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# Effects of boundary conditions on the energy absorption of thin-walled polymer composite tubes under axial crushing

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**Abstract**

Polymer composite tubes can be designed to absorb high levels of impact energy by progressive crushing. When a tube is crushed onto a flat platen, energy is absorbed by bending failure of the plies, delamination and friction mechanisms. In the present work, significant increases in energy absorption are shown when a shear mode of failure is initiated by crushing the tube onto a radiused plug (or initiator). A study of plug radius, $R$, normalised with respect to the tube wall thickness, $t$, in the range of $0 \leqslant R/t \leqslant 5$ for circular tube diameter/thickness ratios of $10 < D/t < 33$ was undertaken with continuous filament random mat glass/polyester composite. Different radii plugs lead to significantly different deformed shapes and crush zone morphologies. Large radius initiators ($R/t > 2$) cause the tubes to split and energy is absorbed primarily through friction and axial splitting. As the initiator radius decreases, the amount of through-thickness shear damage in the fronds increases along with specific energy absorption (SEA). When the plug radius becomes small compared to the wall thickness ($R/t < 0.75$) a debris wedge forms between the initiator and the tube and acts like a larger radius initiator. The highest energy absorption was seen to occur at $R/t \leqslant 1$ when through-thickness shear damage was induced. In this range, under static loading conditions, SEA was seen to be higher than that for tubes crushed onto a flat platen.


*Keywords:* Energy absorption; Composite materials; Initiator; Isotropic; Glass; Polyester

## 1. Introduction

The high specific energy absorbing capabilities of composite structures are well documented, e.g. [1,2]. For a given structure the amount of energy absorbed depends on the mode of failure and the crush zone morphology, which in turn depends on how failure is initiated or triggered [3]. There are two main types of trigger; stress raisers and plug inserts [4]. The bevel-type stress raiser, shown in Fig. 1, is the most common type of trigger and consists of a chamfer applied to one end of the section that is to be crushed. Sigalas et al. [5] investigated the effect of changing the angle of the chamfer and found that the steady-state load and thus specific energy absorption (SEA) was not strongly influenced by the angle of the bevel. Typically, in automotive applications, packaging restrictions and the need to attach the bumper beam to the crash rail mean that plug-type triggers are more practical [4]. Also, since debris is forced to the outside of the tube, the stroke efficiency [1] is increased, over flat platen crush, to values approaching 100%.

Previous work has shown that the SEA is dependent on the radius of the initiator, and that typically a lower SEA is recorded for plug triggers. Johnson et al. [6] reported that the SEA of an E-glass warp knitted non-crimp fabric tube dropped from 42.2 kJ/kg for a flat platen to 25.2 kJ/kg when a plug initiator was used. Hull and Coppola [7,8] studied the effect of a number of trigger geometries on the SEA of woven glass-vinyl ester and woven glass cloth-epoxy tubes. They investigated the effect of plug initiator radius on energy absorption and found that the radius had a strong effect on the mean crush load and SEA, where the SEA was inversely related to radius up to a point where debris builds up between the initiator and the tube. Their results are summarised in Table 1. This work is significant because it shows that at small radii a debris wedge forms between the initiator and the tube. It also shows that tubes

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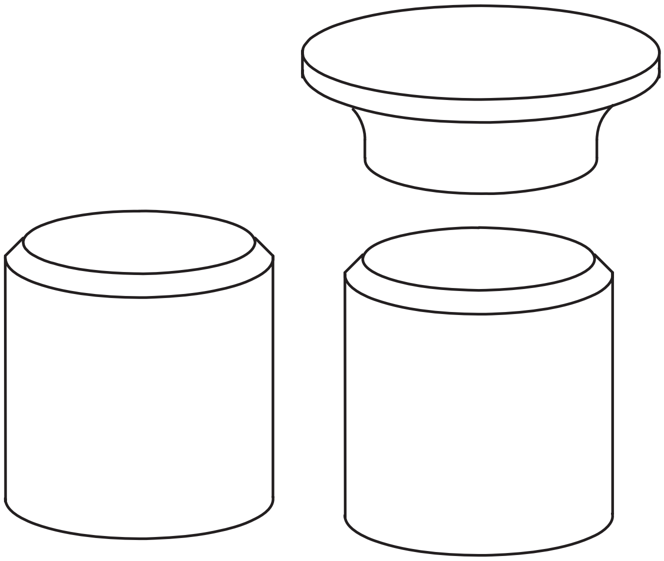


Fig. 1. Different types of crush trigger.

Table 1
Summary of results from Hull and Coppola [7,8] ($D=50$ mm, $t=2.5$ mm)

| Initiator radius (mm) | Glass fibre-vinyl ester SEA (kJ/kg) | Glass fibre-epoxy sea (kJ/kg) |
|---|---|---|
| Flat platen | 62 | 62 |
| 0.5 (0.20$t$) | – | 47 |
| 1.4 (0.56$t$) | 54 | 60 |
| 2.4 (0.96$t$) | 51 | 47 |
| 3.2 (1.28$t$) | 39 | 38 |
| 4.0 (1.60$t$) | 26 | 14 |

Table 2
Summary of results of carbon braid tube [9] ($D$ = 64 mm, $t$ = 2.5 mm (kJ/kg))

| Initiator radius (mm) | Braid architecture | | |
|---|---|---|---|
| | $[0°/30°/-30°]_2$ | $[0°/45°/-45°]_2$ | $[0°/60°/-60°]_2$ |
| Flat platen [18] | 41 | 47 | 26 |
| 4.67 (1.86$t$) | 38 | 30 | 41 |
| 7.94 (3.18$t$) | 23 | 17 | 30 |

crushed on plug initiators can come close to the SEA levels of tubes crushed onto flat platens.

Chang and Beard [9] considered braided carbon fibre composite tubes against plug initiators—three tube architectures were crushed against a flat platen and plug initiators with $R/t$ of 1.87 and 3.18. The results of this work are summarised in Table 2. The SEA for the $[0°/60°/-60°]_2$ tubes against the flat platen are very low because the tubes did not crush in a stable progressive manner. These results are in agreement with other work that shows that an inverse relationship between SEA and plug radius exists.

Table 3
Summary of results from unidirectional glass polyester tube [10,11] ($D=44$ mm, $t=3.0$ mm (kJ/kg))

| Initiator radius (mm) | Without constraint | With constraint |
|---|---|---|
| Flat platen | 44 | 48 |
| 4.0 (1.33$t$) | 39 | 54 |
| 12.0 (4.0$t$) | 6 | 13 |

Table 4
Test matrix showing quasi-static (QS) and dynamic ($D$) tests for various geometries

| Initiator radius (mm) | Circular | | | | Square | |
|---|---|---|---|---|---|---|
| | $D=89$ | | $D=38.1$ | | $B=30$ | |
| | $t=4$ | | $t=2$ | $t=4$ | $t=2$ | $t=4$ |
| | $v_f=27\%$ | $v_f=23\%$ | $v_f=26\%$ | $v_f=23\%$ | $v_f=26\%$ | $v_f=26\%$ |
| Flat | QS | QS | QS + D | QS + D | QS + D | QS + D |
| 0.0 | QS | QS | QS + D | QS + D | QS + D | QS + D |
| 2.5 | QS | QS | QS + D | QS + D | QS + D | QS + D |
| 5.0 | QS | QS | QS + D | QS + D | QS + D | QS + D |
| 7.5 | QS | QS | QS + D | QS + D | QS + D | QS + D |
| 10.0 | QS | QS | QS + D | QS + D | QS + D | QS + D |
| 20.0 | QS | QS | – | – | – | – |

Abdel-Haq and Newaz [10,11] introduced a way of manipulating the energy absorption of composite tubes. Unidirectional glass polyester tubes were crushed against a flat platen and aluminium plug initiators with $R/t$ of 1.33 and 3. A steel band was clamped around the outside of the tube to limit axial splitting. As crushing progressed the band was allowed to slide up the tube. The results from this work are shown in Table 3, and significantly, they show that plug initiators can give higher SEA than flat platens.

## 2. Experimental methodology

A range of tube geometries was manufactured from continuous filament random mat (CoFRM) and polyester resin by resin transfer moulding (RTM). The study included two sizes of circular tube, and square tube, where the cross-sectional area was the same as the smaller circular samples. Two wall thicknesses were considered to give a test matrix of circular sections of $10<D/t<33$ and square sections of width/wall thickness ratio, $B/t$ of 7.5 and 15 (see Table 4). Quasi-static and dynamic/impact loading rates were considered. Preforms were made from Vetrotex Unifilo U750-450 (areal mass 450 g/m$^2$) by rolling a length of material onto a mandrel while compacting the preform and using a hot air gun to melt the binder. The finished preforms had four, five or six layers of material giving fibre volume fractions in the range of 23–26%. The preforms were trimmed and loaded into steel tooling and injected with Reichhold Norpol 420-100 polyester resin. The parts