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Finite Element and Experimental Analysis for the Performance of Hybrid Composite Tubes under Crushing

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Abstract: An Experimental and finite element analysis for axial crushing of hybrid composite tubes of different fiber combinations as cotton, glass and carbon has been carried out throughout this investigation. One size of tube has been selected with a length of 110 mm and 90 mm diameter. These composite tubes were fabricated using the filament winding process. Cotton, glass and carbon fibers were selected to be the reinforcement materials. While epoxy resin and hardener have been used to form the matrix required for the fabrication of the composite tubes.

All the composite tubes were fabricated from six layers. The first three types of tubes were of fully cotton, fully glass and fully carbon type fibers. The other three tubes were done by using all the three types of fibers to form a hybrid type. Each two layers have been made of the same type of fiber.

Compression tests were carried out for all the tubes fabricated. Three tests were done for each type in order to get better results consistency. Load-displacement graphs were drawn for each test. The initial crushing and mean loads were obtained for each case and then drawn against the type of hybrid. The specific energy absorption has also been plotted for each case.

Finite element analysis for tubes of the same dimensions and materials were done for the elastic behavior region. A comparison was done for the tested composite tubes between the finite element and the experimental results.

Results obtained from this study shows that carbon fiber tubes stands higher load than glass fiber and cotton fibers. For hybrid types tested, tubes with the external layer of carbon shows higher strength than those of internal carbon fiber layers.

It has also been found that the difference between the experimental and finite element results at the elastic region of load-displacement response falls in the range of 1.3 to 14%.

Keywords: Hybrid Composite Material, Energy Absorption, Cotton fiber, Glass Fiber, fiber, Epoxy Resin

Notation

- A — Cross-section area.
- CF — Carbon fiber
- CCC, GGG, CoCoCo — Six layers of fully Carbon, Fully glass and fully cotton fibers respectively with epoxy resin matrix
- CGG, GCG, GGC — Six layers of carbon-glass-glass, glass-carbon glass and glass-glass-carbon respectively with epoxy resin matrix
- Co — Cotton fiber
- D_1, D_2 — Internal and external diameters of the tube.
- GF — Glass fiber
- h_c — Crush distance.
- $\bar{P}$ — Mean crush load.
- P — Applied load.
- PEEK — Poly ether ether keton
- E_S — Specific energy absorption
- t — Wall thickness.
- σ — Mean crush stress
- ρ — Density

Introduction

Composite structures have a wide range of applications because of their high stiffness and strength with respect to their weight. In addition, composite materials have high corrosion resistance, thermal expansion, high thermal resistively and considered as non conductive materials.

Wide range of composite material structures have been tested and collected by Jones *et al.* (1999). These structures include flat plates, cylinders, tubes, channels and many others. Usually, axial tension, compression, bending and pressure loading modes are used.

Composite structures could stand high loads and provide a significant increase in the energy absorption when compared to similar metal structures.

The energy absorption capability of composite structures is dependent upon the mechanism by which the structure collapse. Much of the experimental work on the energy absorption of composite materials has been restricted to the axial compression of axisymmetric cylindrical tubes. One end of the tube is chamfered to initiate crushing. Failure starts at the chamfer tip, and the damage zone propagates down the tube without catastrophic fracture Singalas, *et al.*, (1991). Many investigations have been carried out to determine the effects of; tube geometry Fairfull *et al*, (1987) and Khalid *et al.* (1999, 2000), fiber architecture Berry, (1984) fiber type Farley, (1987), resin type Steffen Kerth *et al.* (1996) and testing conditions Ramakrishna, (1992) and Khalid, *et al.* (2001) on the energy absorption capability.

Hamada *et al.*, (1992), investigated that the thermoplastic composite tubes (Carbon/ PEEK) absorb higher energy than the thermoset composite tubes (Carbon/ Epoxy). Hamada and Ramakrishna, (1996), found that the Quasi-static tested tubes displayed higher specific energy absorption than the impact-tested tubes for carbon (PEEK) composite.

Hamada, (1995), developed a calculation method to predict the mean crushing load. The method was applied to GF cloth/ epoxy and CF/ PEEK composite tubes. He concluded that the predicted values were similar than experimental values, and the difference was larger in the case of CF/ PEEK than GF/ epoxy.
Hybrid composite, where multiple fiber types exist in a single matrix, further increase the functionality of composites by allowing the designer to add selectivity stiffer, more costly fibers where the stresses are more critical and add less costly fibers where the stresses are less critical Karbhari *et al.*, (1997) and Brachos *et al.*, (1995).
The main objectives of this present investigation are to determine the energy absorption of hybrid composite tubes and to compare it with the single fiber/ epoxy composite tubes. Also to study the effect of laminate sequence type on the energy absorption of the hybrid composite tubes.

Test specimens Properties
circular cross-section tubes of composite materials were fabricated using a filament winding method. These tubes were fabricated of six composite layers.
The different properties for this type of composite material were found by casting flat plates of the same fiber and matrix types as those used for the cylinders fabrication. The properties developed are :-

Cotton/ epoxy

- Young Modulus, E_{11}= 1.78 GN/m^2, E_{22} = E_{33}= 0.77 GN/m^2 ,
- Poisson's ratios, ν_{12} = 0.40 , ν_{13} = ν_{23} = 0.70
- Modulus of rigidity, G_{12} = 0.26 GN/m^2 , G_{13} = G_{23} = 0.65 GN/m^2 .

Glass / epoxy

- Young Modulus, E_{11} = 52.33, E_{22} = E_{33} = 12.08 GN/m^2 .
- Poisson's ratios, ν_{12} = 0.23 , ν_{13} = ν_{23} = 0.4
- Modulus of rigidity, G_{12} = 4.81 GN/m^2 , G_{13} = G_{23} = 3.19 GN/m^2 .

Carbon/ epoxy

- Young Modulus, E_{11} = 133.4 GN/m^2, E_{22} = E_{33} = 8.78 GN/m^2 .
- Poisson's ratios, ν_{12} = 0.26 , ν_{13} = 0.26 , ν_{23} = 0.36
- Modulus of rigidity, G_{12} = 3.25 GN/m^2 , G_{13} = 3.25 GN/m^2, G_{23} = 3 GN/m^2

Using the above properties, the compliance [S_{ij}] matrix terms could be calculated as :-

$$S_{XX}=\frac{1}{E_{11}},\; S_{XY}=\frac{-\nu_{21}}{E_{22}},\; S_{XZ}=\frac{-\nu_{31}}{E_{33}},\; S_{YY}=\frac{1}{E_{22}},\; S_{YX}=\frac{-\nu_{12}}{E_{11}},\; S_{YZ}=\frac{-\nu_{32}}{E_{33}}$$

$$S_{ZZ}=\frac{1}{E_{33}},\; S_{ZX}=\frac{-\nu_{13}}{E_{11}},\; S_{ZY}=\frac{-\nu_{23}}{E_{22}},\; S_{HYZ}=\frac{1}{G_{23}},\; S_{HZX}=\frac{1}{G_{31}},\; S_{HXY}=\frac{1}{G_{12}}$$

These terms are important to be evaluated and used in the finite element stage of this study. On the other hand, the composite material selected for this study was of an orthotropic material. The epoxy resin (type LECO 811-563-103) and hardener (type LECO 811-563-103) have been used throughout this investigation and obtained from the LECO corporation (USA). The glass fiber used was of 0.3 X 3 mm cross-section (type C glass), while the cotton fiber was of ϕ 0.3 mm diameter. The average volume fraction for cotton/epoxy and glass/epoxy used were 62 and 52% respectively. All the specimens fabricated were cured at room temperature (32C°) for 24 hours to provide an optimum hardness and shrinkage.

Experimental and Finite Element Analysis: Axial compression tests were carried out for each type of tubes fabricated. Six layer tubes were tested. Three tests were done of each type and the average first crush load was evaluated.
Finite element analysis has also been carried out. Shell element was used to create the basic shell geometry for each type. A sample of the original and deformed shape of the hybrid composite tubes are shown in Fig. 1.
Simulating the experimental work, the finite element models also consists of fixing one end and loading the other end using an incremental loading for the compression case. LUSAS finite element package has been used for this part of investigation.
The properties, evaluated experimentally and listed in the test specimens section were used as an input material properties for the finite element program. Each model then run for several loads while displacement and stresses are the interesting issue to be obtained. These results were evaluated at the points below the load simulating the experimental work and for effective comparison.

Experimental Set-up:
Filament Winding Equipment Set up:
The equipment designed and fabricated for this project. It consists of two motors, a mandrel and threaded rotating shaft. Both motors were provided with speed controllers. In order to fabricate a composite tube, the fiber was taken from a creel then pass on a series of pulleys to a carriage fitted on the rotating threaded shaft. Finally the fiber will be wound on the cylindrical mandrel to form the composite tube required. One of the pulleys is immersed in a cup containing the mix of epoxy resin and hardener. This equipment has been designed to be flexible to make composite tubes with different fiber orientation. The fiber orientation is controlled by adjusting the two speeds of the two main motors.

Composite Tubes Fabrication: Composite tubes were fabricated by using the filament winding process and tested under axial compression by using the computerized Instron machine. All tested composite tubes were made of six composite layers of different fiber types, different fiber laminate sequence and a fiber orientation angle of 90° was selected. Tube length of 110 mm and internal diameter was 90 mm were selected for all the tested specimens. One end of each tube was chamfered by an angle of 45°, so that crushing could be initiated without causing catastrophic failure of the specimen. Fig. 2 shows a sketch of typical composite tube specimen. The matrix used for all the cylinders was prepared from mixing of epoxy resin and hardener at 8:1 ratio. Six types of tubes were fabricated depending on the fiber type. The first three were fully made of cotton fiber, glass fiber or carbon fiber. The other three were of a mix where each two layers were made of each fiber from the three types of fibers selected.

Test Procedure: Constant slow speed compression testing was performed using a Computer-controlled servo-hydraulic Instron machine type (8500) with a load capacity of 250 kN. The cross-head speed was adjusted at 2.5 mm/min. Composite tubes were axially crushed between parallel steel flat platens, one static and one moving. The fixed platen was fitted with a load cell from which the load signal was taken directly to the computer. In each test, the crush load was plotted on the Y-axis and the cross-head displacement on the X-axis. For all composite tubes axial compression tests, progressive crushing occurred.
To initiate progressive crushing, a 45° chamfer was ground onto one end of the tube. A sketch of typical tube specimen is shown in Fig. 2.

Results

Compression tests were carried out for each composite tubes. These tests were done for each type to observe results consistency and accuracy.
Results from this investigation includes the load-displacement response and the energy absorption relations for composite tubes. The effect of using different fibers were studied on the load-displacement and the energy absorption response. On the other hand, Load-displacement response were drawn for the composite tubes.

Load-Displacement Results

Load-displacement curves for six layers of fully cotton/epoxy, glass/epoxy and carbon/epoxy tubes respectively are shown in Fig. 3. Initially the load increased linearly to a peak value then a large number of stabile crush load fluctuation occurs till the compaction or failure of the tube. As shown from this figure, the carbon/epoxy tubes stands higher initial and mean crush load than other tested types. Fig. 4 shows the effect of using hybrid composite cylinders under axial compression loading. Cylinders with external layer carbon fiber/epoxy improves the load displacement response and stands higher load than that of internal carbon fiber layer. Finite element load-displacement relations at the elastic region were drawn in Figs. 5 and 6 for the tested composite tubes. Fig. 7 shows the effect of laminate sequence on the initial and mean crushing load of the tested composite tubes. It appears that the initial crushing load was higher than the mean value of the load fluctuations for all tested tubes.

Specific energy absorption: The energy absorbed during progressive crushing of composite tube is defined as the area under the load-displacement (P-d) curve. For composite tubes of uniform cross section, the mean crush load ($\bar{P}$) is independent of the crush distance(Hamada *et al.*, 1992). Hence, the specific energy absorption (E_S) is given by :

$$E_S = \frac{\bar{\sigma}}{\rho} = \frac{\bar{P}}{A\rho} \qquad (1)$$

where

σ : mean crush stress ,

$\bar{P}$: mean crush load ,

ρ : the density of the material, for circular cross-section area:

$$A = \frac{\pi}{4}\left(D_2^2 - D_1^2\right) \qquad (2)$$

D_1, D_2 : The internal and external diameters of the section undergoing crush respectively.
The specific energy absorption has been calculated for all the tested composite tubes.

Fig. 5 shows the effect of laminate sequence of the composite cylinders on the specific energy absorption. As shown from this figure the fully six layers of carbon/epoxy gives highest value of 40 kJ/kg energy absorbed. While the fully six layers of cotton/epoxy gives the lowest value of 8.4 kJ/kg. Also it appears that there is a significant change in energy absorption values when the laminate sequence changes. The test specimens dimensions and the axial compression results ore shown in Table 1.

Table 1:Uniaxial Compression Test Results for Tested Composite Tubes

	CCC	CGG	GCG	GGC	GGG	CoCoCo
Initial Crushing Load, $P_{Initials}$(kN)	135	110	85	61	50	26
Mean Crushing Load, P,(kN)	118	100	78	54	44	21
Wall Thickness t (mm)	6.1	6.4	6.5	6.3	6.3	4.8
Density, ρ (gm/Cm^3)	1.6	1.7	2	1.7	1.7	1.4
Specific Energy Absorption Es, (kJ/kg)	40.0	26.1	17.3	16.9	11.7	8.4

Discussion and Conclusion

The equipment designed and fabricated to conduct the filament winding for tubes of different cross section area and different fiber orientation angles.
It has been observed that the thickness for all the cylinders changed in the range of ± 0.25 mm. Tests were conducted carefully for all the specimens. The average of three tests were taken for each type of composite tubes.
Load-displacement graphs extracted from this investigation show the same trend when compared to other investigations [our previous and from literatures). It was shown that for composite tubes under axial compression, the average load fluctuation remains constant after initial crush up to failure. In addition, chamfering one end of the tube is necessary to initiate crush propagation with high stresses or loads and then the load-displacement trace fluctuating in a constant manner.
A similar trend have been found for the hybrid tube types but there is an effect on the overall performance of the tubes as load capability and absorbed energy.

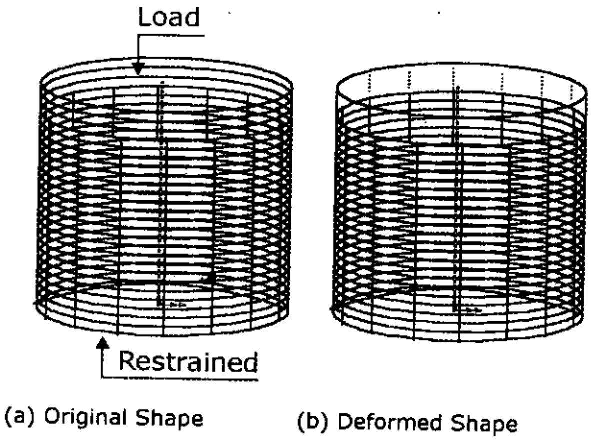

Fig. 1: Sample of Original and Deformed Mesh of Composite Cylinder

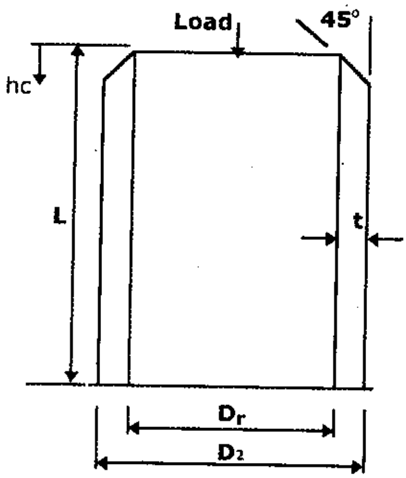

Fig. 2: Sketch of Typical Composite Tube Specimen

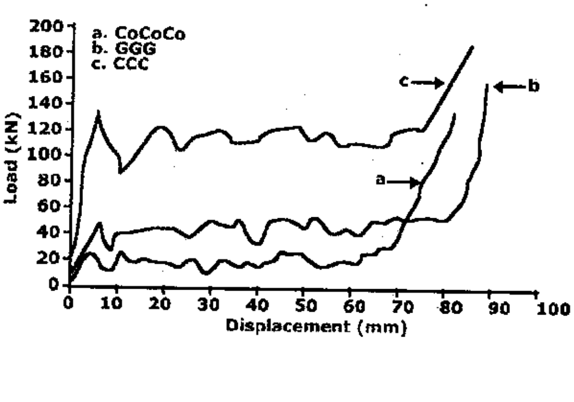

Fig. 3: Experimental Load-Displacement Relation for Six Layers of Composite Tubes

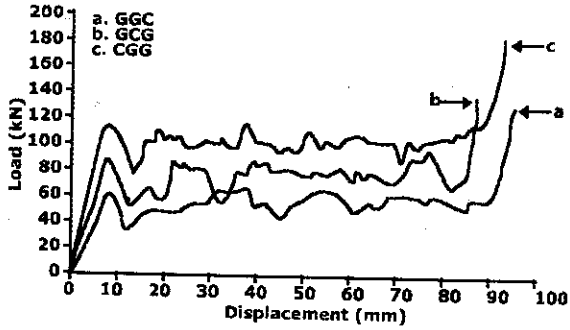

Fig. 4: Experimental Load-Displacement Relation for Six Layers of Hybrid Composite Tubes

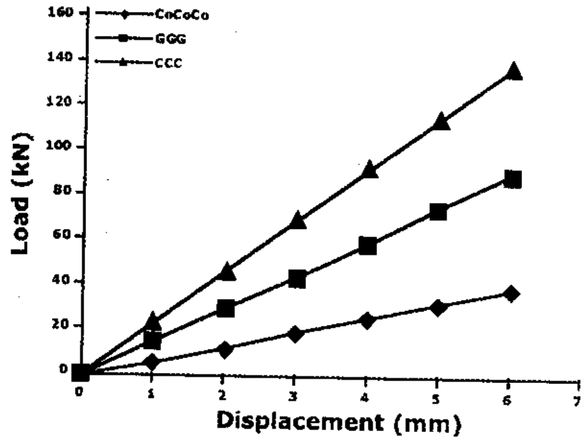

Fig. 5: Finite Element Load-Displacement Results for Six Layers of Composite Tubes

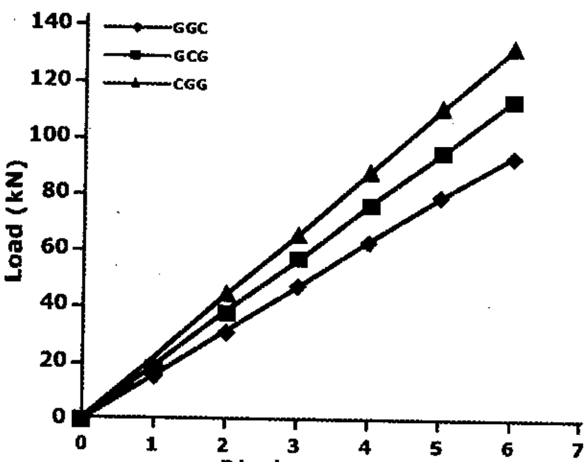

Fig. 6: Finite Element Load-Displacement Results for Six Layers of Hybrid Composite Tubes

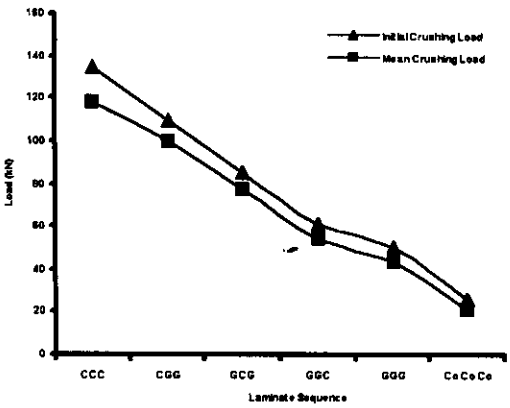

Fig. 7: Laminate Sequence Effect on the Initial and Mean Crushing Load

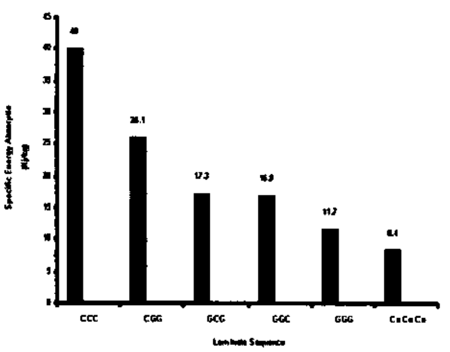

Fig. 8: Laminate Sequence Effect on Energy Absorption

Finite element elastic analysis results throughout this study were compared with the experimental results. Elastic line slops compared. The percentage difference between the theoretical and the experimental first crushing loads and the elastic line slops were also found. It could be noticed, that the difference in slop doesn't exceed the 14%. This is attributed to the fact that the orthotropic properties used to define the composite material for the finite element analysis were all the same for any position in the cone. On the other hand, the fabricated cones were having some small defects with small thickness variation even though they were done very carefully.

The main conclusions that can be drawn from this investigation are:

1. From the load-displacement relations it could be noticed that all the tested composite tubes crushed progressively and the load required is higher for the fully carbon/ epoxy composite tubes.
2. Hybrid composite tubes with external layer of carbon/epoxy shows higher standing load than those of internal carbon layers.
3. There is a small significant difference between the initial and mean crushing load for all the tested tubes. The initial crushing load is higher than the mean crushing load.
4. The glass fiber/epoxy tubes reinforced by carbon fiber crushed with a significant increase in energy absorption than the fully glass fiber/epoxy tubes.
5. The fully cotton/ epoxy composite shows the lowest standing load and lowest energy absorption than all the other tested tubes.
6. There is a slight difference in the specific energy absorption values for the glass/ epoxy tubes internally reinforced with carbon/epoxy.
7. The difference between experimental and finite element results at the elastic region is expected and found to be in the range of 1.3 to 14% for the elastic line slopes of the different cones tested.

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