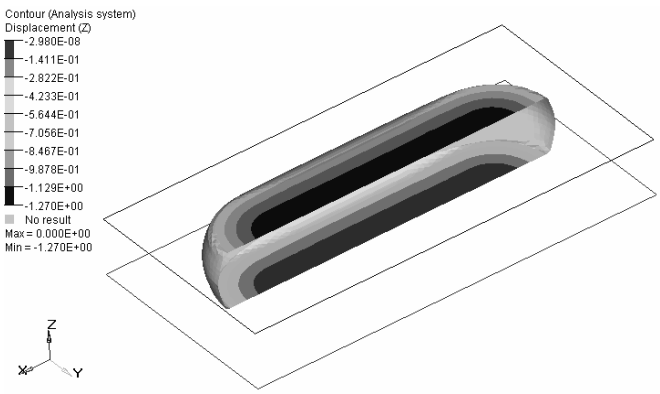

Fig. 2: Half-Symmetry Finite Element Displacement Contours for the Full-Scale Model.

solution of Eq. (1) shows that $\int PV$ scaled directly with the ratio of the full-scale to the quarter-scale volume. Therefore, the full-scale airbeam should absorb 64 times the energy absorbed by the quarter-scale airbeam when compressed between rigid surfaces. The ratio of the initial volumes of the full-scale to the quarter-scale finite element models was 31.2 m^3 to 0.47 m^3 or 66.4. A comparison of the full-scale and quarter-scale airbeam models satisfying the conditions of Eq. (6) and (7) showed that $\int PV$ during impact was 228 kJ and 3.4 kJ, respectively. The resulting ratio was 67.1.

At 50% compression, the ratio of the deformed volumes of the full-scale and quarter-scale models was 24.3 m^3 to 0.35 m^3 or 69.4. This change in volume ratio is attributed to the wrinkling that occurred in the quarter-scale model; the nonlinearities associated with wrinkling cannot be addressed with the analytical solution. A key finding of the analyses validated the use of Eq. (1) for estimating energy absorption even though the ratio of the volumes changed during compression. The total energy absorption, $\int F_{imp}\, d\delta_{imp}$, obtained from the finite element models was slightly greater than their respective $\int PV$ quantities because these models included additional energy absorption paths such as strain energy, kinetic energy, viscous dissipation, etc. as described by Eq. (7). For a pneumatic airbeam, interpretation of the finite element results for energy absorption should be based on all internal energy terms for more precise results. The analytical solution based on $\int PV$ is a good approximation, but yields conservative results.

Effects of Elastic Modulus on Airbeam Performance

The effects of material stiffness on airbeam compressibility were evaluated over a wide range of linear elastic moduli with the quarter-scale model inflated to 34.5 kPa under compression over its entire length. Figure 3 shows the responses for a linear-elastic material having a 6.9×10^5 kPa to 6.9×10^6 kPa elastic moduli range with Poisson's ratio, v, set to 0.3. The value of $\int PV$ remained essentially constant over this range of elastic moduli. It was established that, for membrane airbeams having this range of elastic moduli at equal diametral compression, no appreciable effects were seen with contact force, work done or $\int PV$. However, as the strain energy decreased with increasing elastic modulus, stresses within the fabric increased as expected. While the textile properties do not influence the ability of the airbeam to absorb energy, the mechanical properties must meet the strength requirements imposed by the hoop stress due to inflation, or $(P+P_a)r/2t$, where r is the radius.

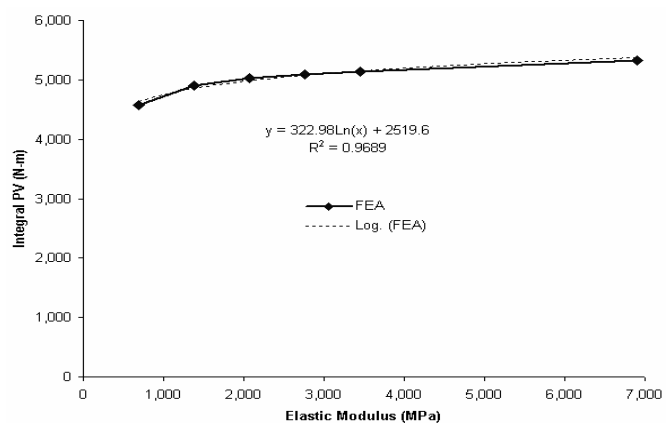

Fig. 3: Graph of the Effect of Elastic Modulus on $\int PV$ at 50% Compression.

PROTOTYPE FABRICATION

An inflatable composite cylinder, 60 cm in diameter and 182.5 cm long, with hemispherical endcaps was fabricated from braided Vectran®, a high strength liquid crystal polymer fiber. A triple ply braided construction formed the cylindrical portion of the airbeam while a double ply braid was used for the hemispherical ends. A pressure relief valve, designed to open at 43 kPa, was added to the airbeam to prevent excessive pressure buildup in the prototype. As a quarter-scale prototype of a full-scale airbeam pneumatic airbeam, testing [7] was performed to validate performance as an energy absorbing device and to validate finite element analysis results.

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LABORATORY TESTING

The prototype airbeam should absorb energy in a manner similar to a pneumatic fender. Consequently, standardized test procedures for pneumatic fenders were used to quantify energy absorption in an airbeam. The quarter-scale prototype was evaluated using applicable test procedures from ISO Standard 17357, Ship and marine technology – High-pressure floating pneumatic rubber fenders [8]. Although the prototype is a textile, tests from this standard can be used to measure the energy absorbing capability of the prototype and evaluate its overall performance. Energy absorption, durability, air leakage, and compression recovery were verified following the ISO protocols. Airbeam measurements, energy absorption tests, leak tests, compression tests and held compression tests were completed at the Natick Soldier Center.

Energy Absorption Results Based on ISO 17357 Test Methods

The energy absorption of the inflated airbeam was measured using a parallel compression test (Section 8.2, ISO 17357). The airbeam was placed between two parallel plates, shown in Figure 4, then uniformly compressed normal to the airbeam at a rate of 50 centimeters per minute. Load data were collected at a rate of 5 Hertz (Hz) and inflation pressures at 1 Hz. The percentage deflection and the energy absorption were calculated using the formulas in the ISO 17357. By design, the airbeam should reach its required energy absorption at less than 50% deflection. Figure 5 shows the load-deflection curves for an initial inflation pressure of 17.2 kPa, where the load steadily increased to approximately 53 kN. The finite element results accurately predicted the experimental load-deflection curve. By integrating the load-deflection curve the energy absorption was calculated, these results are provided in Figure 6 for three slightly different starting inflation pressures. These curves also demonstrate the repeatability and robustness of the energy absorption capability of the airbeam. At 50% deflection, the energy absorbed was approximately 5.4 kJ. Based on the actual dimensions of the prototype, its volume is 1/57 of the full-scale airbeam volume. Therefore, the prototype's energy absorption can be scaled by a factor of 57, resulting in full-scale energy absorption of 290 kJ at 50% deflection.

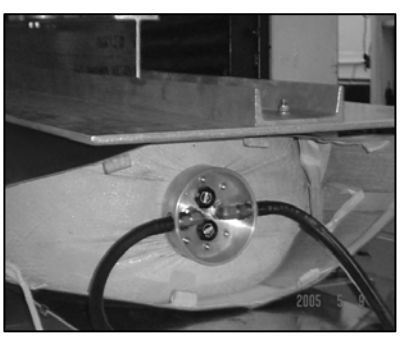

Fig. 4: Compression of the Quarter-Scale Prototype

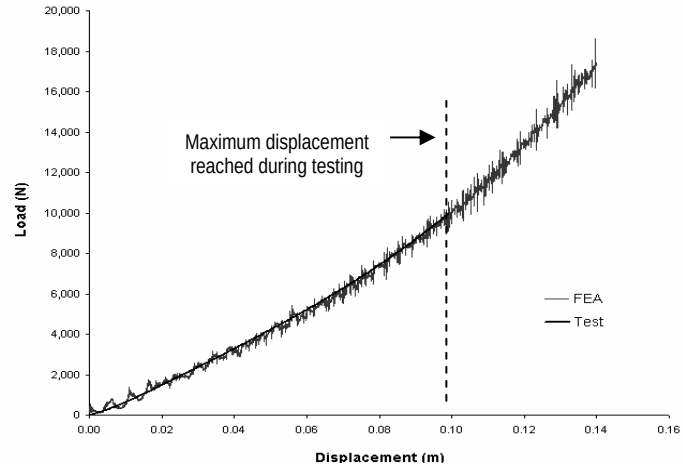

Fig. 5: Load-deflection Curves at Starting Inflation Pressures of 17.2 kPa – Comparison of Experimental and Finite Element Results.

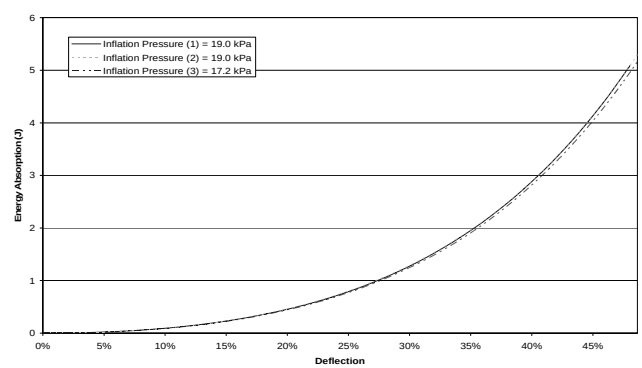

Fig. 6: Energy Absorption Curves for the Quarter-Scale Prototype Airbeam Energy Absorbing Device

The inflation pressure was also monitored during compression testing. Figure 7 displays the rise in experimental inflation pressure up to the deflection where the pressure relief valve opened at 43 kPA. Even though the pressure relief opened, the fender still absorbed additional energy, refer to the continuous curve in Figure 6 up to 45% deflection. A comparison of experimental and finite element results in Figure 7 shows that the finite element analysis could reliably predict changes in pressure during compression up to the time in the experiment when the pressure relief valve opened at 38% displacement. As the finite element model did not include a pressure relief valve, it could not predict the loss in pressure and air mass that occurred experimentally; this functionality will be added to the model in future work.

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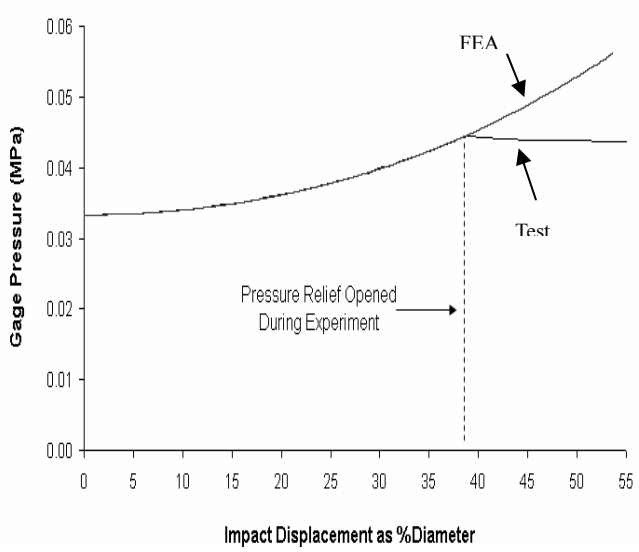

Fig. 7: A Comparison of Inflation Pressures vs. Airbeam Displacement between Finite Element Results and Experimental Test Results.

A critical parameter for evaluating the performance of the airbeam according to the ISO standard was the inflation pressure at specific values of energy absorption. According to the ISO standard, this inflation pressure was representative of the contact pressure on the impacting surface at a specified deflection and energy absorption. At 2.6 kJ, the inflation pressure ranged from 38.3 kPa to 39.9 kPa. These values were taken before the pressure relief valve opened at approximately 40% compression of the diameter. From Figure 6, the finite element results predicted that the deflection would be 38% at 2.6 kJ, in good agreement with experimental results. At 50% deflection, the energy absorption was measured at 5.4 kJ while the maximum pressure did not exceed 55 kPA.

The percent deflection under impact also measures the separation distance that would be maintained by the airbeam between the two impacting bodies. For the quarter-scale prototype, this separation distance would be 0.61 m at 50% deflection and 5.4 kJ of absorbed energy.

Durability Testing

The prototype durability was tested by repetitively cycling the airbeam in compression to 25 % deflection for a total of 200 cycles. While the protocol for the ISO standard was followed, the number of repetitive cycles (3000) called out in the standard was not performed due to resource constraints. After completing 200 cycles, energy absorption and leak tests were conducted. The energy absorption at 50 % deflection was 5.6 kJ and the average leak rate was 0.9 kPa/hr over 16 hours.

CONCLUSIONS

Inflatable composites have demonstrated predictable energy absorbing capability; large scale airbeams can reliably be used in commercial applications for this purpose. Geometry based scaling methods analogous to those for other pneumatic energy absorbing vessels were developed and validated using finite element analysis. For similar geometry, the amount of energy absorbed between two airbeams can be scaled by their volume ratio. Standardized test methods used for pneumatic fenders were adopted to measure the energy absorption in airbeams under large deflections. A laboratory prototype, fabricated from Vectran®, was shown to absorb 5.4 kJ at 50% deflection. Scaling methods predicted that a full-version of the prototype would be able to absorb 290 kJ. At 40% deflection, before the pressure relief valve opened, the airbeam prototype had adsorbed 2.6 kJ; the full-scale would be able to absorb 148 kJ. The full-scale airbeam would be able to maintain a distance of 1.5 meters between two impacting bodies at 40% deflection.

Structural modeling tools based on the mechanics of the materials and numerical analysis were developed to predict the mechanical behavior and internal pressure changes of the pneumatic airbeam during compression. Relationships between airbeam deformations, structural loads, internal pressure, and energy absorption were validated by experimental testing. Examination of the deformed airbeam with prototype and full-scale geometries did reveal one important difference. The deformed prototype finite element model wrinkled at lower deformations compared to the larger full-scale geometry. This difference was attributed to the smaller radii of curvature found in the prototype geometry; these geometric effects should be carefully reviewed in airbeam design studies.

Finite element models of the system were validated against the ISO airbeam parallel compression test results and accurately predicted energy absorption, internal pressure, and impact loads as a function of the percent deflection. Agreement between test data and numerical results was typically within ten percent. Confidence in these tools will enable finite element analysis to now be used in simulations of airbeam compression in its energy absorbing service environment.

Other ISO tests verified the textile construction of the prototype airbeam. Air leakage was minimal, 0.9 kPa/hour. Durability testing proved that the airbeam could be repetitively compressed without change in geometry or loss of energy impact capability.

ACKNOWLEDGMENTS

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