Energy absorption capability of low-cost composite materials

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ABSTRACT

This paper presents a study of energy absorption capability of pultruded glass fibre-reinforced polyester tubes. Compression tests were conducted with three different jig geometries and two different chamfer angles. The results show that the energy absorption capability is very much affected by the geometry of the test specimens. Changing from 65 mm inner diameter and 5.0 mm wall thickness to 55 mm inner diameter and 2.5 mm wall thickness gave a 40% increase in specific energy absorption. The trigger efficiency of chamfers depends on the angle of the chamfers. A reduction in chamfer angle from 45° to 35° led to a lower initial slope of the load-displacement curve and a smaller ratio between the peak load and the average crush load. Finally, the jig geometry is of great importance as it governs the crush mode, and thereby also the energy absorption capability. In the present study tests with flat platens, internal constraint and external constraint were conducted, and the peak loads and average crush loads differed significantly.

1. INTRODUCTION

The interest in using fibre-reinforced plastics (FRPs) for crashworthy automotive structures has increased in recent years. The reason is that FRPs can provide better specific energy absorption capabilities than both aluminium and steel [1]. For instance, Mercedes-Benz is using conical crash elements made of carbon fibre-reinforced epoxy in the new Mercedes-Benz SLR McLaren, and BMW is using cylindrical crash elements made of glass fibre-reinforced polyamide in the front- and rear bumper beams of BMW M3.

A typical compressive failure of a steel crash box is presented in Fig. 1. Apparent in the figure is the progressive folding of the box. Progressive folding involves a successive formation of plastic hinges such that the box folds axially in a manner similar to that of a concertina. The folding usually causes rather large load oscillation, which is detrimental as it reduces the energy absorption capability. FRPs, on the other hand, generally fail by progressive crushing, which involves smaller load oscillation than progressive folding and thereby a better energy absorption capability.

A substantial amount of information exists in the literature regarding energy absorption of FRPs. For review articles about energy absorption of FRPs, see [1-4]. Unfortunately, most of the information in the literature deals with energy absorption of expensive materials with long manufacturing cycle times. For automotive applications, however, cost and cycle times are often determining factors and information regarding energy absorption capability of low-cost FRPs with short manufacturing cycle times are therefore of interest. A summary of some results regarding energy absorption of FRPs is presented below.

Fig. 1. Progressive folding of a steel crash box.

- The crushing mode determines the energy absorption capability
- The energy absorption increase with increasing strain to failure of the fibre
- To obtain the maximum energy absorption from a particular fibre the matrix material must have a greater strain to failure than the fibre
- The energy absorption increase with increasing fracture toughness of the matrix
- Surface treatments that increase the fibre/matrix interfacial strength generally increase the energy absorption capability
- Fibre orientations that increase the number of fractured fibres increase the energy absorption
- Fibre orientations that increase the axial stiffness of the FRP material increase the energy absorption
- Both axial and hoop fibres are necessary to obtain maximum energy absorption
- Symmetrical fibre architecture is important to obtain stable crushing
- The specific energy absorption capability follows the order: circular > square > rectangular
- The specific energy absorption is generally highest for tube thickness in the range 2-3 mm
- Chamfering is generally the most robust trigger mechanism.

The objective of the present investigation was to evaluate the energy absorption capability of pultruded glass fibre-reinforced polyester tubes. The specific energy absorption of glass fibre-reinforced polyester is much lower than the specific energy absorption of e.g. carbon fibre-reinforced epoxy. But the design trigger load for car crash boxes is generally rather low (~60 kN) and the use of carbon fibre-reinforced epoxy results in slender crash elements, which can be sensitive to off-axis impacts. Glass fibre-reinforced polyester can therefore be of interest for crashworthy structures, since the crash elements can be made more robust. Furthermore, if the cost for FRP crash elements shall be equal to, or lower, than the cost for steel crash elements, then pultruded glass fibre-reinforced polyester is for sure an attractive material choice.

2. EXPERIMENTAL

The FRP tubes used in this investigation were standard pultruded tubes from Fiberline Composites, Denmark. The materials in the tubes were E-glass fibres (60 w%) and isophtalic polyester.

Two different tube geometries were tested. Small tubes (UPS) with an inner diameter of 55 mm and a wall thickness of 2.5 mm, and larger tubes (UPL) with an inner diameter of 65 mm and a wall thickness of 5.0 mm. The length of the tube specimens was 100 mm. To facilitate progressive crushing, one end of each tube specimen was chamfered in a lathe to either 35° or 45° top-angle.

All tests were made at ambient room temperature. The tubes were tested in compression in a servo-hydraulic test machine, with a cross-head speed of 100 mm/min. To investigate the effects of jig geometry, tests with flat platens, internal constraint, and external constraint, were carried out. Schematic representations of the different jigs that were used in the tests are presented in Fig. 2.

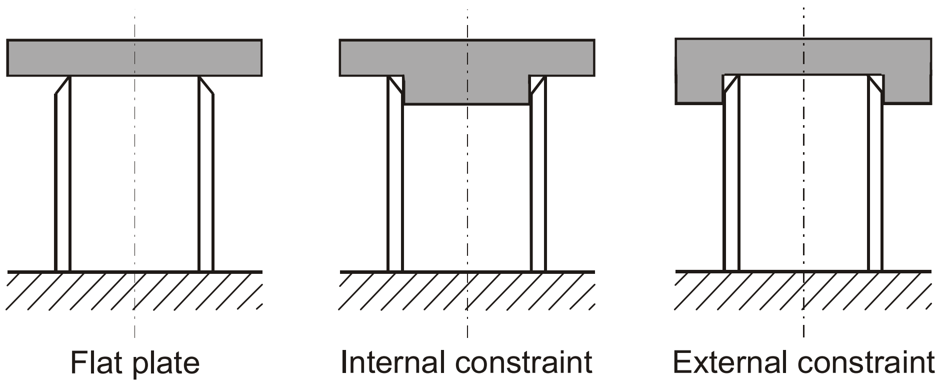

Fig. 2. Schematic representation of the different jigs used in the compression tests.

3. RESULTS & DISCUSSION

Energy absorption capability of pultruded glass fibre-reinforced polyester tubes

FRP tubes generally require some sort of collapse trigger mechanism in order to generate progressive crushing rather than catastrophic failure. Trigger mechanisms that have been shown to work well include chamfers, slots and tulip geometries [5-7]. The efficiency of a trigger is generally defined as the ratio between the peak load and the average crush load, and in the case of an ideal trigger this ratio should be close to one. In the first set of tests a 45° chamfer was used, and the specimens were compressed between flat steel platens.

The pultruded glass fibre-reinforced polyester tubes failed by stable progressive splaying/lamina bending, see Fig. 3. This type of crushing mode is characterised by very long cracks parallel to the fibres, with little or no fracture of the fibres. Crack growth is the principal energy absorption mechanism, although energy is also absorbed through bending of the fibres and by frictional effects between the test platen, fronds, debris, wedge, and adjacent fibres [2]. Splaying/lamina bending does generally occur when most of the fibres are aligned in the loading direction, and the shear strength of the material is low [8].

Fig. 3. Splaying/lamina bending crushing of a pultruded glass fibre-reinforced polyester tube.

Load-displacement curves from the compression tests are presented in Fig. 4. The tubes displayed initially a linear-elastic response up to a peak load value, where after the load dropped and stable progressive crushing took place. The average peak loads for the UPS and UPL tube specimens were 47 kN and 92 kN, respectively.

The specific energy absorption for the UPS and UPL specimens was 51 kJ/kg and 37 kJ/kg, respectively, which are values that are in accordance with values presented in the literature [9-10]. The very large difference in specific energy absorption between the UPS and UPL specimens is somewhat surprising, since the material, fibre orientation and fibre content is the same. A decrease in specific energy absorption with increasing tube diameter was, however, also noticed by Fairfull [11], and it is clear that crushing modes and mechanisms, and thereby also energy absorption capability, are very much affected by the geometry of the test specimens.

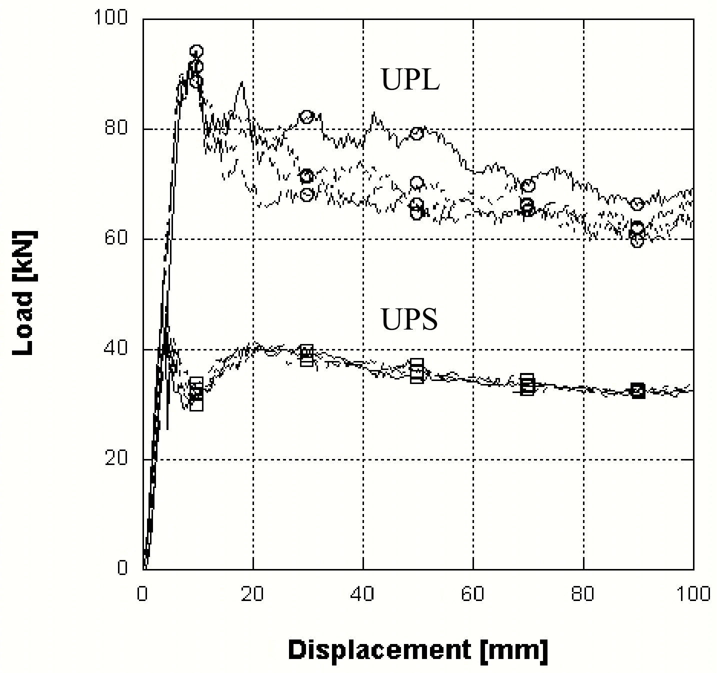

Fig. 4. Load-displacement curves from compression test of two different sorts of pultruded glass fibre-reinforced polyester tubes.

Effects of chamfer angle

Typical load-displacement curves for UPS and UPL tube specimens with different chamfer angles are presented in Fig. 5. The chamfer angles tested were 35° and 45°. Apparent in the figure is that a decrease in chamfer angle leads to a lower initial slope of the load-displacement curve. The reason to the reduction in slope is that crushing of the chamfer occurs in addition to the elastic deformation of the tube [8]. Furthermore, the drop in load after the peak load appears to be somewhat smaller with 35° chamfer angle than with 45° chamfer angle.

The specific energy absorption was slightly higher with 35° chamfer angle than with 45° chamfer angle. The average specific energy absorption values for the UPS and UPL tubes with 35° chamfer angle were 54 kJ/kg and 40 kJ/kg, respectively, which is approximately 3 kJ/kg more than for the UPS and UPL tubes with 45° chamfer angle.

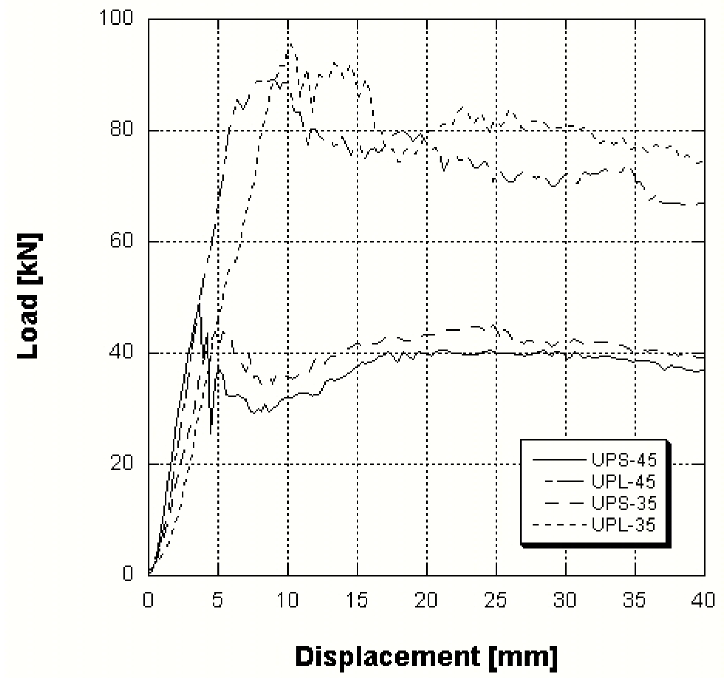

Fig. 5. Load-displacement curves for pultruded glass fibre-reinforced Polyester tubes with different chamfer angle (35° and 45°).

Effects of internal and external constraints

Fixation and triggering are two important factors in design of robust crashworthy automotive structures. Chamfering is usually considered to be one of the most robust trigger mechanisms, and is for example used in the crash elements for BMW M3.

To ensure stable progressive crushing it is important to know how different fixation strategies influence the triggering and failure of FRP structures. The effects of internal and external constraints in the compression of UPS tube specimens are presented in Figs. 6-8. In Fig. 6(a) the crushing mode for internal constraint is presented. The tubes failed by splaying/lamina bending, but since the internal constraint made it impossible for the fibres to bend inwards, no debris wedge could form [8], and the crushing mode and load-displacement response were therefore quite different compared to the crushing mode and load-displacement response with flat platens, see Fig. 7. The average peak load increased approximately 10%, compared to the tests with flat platens, but since the average crush load was lower in the tests with internal constraint than in the tests with flat platens the specific energy absorption was also lower.

Fig. 6. Crushing mode with (a) internal and (b) external constraints.

The crushing mode in the tests with external constraint is presented in Fig. 6(b). The fibres did not fracture, but only bent inwards, which led to a very high peak load values followed by large drops in load, see Fig. 8. The peak load was almost 50% higher in the tests with external constraint than in the tests with flat platens. High peak loads and sudden large drops in load are unwanted in automotive structures as they can cause undesired deceleration levels that can cause serious injuries to the passengers.

After the initial peak and drop in load, the average crush load was quite high, which led to higher specific energy absorption with external constraint than with internal constraint or flat platens. Therefore, if the high peak load can be reduced, by changing for instance the trigger mechanism, then external constraint can be an attractive fixation method for automotive crash elements.

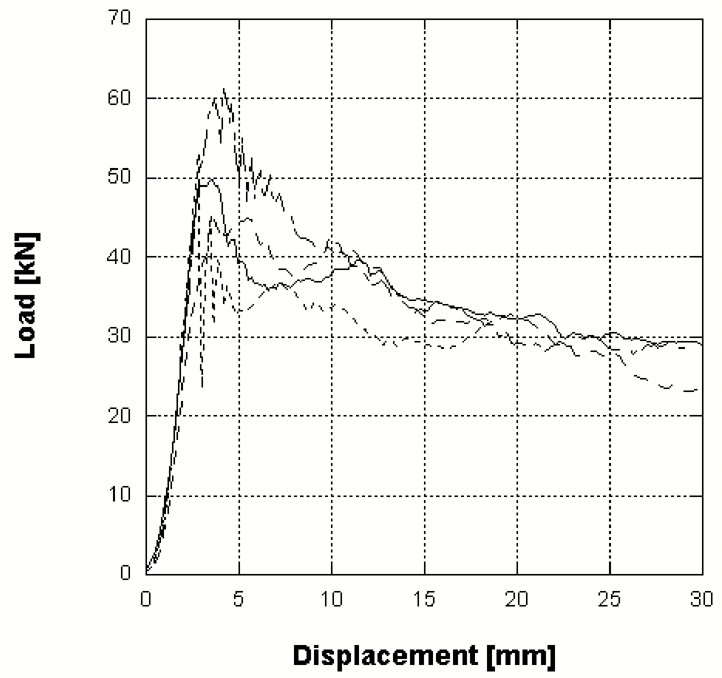

Fig. 7. Load-displacement curves for UPS tube specimens tested with internal constraint.

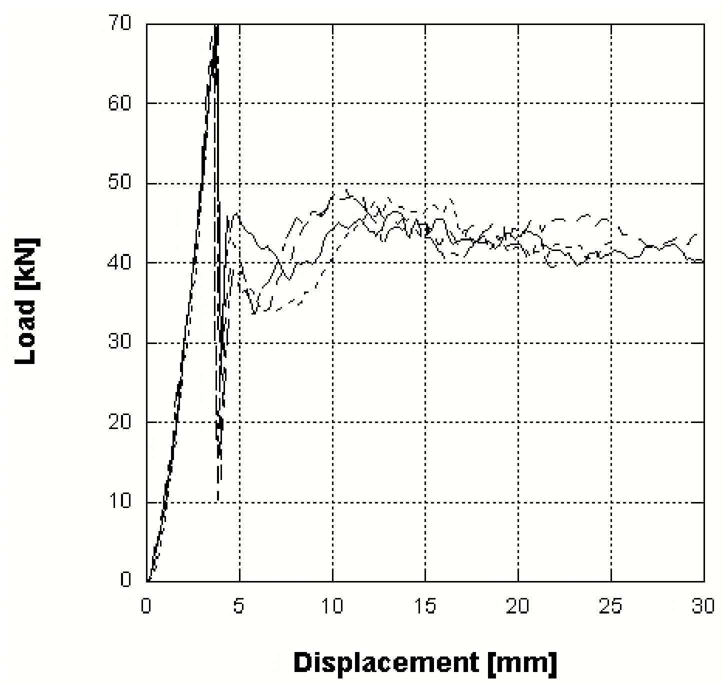

Fig. 8. Load-displacement curves for UPS tube specimens tested with external constraint.

4. CONCLUSIONS

Compression tests of pultruded glass fibre-reinforced polyester tubes have been conducted to evaluate the energy absorption capability. From the results obtained the following conclusions can be drawn.

1. The glass fibre-reinforced polyester tubes failed by stable progressive splaying/lamina bending.
2. The specific energy absorption was almost 40% higher for the tubes with 55 mm inner diameter and 2.5 mm wall thickness than for the tubes with 65 mm inner diameter and 5.0 mm wall thickness.
3. A reduction of the chamfer angle from 45° to 35° led to a lower initial slope of the load-displacement curve and a somewhat smaller load drop after peak load.
4. Tests with internal constraint gave less efficient crushing and thereby lower specific energy absorption than tests with flat platens.
5. Tests with external constraint gave very high peak loads, which is detrimental in for instance automotive applications. The specific energy absorption was however higher in the tests with external constraint than in the tests with internal constraint and flat platens.

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