Proceedings of COBEM 2005
18th International Congress of Mechanical Engineering
November 6-11, 2005, Ouro Preto, MG

ENERGY ABSORPTION CAPABILITY OF COMPOSITE TUBES UNDER COMPRESSION LOAD

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Abstract. *Automotive and aircraft crashworthiness have been improving over the years with the development of structures with high energy absorption capabilities, thus reducing the impact of the crash on passengers. Properties of composite materials can be tailored to provide specific energy absorption capabilities superior to those of metals and therefore can be an appealing option as a substitute of more traditional materials in crashworthiness applications. The present investigation evaluates the energy absorption properties of glass/polyester composite tubes. Specimens of circular and square cross-sections are manufactured and tested under compression load. Two different lay-ups are used: $[0/90]_n$ and $[\pm 45]_n$. A 45º chamfer was machined onto one end of the specimens working as a collapse trigger mechanism to initiate stable, progressive crushing, thus increasing the energy absorption. The influence of cross-sectional geometry and lay-up sequence on the energy absorbing capacity of the tubes and the efficiency of the trigger mechanism are examined and discussed. The primary results observed include a significant influence of the cross-sectional geometry on energy absorbing capacity given that stable progressive crushing occurred only in tubes of circular cross-section. Overall, specimens of circular cross-section with fibers oriented at $[0/90]_n$ showed the highest specific energy absorption.*

Keywords*: Composites, Crashworthiness, Energy Absorption, Compression Load.*

1. Introduction

Crashworthiness may be defined as the capability of a vehicle to protect its occupants from serious injury or death in case of accidents of a given proportion (Jacob *et al*., 2002; Laananen and Bolukbasi, 1995). Vehicle and aircraft crashworthiness has been a topic of great interest for engineers and scientists over the years. The main goal has been directed towards producing structures capable of absorbing energy, thus reducing the impact on the passengers. Thus, crashworthy efficient structures must be able to dissipate large amounts of energy.

Ultimately, the objective of engineers is to design vehicle structures where the maximum amount of energy is dissipated while the material surrounding the passenger compartment retains its functional integrity (Mamalis *et al*., 1997). Thus, the design may include strategically located energy absorbing devices. Properties of composite materials can be tailored to provide specific energy absorption capabilities superior to those of metals and therefore can be an appealing option as a substitute of more traditional materials in crashworthiness applications.

High specific mechanical properties such as stiffness and strength are some of the important advantages of composite materials. Moreover, the design flexibility and reduced weight are indeed advantageous, especially to the automotive and aircraft industries. With composite materials, structures can be designed with using a variety of reinforcement type and orientation, various matrix materials, and lay-up sequences, to produce composites with improved material properties. Previous investigations have indicated that the energy absorption mechanisms in composite materials are more complex than those observed in conventional materials, and include matrix cracking, delamination, and fiber breakage (Mamalis, *et. al.*, 1997).

In addition to the material properties, in the event of a collision the dissipated energy depends on geometry factors. Trigger mechanisms can be used to control collapse in the event of a collision, increasing the dissipated energy. A trigger is a stress concentrator, which is located at a specific location within the structure, to cause failure in a progressive crushing mode. The effects of the type of composite material, laminate design, specimen geometry (such as wall thickness and specimen length), loading method and strain-rate on the energy absorption capability of the components have been investigated, by many authors (Mamalis *et al*., 1997; Carruthers, 1997; Jacob *et al*., 2002). Moreover, the influence of environmental effects on the crashworthy behavior composites components has also been studied (Mamalis *et al*., 1997).

Many materials used in crashworthy structures - such as polymeric matrix composites - are sensitive to crushing speed. Energy absorption dependence on the rate of applied stress has been related to the mechanism which controls the crushing process (Mamalis *et al*., 1997). Hence, the energy absorption associated with interlaminar crack growth may be considered as a function of the crushing speed due to the viscoelastic behavior of the polymeric matrix, while fracture of brittle fibers is less dependent on strain rate (Farley, 1991).

In the event of a collision, the structure is subjected to a load of decreasing speed, from the initial impact speed to rest, as the material is crushed. An adequate simulation of these conditions may be obtained through impact tests. However, since the whole crushing process may take place in a fraction of a second, these tests are complicated to control and often require expensive equipment to study the failure mechanisms, such as high-speed camera. Therefore, laboratory crush tests have been carried out not only under impact, but also under quasi-static conditions (Jacob *et al.*, 2002). Quasi-static crush tests, are carried out at a constant speed, and therefore, are simple and easy to control. Hence, they have been used, by many authors, to study energy absorption properties of composite components (Bannerman and Kindervater, 1986; Laananen and Bolukbasi, 1995; Hamada and Ramakrishna, 1995; Hamada *et al.*, 1992; Lavoie and Kellas, 1996). By selection of appropriate crushing speeds, quasi-static tests may provide important information regarding the failure mechanisms and energy absorption capability of composite structures in crushing conditions.

Although extensive research work has been performed on the energy absorption properties of composite structures, their crushing behavior is very complex and conflicting results are still being produced (Mamalis *et al*., 1997). Topics such as the effects of processing conditions and matrix properties on the energy absorbing capacity of composites need more investigation. Therefore, additional research is needed to study the energy absorption behavior of practical composite structural elements and to develop a better understanding of the crushing mechanisms which will support the design of composite structures for crashworthiness applications.

Tubular elements are widely used as structural components and most of the existing work on the energy absorption capability of FRP's has focused on tubular specimens (Carruthers, 1997; Bannerman and Kindervater, 1986). Following these previous works, the present investigation evaluates the energy absorption properties of glass/polyester composite tubes. Specimens of circular and square cross-sections are manufactured and tested under compression load. Two different lay-ups are used: $[0/90]_n$ and $[\pm 45]_n$. A 45º chamfer was machined onto one end of the specimens working as a collapse trigger mechanism to initiate stable, progressive crushing, thus increasing the energy absorption. Based on the experimental results of the two geometries and two lay-ups tested, the influence of cross-sectional geometry and lay-up sequence on the energy absorbing capacity of the tubes and the efficiency of the trigger mechanism are examined and discussed.

2. Experimental Program

2.1. Materials and test specimens

The test specimens used in the crush tests were tubes of circular and square cross-sections. Two 40cm long molds were prepared for specimen fabrication: an aluminum tube of circular cross-section with 50mm of external diameter, and a wooden mandrel of 50x50mm square cross-section. For the wooden mandrel a corner radius of 5 mm was machined to facilitate fabrication and to reduce fiber damage at the corners. Then, a resin layer was applied for a better surface finish. For an ease removal of the tubes from the molds, cellophane paper was wrapped on all molds, in addition to a mold release wax (carnauba wax based TEC GLAZE-N) applied on the mold surface. The two molds used are shown in Fig. 1.

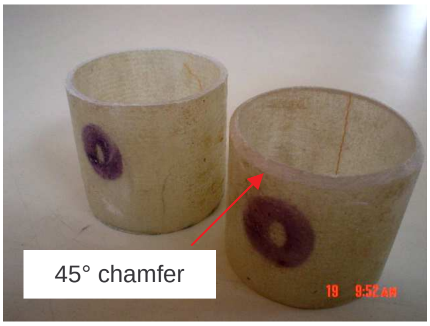
Figure 1 - Molds for specimen fabrication.

All specimens were fabricated using polyester (orthophthalic) resin and a balanced plain weave fabric E-glass ($120 g/m^2$). The unsaturated polyester resin used was prepared with 1% MEKP initiator. The tubes were fabricated by mandrel wrapping of the fabric pre-impregnated with resin. Two different lay-ups were used: $[0/90]_n$ and $[\pm 45]_n$, with respect to the longitudinal axis of the tube. The lay-ups were defined by the orientation of the fabric wrapped on the mandrel. A total of 18 layers of glass/polyester were used to produce a cured nominal wall thickness of 3mm. Brushes and rollers were used to remove excess resin, porosities and air bubbles and to improve compaction.

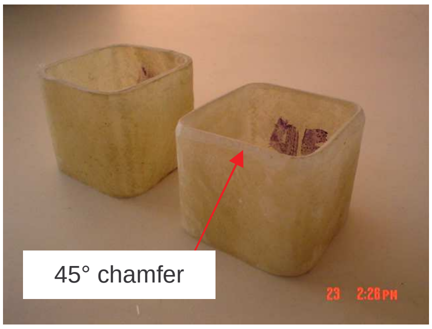
The fabricated tubes were allowed to cure for 24h at ambient temperature before they were removed from the molds. Once removed from the molds, the fabricated tubes were cut into specimens 50 mm long with square ends, using a diamond abrasive saw. Five test specimens were fabricated from each tube. Also, to initiate progressive crushing, a 45° chamfer trigger was machined onto one end of some test specimens using an abrasive disk. In addition, three specimens were collected from each tube for the determination of the material density to allow the computation of the specific energy absorption. A total of eight tubes were produced as described in Tab. 1. Figure 2 shows the test specimens produced.

Table 1 – Composite tubes produced.

Cross-Section	**Circular**				**Square**			
Fiber Configuration	$[0/90]_n$		$[\pm 45]_n$		$[0/90]_n$		$[\pm 45]_n$	
Type of Specimens	square ended	chamfered	square ended	chamfered	square ended	chamfered	square ended	chamfered



(a)



(b)

Figure 2 - Specimens of circular (a) and square (b) cross-sections.

2.2 Determination of material density

For the determination of the material density, the composite specimens were weighed on a laboratory scale. Then, the specimens were embedded in a paraffin wax of known density and weighed again. After that, the impermeable specimens were submerged in water and the displacement of water was used to determine the volume of the specimen (composite material and paraffin). The volume of the paraffin wax was then subtracted and the density was calculated as the mass of the composite specimen divided by its volume.

2.3. Crush testing procedure

The mechanical tests were carried out using a Shimadzu Autograph 100kN universal testing machine, in quasi-static compression testing mode. All tests were conducted under a displacement-controlled mode with cross-head speed of 5.0mm/min. Quasi-static tests with testing speeds of 1.0, 1.25, 2.5 and 12.0mm/min, have been reported in the literature (Hamada *et al.*, 1992; Lavoie and Kellas, 1996; Hull, 1991). In the present work, a testing speed of 5.0mm/min was used to allow observation of the crushing process and, yet, avoid time-consuming tests.

The compression tests were carried out to investigate the energy absorbing capacity of the specimens during compressive crushing. Thus, based on the measurements, the effects of fiber architecture, specimen geometry and chamfer trigger on the energy absorption of the composite specimens can be studied.

3. Results and Discussion

Square-ended (unchamfered) specimens were produced for the determination of the compressive strength of each cross-section type and fiber orientation. The results of compressive strength measurements for all specimens are shown on Tab. 2, which presents the mean value and the standard deviation. For both fiber configurations studied, $[0/90]_n$ and $[\pm 45]_n$, specimens of square cross-section failed at lower stress levels. This behavior may be attributed to stress concentration at the corners, which caused premature failure of the specimens (Fig. 3).

Table 2 – Compressive strength of square-ended (unchamfered) specimens.

Cross-Section	**Circular**				**Square**			
Fiber Configuration	$[0/90]_n$		$[\pm 45]_n$		$[0/90]_n$		$[\pm 45]_n$	
Strength / Standard deviation	σ (MPa)	S (MPa)	σ (MPa)	S (MPa)	σ (MPa)	S (MPa)	σ (MPa)	S (MPa)
	110.5	11.6	73.6	15.4	79.7	10.3	50.8	13.9

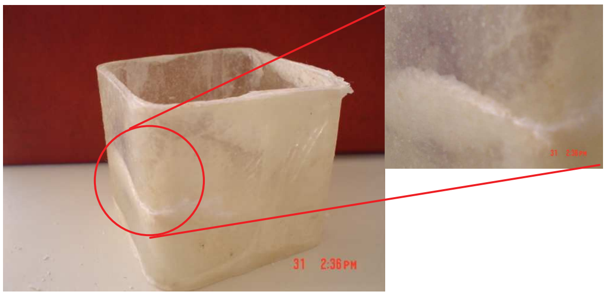


Figure 3 – Cracks on square cross-section specimens.

Load-displacement curves for all chamfered specimens are shown in Figs. 4 to 7. As shown in these figures, progressive crushing occurred only in specimens of circular cross-section (Fig. 4 and Fig. 5).

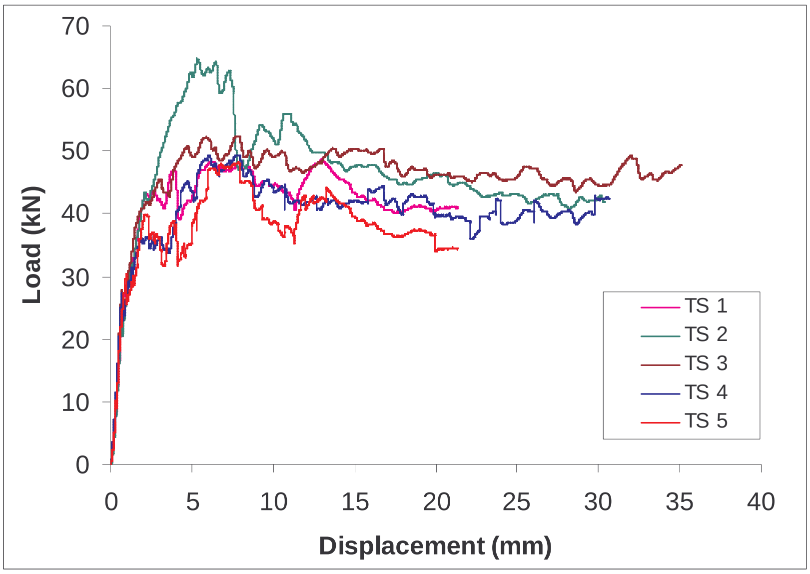


Figure 4 - Load-displacement curves for $[0/90]_{18}$ specimens of circular cross-section.

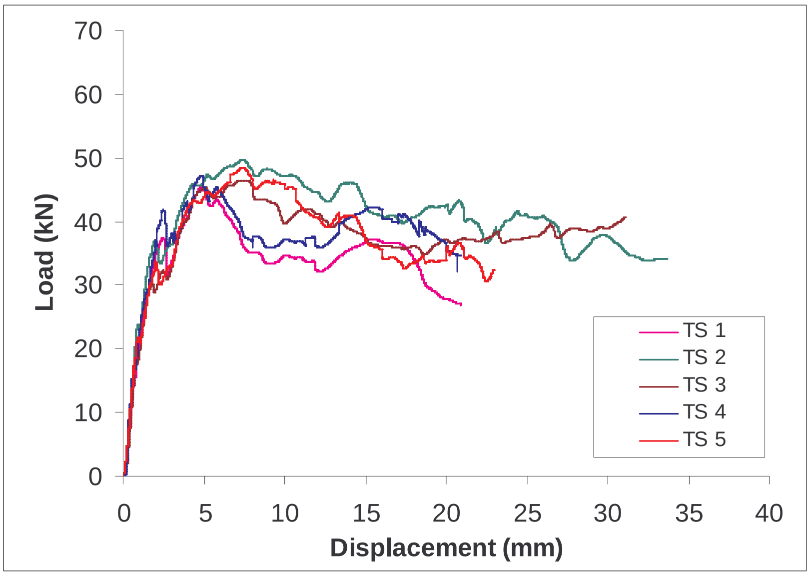


Figure 5 - Load-displacement curves for $[\pm 45]_{18}$specimens of circular cross-section.

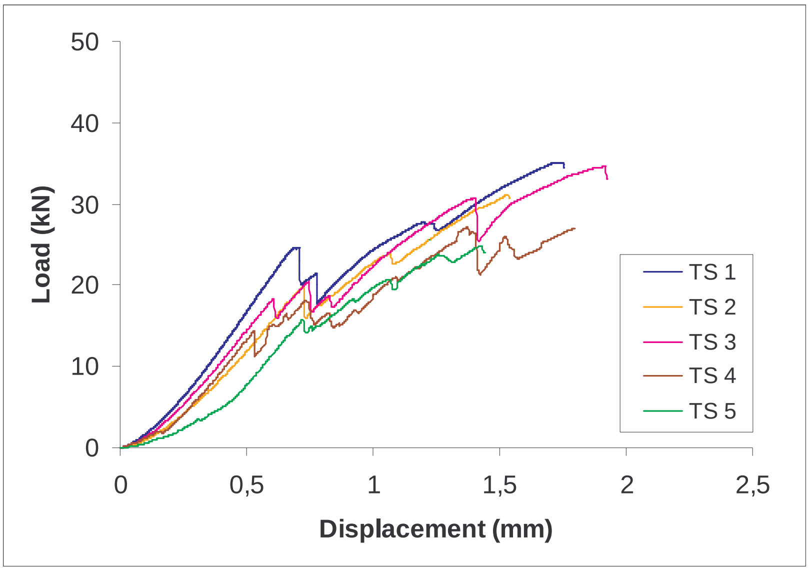


Figure 6 - Load-displacement curves for $[0/90]_{18}$ specimens of square cross-section.

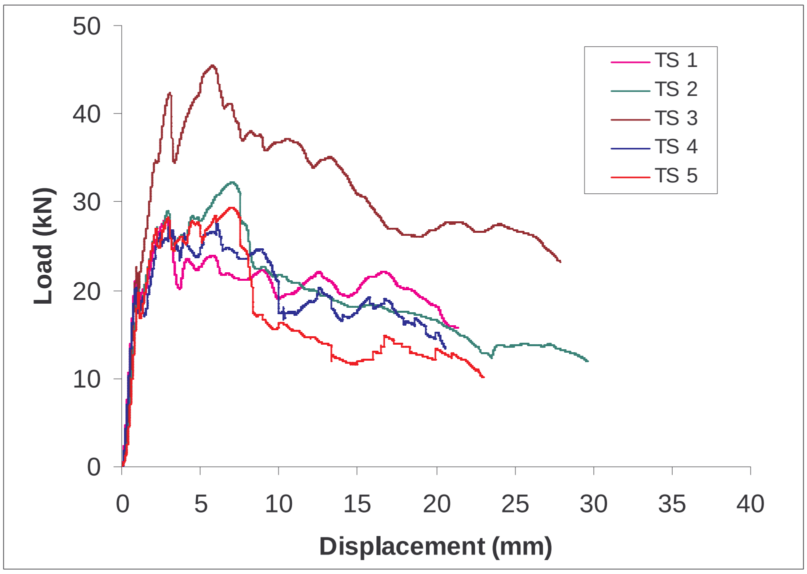


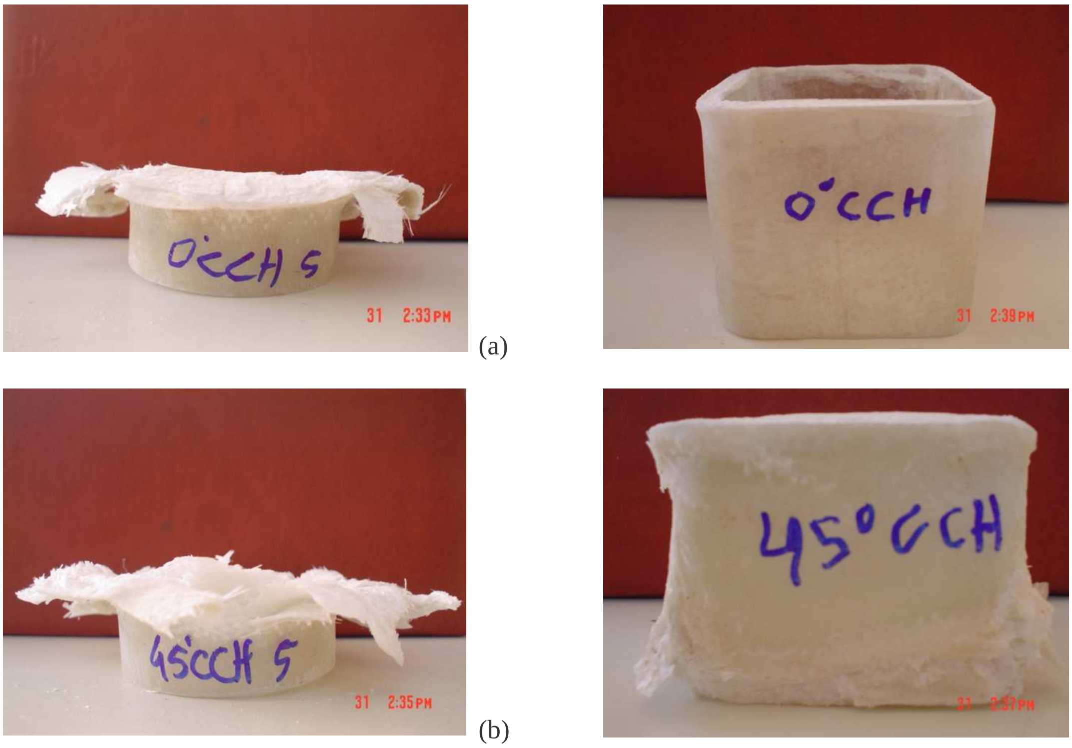
Figure 7 - Load-displacement curves for $[\pm 45]_{18}$ specimens of square cross-section.

According to the curves presented in Figs. 4 and 5, for circular cross-section tubes, the load increased to a peak value and a progressive crushing is then triggered as the chamfer region is crushed. The progressive crushing mode observed in the circular cross-section specimens is characteristic of splaying crush mode (Hull, 1991). The crushed specimens exhibited large interlaminar and intralaminar cracks. This crushing mode is typical in tubes with brittle fiber reinforcement, where the main energy absorbing mechanism is matrix crack growth. The appearance of the crushed zone for the circular cross-section specimens is shown in Figs. 8.a and 8.b.

In square cross-section specimens, even with the chamfer trigger, progressive crushing did not occur (Figs. 6 and 7). In these cases, the chamfer was compressed flat (Figs. 8.c and 8.d) and thus, the trigger mechanism did not initiate progressive crushing. The failure mode observed was the same as in the unchamfered specimens. The presence of cracks at the corners, at relatively low stress levels, ultimately caused the failure of the specimens before any progressive crushing could take place. Cracking noises could be heard during these tests, corresponding to drops in load shown in Figs. 6 and 7.

Since the specimens of square cross-section did not show stable progressive crush, the specific energy absorbed was calculated only for the tubes of circular cross-section. Specific energy absorption is defined as the energy absorbed per unit mass of material, *i. e.*, $Es=\sigma/\rho$, where ρ is the density of the composite material and σ is the mean crush stress

(Jacob *et al.*, 2002). The mean crush stress was computed based on the mean crush load and the cross-sectional area of the specimens. A material density of 1.7 g/cm^3 (1700 kg/m^3) was determined according to the procedure previously described, from three specimens collected from each tube. The mean crush load, mean crush stress and specific energy absorbed for these tube specimens are presented in Tab. 3.



(a) (c)
(b) (d)

Figure 8 - Failure modes of chamfer-triggered specimens: (a) $[0/90]_{18}$ (circular); (b) $[\pm 45]_{18}$ (circular); (c) $[0/90]_{18}$ (square); and (d) $[\pm 45]_{18}$ (square).

Table 3 – Specific energy absorption for specimens of circular cross-section.

Fiber configuration	Mean crush load, *P* (kN)	Mean crush stress, σ (MPa)	Specific energy absorption, *E* (kJ/kg)
$[0/90]_{18}$	43.5	90.4	53.2
$[\pm 45]_{18}$	39.0	61.4	36.1

The specific energy absorption data for circular tube specimens using plain weave fabric (Tab. 3) show higher values for the $[0/90]_{18}$ lay-up compared to $[\pm 45]_{18}$. Previous investigations (Thornton and Edwards, 1982) have reported the same trend observed in the present investigation. Further, circular cross-section tubes have been reported as more effective to absorb energy than the square and rectangular ones (Thornton and Edwards, 1982). The lower specific energy absorption of square and rectangular sections has been related to stress concentrations at the corners, which contributes to the formation of splitting cracks and leads to unstable collapse with low energy absorption.

In summary, according to the results presented, only tubes of circular cross-section were able to undergo progressive crushing. Between tubes of circular cross-section studied, the experimental results show that tubes with fibers oriented at $[0/90]_n$ displays the highest absorbed energy. The results presented in this work also indicate that the methodology used produces results which are in agreement with those published in the literature.

4. Future Work

The rudimentary compaction method used in this work may lead to a high level of porosity and air bubbles. Porosity is known to play an important role especially in the shear properties of composites. More controlled processing conditions to fabricate the test specimens – such as vacuum bagging – are known to reduce the effects of porosity and improve compaction and therefore may also affect the energy absorbing capacity. Thus, the effect of the manufacturing conditions on the specific energy capacity should be investigated.

Previous investigations have reported that the specific energy absorption of composites is a linear function of the matrix resin properties, such as tensile strength, tensile modulus (Thornton and Jeryan, 1988), compressive strength (Tao *et al*., 1993), failure strain (Jacob *et al*., 2002), and fracture toughness, which inhibits crack growth (Hamada *et al.*, 1992; Hamada *et al.*, 1995; Hamada *et al.*, 1996). Polymer matrix composite materials are known to display viscoelastic behavior, which is related to the dissipation of energy. An experimental program to investigate the energy absorption properties of composite materials considering the viscoelastic properties of the polymeric matrix is also planned. The influence of the viscoelastic properties of the matrix on the energy absorbing efficiency of composite materials will be studied. The understanding of the role of polymeric matrix properties on the energy absorption capability of composite materials is very important.

5. Conclusions

In this investigation, the specific energy absorption properties of glass/polyester composite tubes have been evaluated. Specimens of circular and square cross-sections were manufactured and tested under compressive quasi-static load. Two different lay-ups were studied: $[0/90]_n$ and $[\pm 45]_n$. A 45º chamfer was machined onto one end of the specimens, working as a collapse trigger mechanism to initiate stable, progressive crushing, thus increasing the energy absorption.

Based on the experimental results, it can be concluded that:

- In tubes of circular cross-section, the chamfer trigger was able to initiate failure in a stable progressive mode which increases substantially the absorbed energy.
- The highest specific energy absorption was obtained with tubes of circular cross-section with fibers oriented at $[0/90]_n$.
- In tubes of square cross-section, the chamfer trigger proved ineffective since stress concentrations at the corners caused premature failure of the specimens before any progressive crushing could take place.

6. References

Bannerman, D.C. and Kindervater, C.M., 1986, “Crash Impact Behavior of Simulated Composite and Aluminum Helicopter Fuselage Elements”, Vertica, Vol. 10, No. 2, pp. 201-211.

Carruthers, J.J., 1997, “Some Aspects of the Energy Absorption of Composite Materials”, PhD Thesis, University of Sheffield.

Farley, G.L., 1991, “The Effect of Crushing Speed on The Energy-Absorption Capability of Composite Tubes”, Journal of Composite Materials, Vol. 25, pp.1314.

Hamada, H., Coppola, J.C., Hull, D., Maekawa, Z, and Sato, H., 1992, “Comparison of Energy Absorption of Carbon / Epoxy and Carbon / PEEK Composite Tubes”, Composites, Vol. 23, No. 4, pp. 245-252.

Hamada, H. and Ramakrishna, S., 1995, “Scaling Effects in The Energy Absorption of Carbon-Fiber/PEEK Composite Tubes, Composites Science and Technology”, Vol. 55, pp. 211-221.

Hamada, H., Ramakrishna, S. and Sato, H., 1995, “Crushing Mechanism of Carbon Fibre / PEEK Composite Tubes”, Composites, Vol. 26, No. 11, pp. 749-755.

Hamada, H., Ramakrishna, S. and Sato, H., 1996, “Effect of Fiber Orientation on the Energy Absorption Capability of Carbon Fiber / PEEK Composite Tubes”, Journal of Composite Materials, Vol. 30, No. 8, pp. 947-963.

Hull, D., 1991, “A Unified Approach to Progressive Crushing of Fiber Reinforced Composite Tubes”, Composites Science and Technology, Vol. 40, pp. 377–421.

Jacob, G.C., Fellers, J.F., Simunovic, S. and Starbuck J.M., 2002, “Energy Absorption in Polymer Composites for Automotive Crashworthiness”, Journal of Composite Materials, Vol. 36, No. 07, pp. 813-850.

Laananen,D.H. and Bolukbasi, A.O., 1995, “Prediction of Energy Absorption in Composite Stiffeners”, Composite Structures, Vol. 32, pp. 173-186.

Lavoie, J.A. and Kellas, S., 1996, “Dynamic Crush Tests of Energy-Absorbing Laminated Composite Plates”, Composites Part A, Vol. 27A, pp. 467-475.

Mamalis, A.G., et. al., 1997, “Crashworthy Capability of Composite Material Structures”, Composite Structures, Vol. 37, pp.109-134.

Thornton, P.H. and Edwards, P.J., 1982, “Energy Absorption in Composite Tubes”, Journal of Composite Materials, Vol.16, pp. 521.

Thornton, P.H. and Jeryan, R.A., 1988, “Crash Energy Management in Composite Automotive Structures”, International Journal of Impact Engineering, Vol. 7, No. 2, pp. 167-180.

Tao, W.H., Robertson, R.E. and Thornton, P.H., 1993, “Effects of Material Properties and Crush Conditions on the Crush Energy Absorption of Fiber Composite Rods”, Composites Science and Technology, Vol. 47, pp. 405-418.

7. Responsibility notice

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