Innovative Energy Absorbing Composite Material for Crashworthy Structures

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14. ABSTRACT

This research aims to develop, analyze, and evaluate a new type of structural element that will enhance the crashworthiness of naval vehicles by providing outstanding energy absorption with minimal weight. The structural element is an array of concentric fiber reinforced composite tubes with extension-twist coupling and ultra-high Poisson's ratio. The tubes are configured to crush or shear internal foam as a means of absorbing energy. This interim report includes technical progress, plans, publications, and various administrative matters. In the current period, work has focused on evaluating the mechanisms of energy absorption in composite tubular structures and the development of analytical models for predicting the deformation and damage in these tubular structures. A significant effort was dedicated towards developing the manufacturing and testing technology for tubes having extension-twist coupling. This effort culminated in the successful demonstration, for the first time, of energy dissipation in extension-twist coupled tubes with sandwich foam.

15. SUBJECT TERMS

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1. Overview of Project

The proposed research aims to develop, analyze, and evaluate a new type of structural element that will enhance the crashworthiness of naval vehicles including fixed wing and rotary wing aircraft, land vehicles, and littoral vehicles by providing outstanding energy absorption with minimal weight. The envisioned structural element is an array of concentric fiber reinforced composite tubes with extension-twist coupling and ultra-high Poisson's ratio. The tubes are joined with threads and/or lightweight closed-cell core materials which fracture and crush as tensile force is applied to the tubes. By combining multiple energy dissipation mechanisms, the specific energy absorption of the structural element will be maximized and, after iterations based on experimentation and analysis, is expected to be superior to current energy absorbing structural elements. Little is known about the various mechanisms of energy absorption (EA) in this type of structural element and how these mechanisms interact with each other to govern the overall performance in a crash event. This project aims to devise methods of fabricating the novel energy absorbing tubes, analyze the operative mechanisms of energy absorption and their interaction, select materials and configurations for the best performance, test the tubes at stroke rates resembling those likely to be encountered in nominally survivable crashes of naval vehicles, develop mechanism-based analytical models of EA behavior using experiments as guidance, evaluate environmental durability, and validate/improve the analytical models using experimental data. Upon completion of the proposed basic research program, a new class of energy absorbing material for improved crashworthiness of naval vehicles will be demonstrated, the behavior of this type of material will be better understood through validated analysis methods developed over the course of the work, and data and analytical tools will be available for advancing the technology to the stage of practical development. In the long run, this research may benefit the needs of the US Navy by exploring means of improving the safety of vehicles and saving the lives of Navy personnel involved in crashes.

The work is organized into three tasks:

- Task 1. Evaluate mechanisms of energy absorption.
- Task 2. Develop analytical models for the observed deformation and damage mechanisms.
- Task 3. Validate and improve the models with a comprehensive set of experiments encompassing loading and environmental conditions encountered by the Navy.

2. Summary of Activity

In the current reporting period, progress has been made in Tasks 1 and 2. This progress is detailed below.

2.1. Task 1 - Evaluate mechanisms of energy absorption

Experiments were conducted in order to evaluate the energy absorbing mechanisms of foam-filled composite tubes. Two types of foam-filled flexible matrix composite (FMC) tubes were investigated:

- A balanced $\pm\theta$ angle-ply tube which, due to a high Poisson's ratio, undergoes a large transverse contraction as tension is applied longitudinally. This device is denoted a *crush* *tube*. As tension is applied, the tube contacts and exerts radial compression on foam situated in its interior region. Energy is dissipated by crushing the foam and damaging the tube.

- A pair of concentric off-axis unidirectional tubes that have extension-twist coupling of mutually opposite sign and foam placed in the thin annular gap between the two tubes, denoted *sandwich core device*. During longitudinal tension, these tubes twist in opposite directions and exert shear stress onto the annular foam. Energy is dissipated by shear-failing the foam (by fracture or plastic deformation) and damaging the tubes.

2.1.1. Crush Tubes

Angle-ply tubes with fibers at $\pm\theta$ relative to the longitudinal axis were manufactured in-house by the wet filament winding technique. The wall thickness was 1.2 mm in all angle-ply tubes. The tube material system was selected based on preliminary analyses: standard strength carbon fibers (AS4D-12K, Hexcel Inc., Stamford, CT) and an elastomeric polyurethane matrix (Adiprene® L100 prepolymer with Caytur® 21 curative, Chemtura, Middlebury, CT). The two-step curing schedule for this material system is 120°C (248°F) for 2 hours followed by 100°C (212°F) for 16 hours. This schedule was followed for tubes with $\theta = \pm45$ and ±60 degrees. For the ±30 and ±35 deg. tubes, a slightly different curing schedule of 100°C (212°F) for 2 hours followed by 120°C (248°F) for 10 hours was followed. Evidence suggests that the slightly altered cure schedule did not affect the properties of the tubes. Tubes were tested with no foam inside and with two kinds of polyurethane foam (FOAM iT, Smooth On Inc., Easton, PA). One foam had a mass density of 48 kg/m^3 (3 lb/ft^3) and the other 128 kg/m^3 (8 lb/ft^3). The foams are self-expanding and cure in about two hours at room temperature. For each test, a tube was bonded into grips and loaded in tension as shown in Fig. 1. The bonding regimen involved heating the tube and grips for 10 hours at 49°C (120°F). The tubes experience rapid decrease in diameter under tension and therefore radially crushed the foam filling inside.

In order to model the behavior of the crush tubes and to carry out predictions, the properties of the tubes and the foam need to be determined. The elastic and strength properties of the carbon/polyurethane composite, determined in previous work, are reported in Table 1. The mechanical properties of the polyurethane foams were characterized using uniaxial compression tests. The experimental set up and selected results are shown in Fig 2. Material properties such as Young's modulus and uniaxial crush strength are presented in Table 2. The average of three tests is reported for the un-aged foams. Only one aged specimen was tested for each type of foam. The Poisson's ratio, measured only for the un-aged 48 kg/m^3 foam, was found to be 0.15. This Poisson's ratio was used in calculations for any type of foam. It was observed that the foams demonstrate an aging phenomenon when kept at 48°C for 10 hours (i.e, the time and temperature needed to cure the grip adhesive). This results in a change in modulus and crush stress.

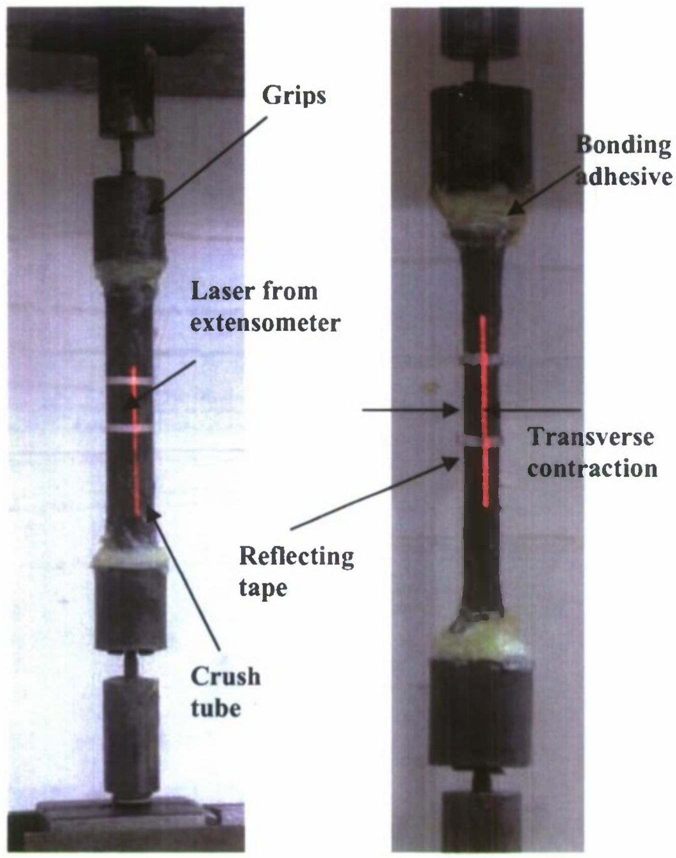

Figure 1. ±30 deg. crush tube in the tensile testing fixture before (left) and after (right) the application of force.

Table 1. **Elastic and strength properties assigned to the carbon/polyurethane lamina material used to make crush tubes (fiber volume fraction = 0.5).**

Parameter	Carbon/polyurethane (FMC)
Longitudinal modulus, E_L (GPa)	115
Transverse modulus, E_T (GPa)	0.275
Shear modulus, G_{LT} (GPa)	0.250
Poisson's ratio, ν_{LT}	0.314
Long. tensile strength, F_{1T} (MPa)	1955
Long. compressive strength, F_{1C} (MPa)	110
Transverse tensile strength, F_{2T} (MPa)	15
Transverse comp. strength, F_{2C} (MPa)	30
In-plane shear strength, F_6 (MPa)	23
Density (g/cm^3)	1.4

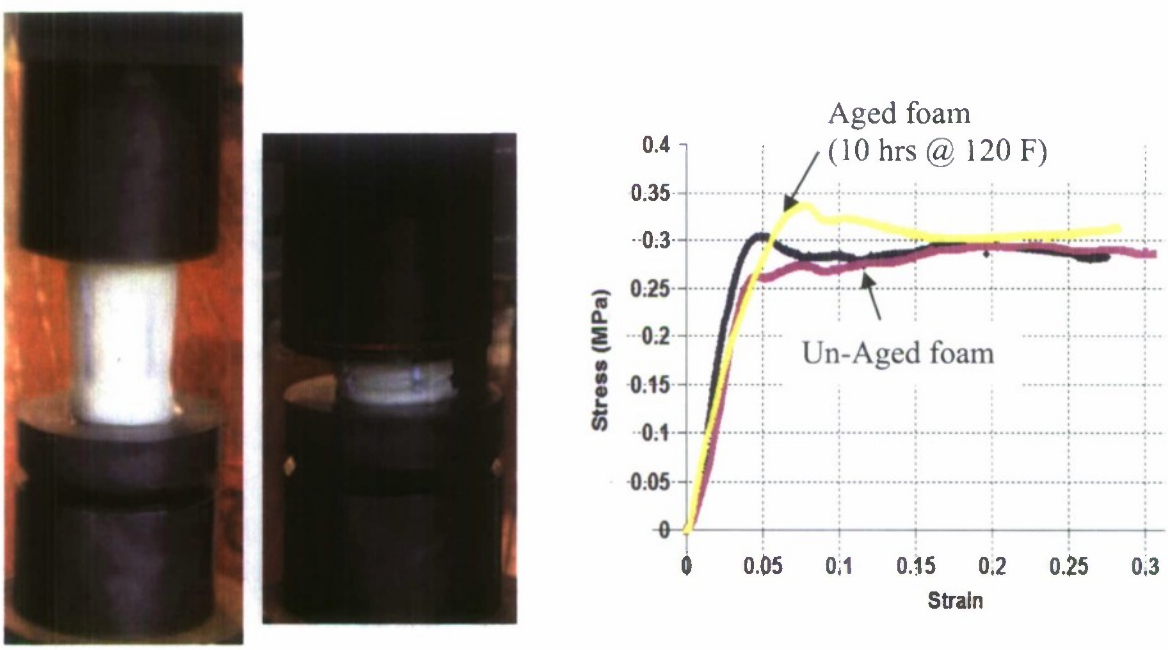

Figure 2. Crushing process (left) and compressive stress-strain curves (right) of the 48 kg/m^3 polyurethane foam.

Table 2. Mechanical properties of polyurethane foams.

Foam Type	Young's Modulus (MPa)	Crush Strength (MPa)
48 kg/m^3 Un-aged	7.82	0.284
48 kg/m^3 Aged	6.45	0.316
128 kg/m^3 Un-aged	33.4	1.10
128 kg/m^3 Aged	38.7	1.37

Experiments were also conducted to determine the effect of ageing on composite tubes. Aging was done by subjecting the tubes to their ultimate cure temperature for one week. It was found that ageing does not affect the material properties of the composite system.

Crush tubes of several fiber angles were tested: ±30, ±45, and ±60 deg. Stress-strain characteristics were measured for different fiber angles of the crush tube. The axial stress calculation is based on the cross-sectional wall area of each tube. Specimens were loaded in multiple load/unload cycles to measure the axial Young's modulus during the course of loading, as shown in Fig 3 for some typical results. The area under the stress-strain curve gives the energy absorbed by the device per unit volume of the tube (excluding the internal area filled with foam).

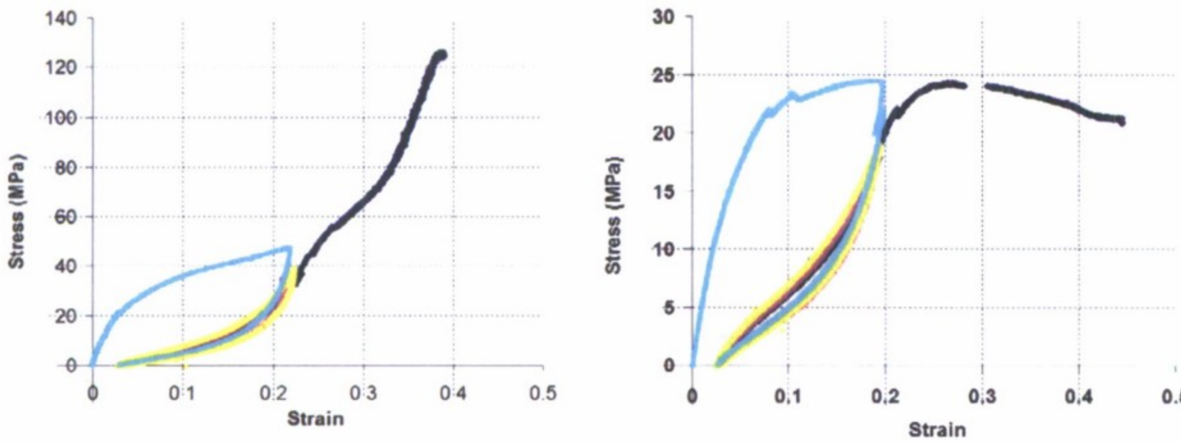

Figure 3. Stress-strain curves for ±45 deg (left) and ±60 deg (right) crush tubes with 48 kg/m^3 foam.

As can be seen from Fig. 3, stiffness of the crush tube devices vary significantly with respect to the fiber angle. Since these devices are developed with the objective of serving as crashworthy payload restraint mechanisms, the total energy absorbed by them is a key performance parameter. To quantify such performance, metrics such as specific energy absorption (SEA) and volumetric energy absorption (VEA) have been evaluated and are presented in Table 3. Energy absorption should be interpreted as the total kinetic energy of the moving payload which gets dissipated by the device as well as elastically stored inside the device.

Table 3. Specific energy absorption (SEA) and volumetric energy absorption (VEA) of FMC-based crush tube devices with 48 kg/m^3 foam filling.

Fiber angle (deg.)	SEA (J/g)	VEA (MPa)
±30	7.25	10.2
±45	17.4	24.3
±60	6.9	9.63

2.1.2. Sandwich Core Device

The main activities on sandwich cores devices during this reporting period were aimed at:

- designing, building, and evaluating a set of rudimentary grips for applying torque-free tension to two concentric extension-twist coupled composite tubes with or without foam in annular region between the tubes
- developing a method of filament winding off-axis unidirectional composite tubes, and
- evaluating the behavior of extension-twist coupled tubes and sandwich core devices in tension tests.

An illustration of one grip is shown in Fig 4. The purpose of the bearing is to minimize torsional drag between the inner grips and outer grips as tension is applied to both via a bolt which passes though both and is anchored at the bottom of the figure at the spherical bearing. The spherical bearing prevents moments from being introduced to the grips from the remainder of the load train. The inner and outer grips each consist of an insert and shell, the purpose of which is to apply tensile load to a tube on the inside and outside diameters. Thus, each tube is loaded on the inside and outside surfaces to maximize tensile load carrying capacity.

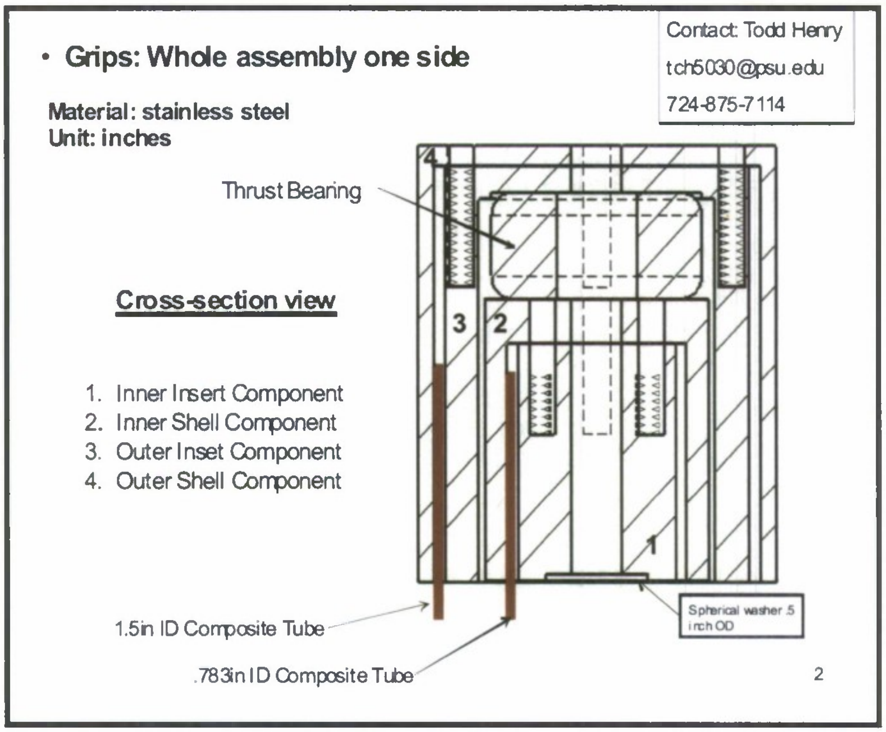

Figure 4. Longitudinal cross-section of one grip for tension-twist coupled concentric tubes.

Unidirectional off-axis filament wound composite tubes were manufactured using a new McClean Anderson Super Hornet filament winder procured with an ONR DURIP contract (No. N00014-08-1-0822). This winder has the new capability to wind a complete coverage of unidirectional off-axis fibers over a cylindrical mandrel. A tube partially wound with dry glass fibers as practice is shown in Fig. 5. The direction of rotation of the mandrel must reverse after each traverse of the payout eye. A finished carbon/polyurethane off-axis tube is shown in Fig. 6.

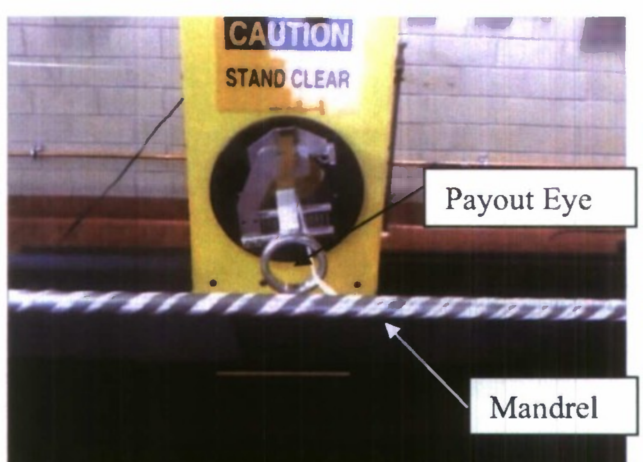

Figure 5. Unidirectional off-axis filament winding in progress.

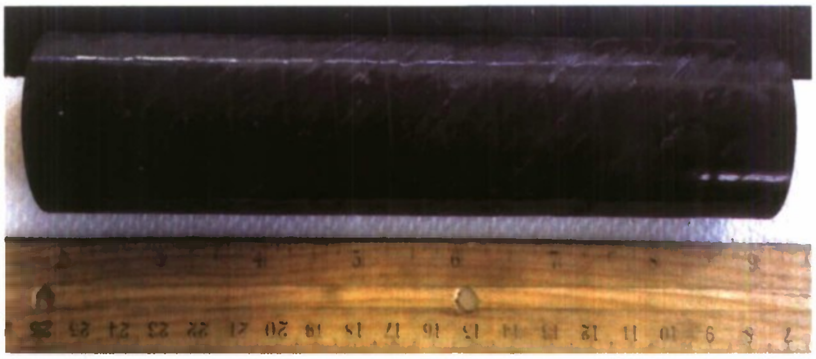

Figure 6. Finished 45-deg. unidirectional off-axis carbon/polyurethane tube.

Two types of carbon/urethane tubes were manufactured: one with inside diameter equal to 19 mm and a fiber angle of -45 deg. and the other with inside diameter equal to 38 mm and a fiber angle of +45 deg. The same fibers and matrix were used for these tubes as for the angle-ply tubes discussed in the previous section. The wall thickness for these tubes was 1.0 mm and the curing schedule was 120°C (248°F) for 2 hours followed by 100°C (212°F) for 10 hours. The annular space between the tubes was either unfilled or filled with the 48 kg/m^3 rigid polyurethane foam discussed earlier. Figure 7 shows an end view of a sandwich core device, before attaching the grips.

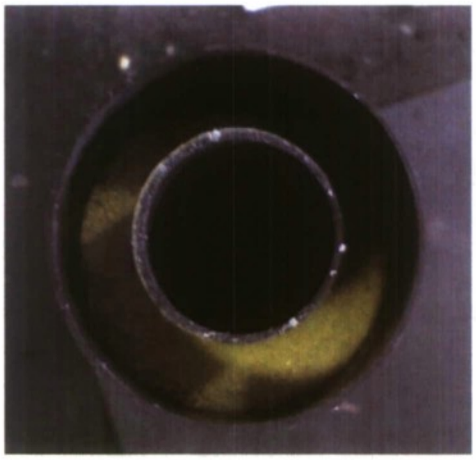

Figure 7. End view of sandwich core device, showing foam (yellow material) in between two carbon/polyurethane unidirectional off-axis tubes.

The concentric tubes and foam were bonded to the grips (48°C for 10 hours) and tested in tension as shown in Fig. 8. Two strain-gage based extensometers were used to measure the average longitudinal strain of the outer tube, which is required to strain the same amount as the inner tube by the design of the grips. Two rotary encoders were used to measure the rotation of the inner and outer tubes. These instruments are also shown in Fig. 8.

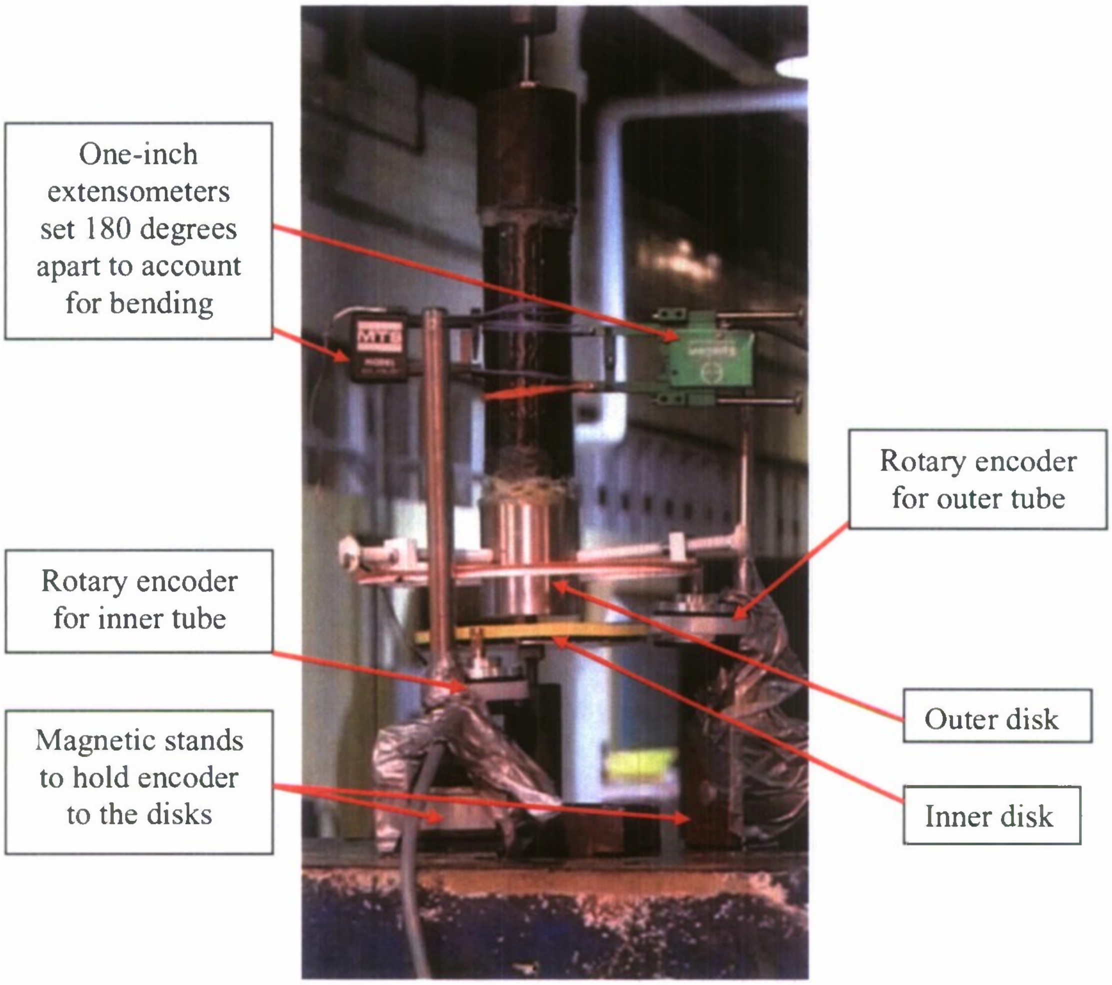

Figure 8. Test set up for sandwich core device.

Figure 9 shows a comparison of axial stress-strain curves of pairs of 45 deg. tubes with and without foam. In one of the sandwich cases, a supplementary adhesive, Lord 7650 from Lord Corp, Erie, PA) was used to improve adhesion between the foam and the tubes. The supplementary adhesive had a slightly beneficial effect, although the foam itself was not observed to fail in any case. The sandwich core devices were significantly stiffer than the pair of tubes without foam in the annulus. This is because the foam prevents the tubes from rotating relative to each other up till the force where the foam debonds or one of two tubes fails.

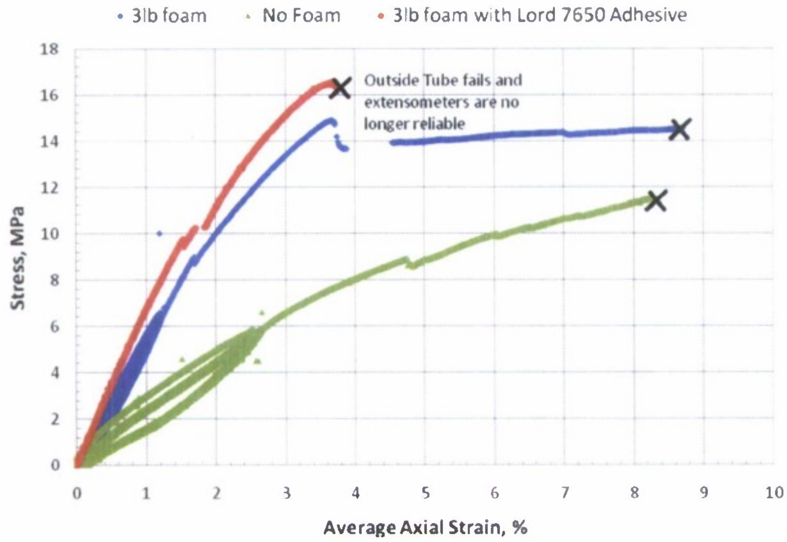

Figure 9. Comparison of axial stress-strain curves for 45-deg. tube pairs with and without 48 kg/m^3 foam.

The relative rotations of the two tubes with foam and no supplementary adhesive can be seen in Fig. 10, where both rotations have been plotted with the same sign of rotation for ease of comparison. Prior to failure of any sort during the first three loading cycles, rotations of both tubes are less than a degree. At roughly 550 seconds, it is believed that the foam debonded, allowing both tubes to rotate relatively freely to twist angles of 11 to 16 degrees.

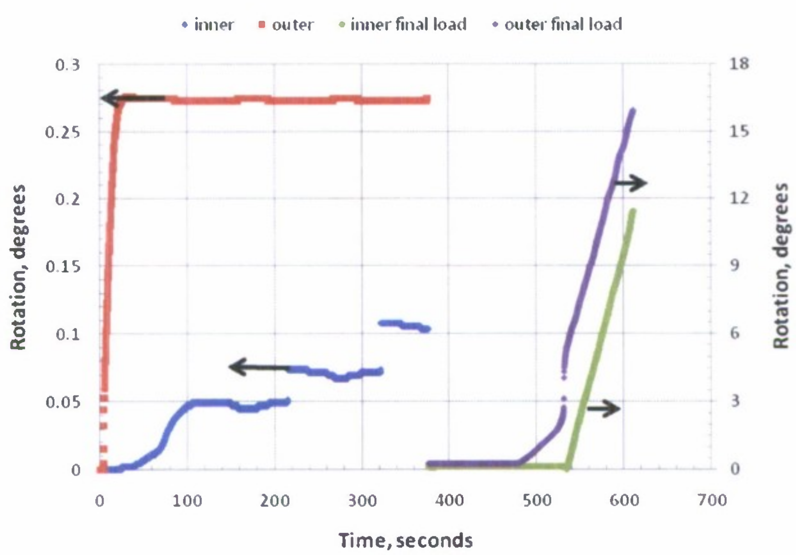

Figure 10. Rotation versus time graph for 45-deg. sandwich device with 48 kg/m^3 foam and no supplementary adhesive. Failure occurs at the right-most plotted point.

In summary, grips have been designed for evaluating the relative twist of a pair of extension-twist coupled tubes under tension. The grips are able to record twist angles while providing enough force to fail the tubes. These grips should suffice for future testing needs in the investigation, provided axial forces do not exceed approximately 10 kN. Such a force is sufficient for model development and validation work.

2.1.3. Stitch-ripping device

Similar to the sandwich devices discussed above, concentric off-axis composite tubes joined by high strength stitches can dissipate energy as the stitches are ripped due to differential rotations of the two extension-couple tubes. Thus, sewing machines suitable for stitching together concentric flexible matrix composite were explored as part of the associated ONR DURIP grant mentioned earlier. However, no suitable machines for penetrating pre-cured tubes could be found. A machine for stitching together uncured laminas or dry fiber preforms without any resin content can be custom made, but the only vendor (Neal Lund, NIT, Inc. Centerville, Utah) who was willing to discuss this with us quoted a price of over a hundred thousand dollars for a machine that would sew only short tubes of several-centimeters length. Assuming we had the budget for this equipment (we did not), a means of impregnating the sewn dry-fiber tubes while keeping them from bonding to each other would still need to be devised. Given the hurdles encountered, it appears that using the stitch ripping mechanism for extension-twist coupled composite energy absorbers is not a viable avenue of research in scope of the current project. Removing this item from the scope of work will allow us to make more headway on foam crushing and shearing as key energy dissipation mechanisms. However, we intend to continue an informal search for effective ways to manufacture tubular stitch-ripping devices economically. If one is found, we may revisit the idea in future work.

2.2. Task 2 - Develop analytical models for the observed deformation and damage mechanisms.

Based on experimental evidence (tube deformation, foam crushing, and foam fracture) analytical models are being developed and refined for the purpose of compact, lightweight, flexible matrix composite (FMC) devices with enhanced energy absorption capability.

2.2.1. Crush tubes

The crush tube device contains a low density crush-foam filling inside a helical wound composite tube. Analytical modeling of the device involves tube and foam characteristics such as tube geometry, foam strength, modulus etc. which have been experimentally determined. The modeling includes analyzing a circumferential plate element (using fundamental equations of lamination theory) to predict the behavior of the entire cross section of the tube. The overall objective is to obtain force-displacement characteristics of the device.

The in-plane laminate constitutive equations of the FMC tube are written as:

$$\begin{Bmatrix} N_{xx} \\ Pr \\ 0 \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{12} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{ss} \\ 0 \end{Bmatrix} \tag{1}$$

where P is the internal pressure on a tube of radius r, exerted by the foam. The A terms are the in-plane stiffness matrix, N is the stress resultant (force per unit width of laminate), ε is strain, and xx and ss refer to the longitudinal and circumferential directions. There are no shear stresses or strains in the xs coordinates in this problem.

The mechanics of energy absorption involves crushing of the brittle foam filling as a result of large transverse contraction of the tube diameter due to axial tension, as shown in Fig. 11. Equations accounting for the interaction between the FMC tube and the core have been presented in detail by Tiwari et al. (2009). Aged properties of the foam were used in the calculations.

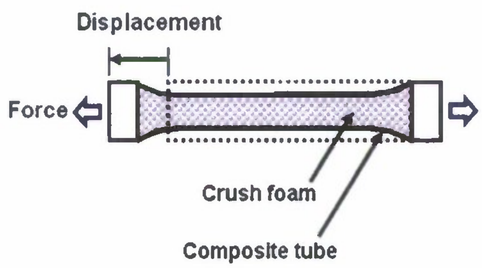

Figure 11. Illustration of initial (dashed) and final (solid) shapes of a crush tube

Comparison of experimental and analytical results points to the need to consider several processes during the large deformation of crush tubes. During the initial phase of tensile loading, the tube strains longitudinally and in the circumferential direction. This causes a compressive stress on the foam filling, which exerts an internal pressure, P on the tube. Upon being loaded further, the tube experiences large transverse contraction due to Poisson's effect. At a certain load, the tube experience shear failure in its wall (i.e., failure due to high shear stresses in the ply coordinate system aligned with the fibers at $\pm\theta$. Additional tensile loading results in fiber re-orientation and a further decrease in diameter. With additional tensile loading, the foam filling beings to crush and the elastic energy stored inside the foam is dissipated. The shear failure in the matrix was detected using ply failure theories such as the Maximum Stress Theory or the Tsai-Wu Polynomial Theory. At first, it was assumed that the composite tube exhibits constant elastic properties until ply failure occurs. The stiffness parameters of the composite lamina decrease by a constant factor after the ply failure. A comparison of experiment and analytical fit by such analysis is shown in Fig. 12. The portion of the curve shown in green has been adjusted in the model to fit the experimental data.

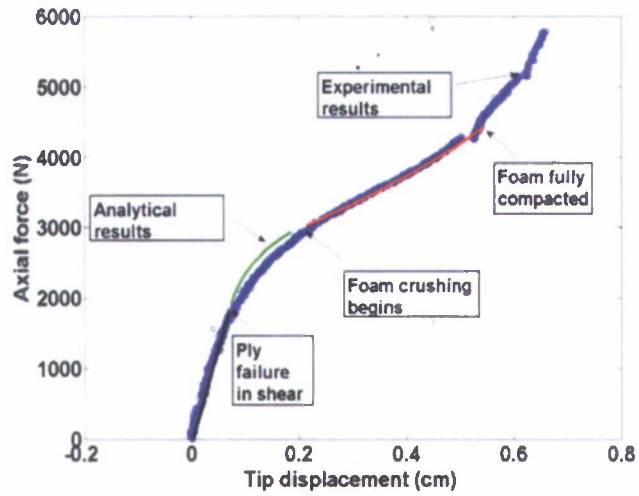

Figure 12. Results of analytical modeling for ±45 degree FMC crush tube, showing the various phases of deformation. Transverse and shear moduli were each decreased to 11% of respective initial values to match the experimental data.

It was observed in some of the experimental-analytical comparisons that instead of a step decrease in the moduli of the composite upon ply failure, the change may need to be more gradual. Thus, the next level of analysis involves the determination of such a gradual dependence of ply-level stiffness parameters on stresses or strains. To obtain such a characteristic, a polynomial fit of the experimental data was done (Fig. 13). The global incremental stiffness of the composite tube was obtained from the slope of the stress-strain curve. The ply level stiffness parameters at every stage of the loading were then determined by back-calculations.

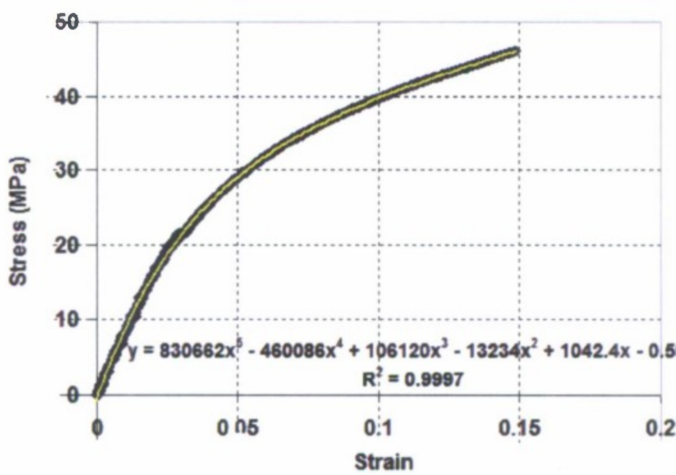

Figure 13. Polynomial fit to experimental longitudinal stress-strain data for ±45 deg. crush tube

Using the method explained above it was found that ply level stiffness parameters do indeed exhibit a gradual reduction with strain. This is illustrated with the graph of shear modulus (G_{LT}) versus shear strain at the ply level (γ_{LT}) in Fig. 14. A similar type of behavior can be observed for transverse modulus at the ply level, as well. It can be inferred that indeed stiffness change during the course of loading is gradual and therefore incorporating these non-linear behavior of ply level stiffness parameters into the model will help improve the correspondence with experimental results. Work to this end is currently ongoing.

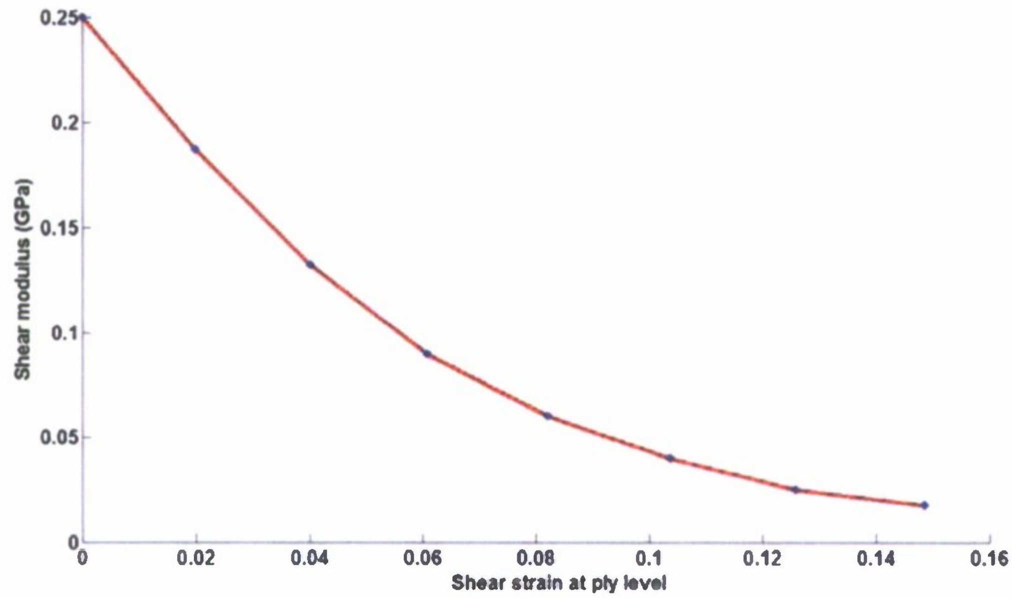

Figure 14. FMC shear modulus, G_{LT}, versus shear strain, γ_{LT}, at the ply level

3. Current Status and Plans for Next Reporting Period (1 Jan. - May 30, 2010)

The project is on-schedule, overall. Task 1 is slightly behind due to difficulties encountered in modeling the non--linear behavior of the FMC tubes. Task 2 is ahead of schedule. Task 2 was started early because it made good sense to do multi-mechanism modeling concurrently with the individual mechanism experiments.

Task 1

- Conduct additional experiments to develop better understanding of the sandwich-core-shear and foam-crush energy dissipation mechanisms.
- Fabricate and test sandwich core specimens with stronger FMC tube walls to enable shearing of the foam before tube wall failure. This may require additional modifications to the specimen grips.

Task 2

- Continue to refine the analytical model based upon experimental findings for crush tubes. Need to incorporate nonlinearity of FMC tube material.
- Begin to model the mechanism of energy absorption in a sandwich core tube device using experimental results.

Task 3

- No activity scheduled or planned.

4. Project Schedule and Milestones

	2009		2010				2011				2012	
Task	Q3	4	1	2	3	4	1	2	3	4	1	2
1. Mechanisms	------	------	------	------								
2. Analysis					------	------	------	------				
3. Validation									------	------	------	------
4. Report		*		*	*	*		*	*	*		†

*Reporting milestone; † Final report.

7. Budget Information

Budget information has been compiled through the end of Dec. 2009. Due to "continuing resolution," spending and monies received are behind schedule. ONR has fixed this problem as of the date this report was written.

Recv'd from ONR to-date	Planned expenditures to-date	Actual expenditures to-date	Balance
$43K	$48K	$37K	$6K

8. Upcoming Events

ONR/Army review of Penn State Vertical Lift Research Center of Excellence, approximately April 2010.

9. Publications and Patents

The PSU-internal patent application for extension-twist coupled energy absorbers as proposed in this investigation was filed in 2008. This has moved ahead to a formal patent application with the US Patent Office.

10. Presentations & Interactions

Discussed availability of cylinder- or annular-shaped energy absorbing foams from Plascore Inc. New Fairfield, CT (Nick Ogrizovich, representative for Central PA region). They have rolled open cell (1/16th inch) aluminum 5052 sheets into cylinders of almost-zero to some specified inner radius. While this is an attractive way to make tubular and cylindrical foams of considerable energy dissipation capability, the open cell geometry offered by Plascore is not attractive for the naval environment.

Discussed stitching machines with Neal Lund, NIT, Inc. Centerville, Utah, for making stitch-ripping FMC tubes. It was determined that a custom machine for stitching FMC tubes is prohibitively expensive for this project. Such a machine is therefore deemed "off the table" for the current project unless a low-cost way of doing the stitching can be found.

Discussed primers for improving the bond of FMC tubes to metallic end fixtures with Rick Clark and Brian Stull of Lord Corp. This discussion led to the adoption of Lord 7650 supplementary adhesive for use with the sandwich core device.

11. Degrees Awarded

Tiwari, C., "Innovative Energy Absorbing and Load Limiting Devices Based on Composite Tubes," MS Thesis in Aerospace Engineering, The Pennsylvania State University, Aug. 2009.

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