"STRAIN RATE EFFECTS ON THE ENERGY ABSORPTION OF RAPIDLY MANUFACTURED COMPOSITE TUBES."

Aaron Brighton[a], Ben Luedtke[b], Dale Brosius[b], Mike Starbuck[c], Donald Erdman[c], Bronwyn Fox[a]

[a]*Victorian Centre for Advanced Materials Manufacturing, Deakin University, Geelong, VIC, Australia*

[b]*Quickstep Technologies, North American Center of Excellence.*

[c]*Oak Ridge National Laboratory, Tennessee, USA*

Abstract:

As a result of recent increases in fuel prices and the growing number of accident fatalities, the two major concerns of the automotive industry and their customers are now occupant safety and fuel economy [1, 2]. Increasing the amount of energy and optimizing the manner in which energy is absorbed within vehicle crush zones can improve occupant survivability in the event of a crash, while fuel economy is improved through a reduction in weight.

Axial crush tests were conducted on tubular specimens of Carbon/Epoxy (Toray T700/G83C) and Glass/Polypropylene (Twintex). This paper presents results from the tests conducted at quasi-static rates at Deakin University, Victoria Australia, and intermediate rate tests performed at the Oak Ridge National Laboratory, Tennessee USA.

The quasi-static tests were conducted at 10mm/min (1.67x10-4m/s) using 5 different forms of initiation. Tests at intermediate rates were performed at speeds of 0.25m/s, 0.5m/s, 0.75m/s 1m/s, 2m/s and 4m/s. Quasi-static tests of tubular specimens showed high specific energy absorption (SEA) values with 86 kJ/kg for Carbon/Epoxy specimens. The SEA of the Glass/Polypropylene specimens was measured to be 29 kJ/kg.

Results from the intermediate test rates showed that SEA values did not fall below 55kJ/kg for carbon specimens or 35kJ/kg for the Glass/Polypropylene specimens. When compared with typical steel and aluminium, SEA values of 15 kJ/kg and 30kJ/kg respectively, the benefits of using composite materials in crash structures is apparent.

Introduction:

Increasing both the amount of energy and improving the manner in which energy is absorbed within the crush zones in automotive vehicles can substantially improve vehicle safety. If modern lightweight materials are used in crash structures then vehicle fuel economy can be improved, leading also to a reduction in polluting emissions. If a weight reduction is realised in one area of a vehicle the effect of this cascades through the entire vehicle, smaller brakes, power assistance systems and engines[3]. Carbon fibre composites offer a solution to fulfil both of these requirements simultaneously as a result of their excellent crash characteristics and high strength to weight ratios.

Recently, automotive manufacturers have been under increasing legislative pressure to reduce fuel consumption. [4]. Reducing vehicle weight has a number of follow on benefits. Firstly, it reduces fuel consumption, not only reducing the cost to the consumer but also decreasing environmental impact. Secondly, in a collision the vehicle has less momentum and therefore less energy to be dissipated to bring the vehicle to a stop.

Composite crush structures are an exceptional method for both enhancing passenger safety and reducing the weight of automobiles. Much research has been devoted to investigating the crush behavior of fibre reinforced plastic tubes. However, there is a lack of consensus whether the energy absorption capability of composite tubes is a function of crushing speed[5].

By definition the area under a load displacement curve is the energy absorbed during an event, a rectangular load-displacement curve represents the maximum energy absorption capability of a material. The progressive crushing of fibre reinforced plastic tubes approaches this ideal [6].

To initiate the progressive crushing failure mechanisms, some form of stress concentration is required to reduce the chance of catastrophic failure and reduce initial peak loads, This stress concentration, usually in the form a chamfer at varying angles, is machined into one end of the tube. Another form used is the plug initiator with a varying radius. Altering the radius produces varying results; as the radius approaches the wall thickness of the specimen the SEA values increase[7].

The uptake of composite components by the automotive industry has been slow as a result of high material and manufacturing costs. The development of the Quickstep 'out of autoclave' manufacturing process enables rapid manufacture of composite components without incurring excessive plant costs. The Quickstep process utilises the high heat transfer characteristics of a fluid as opposed to the nitrogen present in an autoclave. Due to the higher heat transfer rate of the fluid medium shorter cycle times are achievable. The process does not require the use of high pressures; consequently lower cost, less rigid tooling is required. Both of these aid in reducing the cost of the end product by increasing productivity and reducing capital costs.

Test Specimens:

Circular test specimens with 60mm nominal internal diameter and 2mm wall thickness, were manufactured using the "Quicktubes" male mandrel method[8]. This involved using a hollow aluminium mandrel with cam-lock connectors at one end Fig 1. These connectors allowed the mandrel to be hooked into the fluid lines of the Quickstep machine. The flowing fluid controls the temperature of the tool; as the tool heats up the aluminium expands and applies pressure to the part to aid with consolidation. As the tool cools it contracts to aid in part removal.

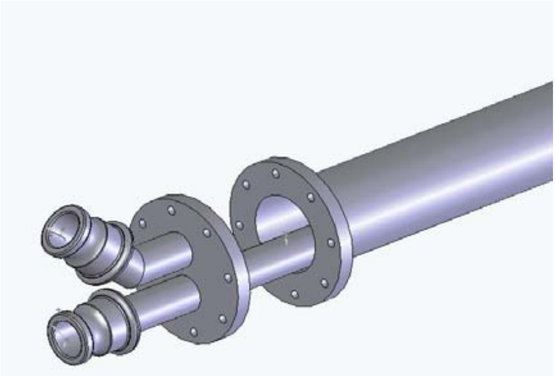

Figure 1 Male aluminium mandrel showing cam-lock connectors

Carbon/Epoxy specimen tubes were manufactured from T700 fibres in a 2x2 weave, pre-preged with G83C quick cure resin. The lay up schedule was $[0/90]_4$ on the aluminium mandrel in a Swiss roll type arrangement. The 1m length of Carbon/Epoxy tubing was then shrink-wrapped with 19mm wide Airtek (A575) shrink tape. A 4mm shrink-wrap overlap was created using the tool feed feature of the tool shop lathe. The shrink-wrapped mandrel was then vacuum bagged and connected to the Quickstep machine. The curing cycle employed a fast ramp to 100°C, dwell for 5mins then a second fast ramp to 150°C and dwell for 3mins. The mandrel was then brought down to a handling temperature of approximately 60°C on average this took 3 minutes. This cure cycle took approximately 15 minutes.

The Twintex material (obtained from Saint-Gobain Vetrotex, France) consisted of a plain weave of commingled Glass/Polypropylene fabric. Specimen tubes were wrapped in a similar 4-layer Swiss roll arrangement then shrink-wrapped using the same method as used for the carbon tubes. The mandrel was wrapped with 2 layers of 0.05mm stainless steel, to act as a heat reflector and wrapped in an insulating wool blanket. The cure cycle used was a fast ramp to 180°C, hold for 1min, before the mandrel was cooled to a handling temp of approximately 60°C again on average this took 3 minutes. This cycle took approximately 20 minutes.

The tubes for dynamic testing were removed from the tool and each parent tube cut, using a diamond saw, into 250mm specimens and labelled according to material type, parent tube and section from where the specimen was cut. The parent tubes were named DT and DTT, for the carbon and Twintex materials respectively. Specimens were then numbered sequentially with respect to the order in which they were cured, and labelled 1 through 4 depending on the section cut from the parent tube. The tubes for quasi-static testing were cut into 110mm specimens and labelled.

These specimens were placed on a steel centre in a lathe allowing one end to be square cut and the other a 45° chamfer cut. After machining all tubes had a nominal length of 240mm and 100mm for dynamic and quasi-static specimens respectively.

Testing methodologies:

Quasi-Static tests were performed on an MTS 100kN screw driven 20/g load frame at Deakin University, Geelong, Victoria, Australia. Five forms of initiation were used for testing: 45° chamfer, 10mm plug, 7.5mm plug, 5mm plug and 2.5mm plug. Each initiator type was used with 3 specimens of Twintex tubes at a rate of 10mm/min ($1.67x10^{-4}$m/s) between universal MTS compression platens. The same approach was used when conducting tests on Carbon/Epoxy specimens; a fellow researcher conducted these tests at Deakin University as part of his PhD thesis[9].

The dynamic tests were performed using the Testing Machine for Automotive Crashworthiness (TMAC) located at the Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee, USA. The TMAC is a unique purpose built servo-hydraulic test machine built by MTS. Two forms of failure initiation were used, namely the 45° chamfer and the 45° chamfer combined with a 2.5mm plug initiator. Each initiator type was utilised with both materials at speeds of 0.25m/s, 0.5m/s, 0.75m/s, 1m/s, 2m/s and 4m/s for 24 different test configurations.

Each of these configurations was reproduced three times, reducing the likelihood of testing anomalies affecting the final results. Ram position, time, load cell (strain gauge load device) and load washer (piezoelectric load device) data were recorded at 4kHz for the 0.25m/s tests, 10kHz for the 0.5m/s tests and 20kHz for the 0.75m/s, 1m/s, 2m/s and 4m/s tests.

Utilising the data the specific energy absorption (SEA) was calculated for each test specimen and average SEA values were reported for each test configuration.

$$SEA = \frac{Energy\ Absorbed(kJ)}{Mass\ of\ crushed\ tube(kg)}$$

$$= \frac{\int_0^{x_f} Load\ dx}{Mass\ of\ crushed\ tube}$$

However, for simplification the integral is sometimes reduced to the average sustained crushing load multiplied by the crush distance[6].

$$SEA = \frac{Energy\ Absorbed(kJ)}{Mass\ of\ crushed\ Tube(kg)}$$

$$= \frac{Average\ Sustained\ Crush\ Load \times Crush\ Distance}{Mass\ of\ crushed\ tube}$$

In addition to numerical data, each test was recorded using high-speed digital photography so failure modes and possible anomalies could be observed. When a large variance was evident in the results the high-speed video was consulted to look for potential testing abnormalities. If anomalies were present the test result was discarded. The most common reason for excluding a test was failure by wall shear, as this was more likely caused by manufacturing defects than a representation of the normal failure mechanism. Another reason for discarding a result was when an incorrectly fastened fixture slipped, thus invalidating the test.

Discussion:

Tube crush mechanisms

Carbon/Epoxy Tubes

The results from the Quasi-static tests, which were conducted previously, showed that the 45° chamfer and the 2.5mm plug produced the highest SEA values. Therefore, these initiators were selected for use during the intermediate rate tests. The trend for varying plug radii is show in Fig 2,

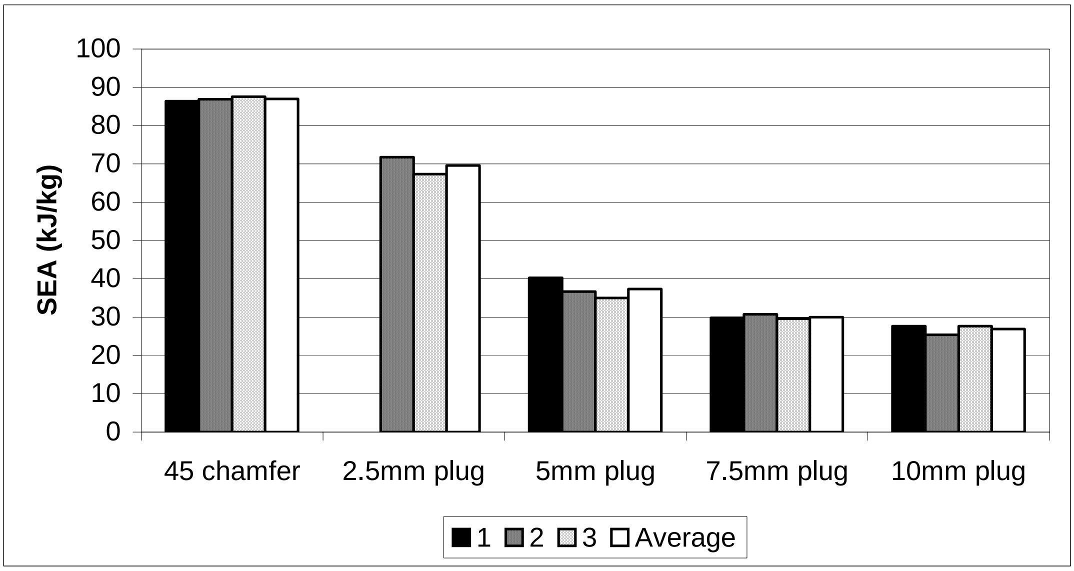

Figure 2 Carbon performance for different forms of initiation at quasi-static rates, testing conducted by Mr M. D. Silcock [9].

The amount of energy absorbed during axial crush tests is dependant on the failure modes that develop during the crush. The Carbon/Epoxy tubes fail in a brittle fracture mode that results in frond development. As the material fails, hoop fibres are stressed to failure. This causes axial tears in the tube, creating fronds that are forced to bend through a 90° angle at the failure zone Fig 3.

The effects of friction and matrix strain added to the energy that was absorbed. A significant difference was observed in both the energy absorbed and the failure mechanism of the 2.5mm initiated test specimens and the 45° chamfer initiated specimens. During the 2.5mm plug tests all fibres splayed outwards, the only resistance to failure was the breakage of hoop fibres and frictional effects. By contrast during the 45° chamfer initiated tests, the material was also forced inwards.

Some of the failed material formed a debris wedge Fig 4 Fig 5 and Fig 6 while the rest was folded and compressed into the centre of the tube.The debris wedge was a region of crushed material that initiated and helped maintain the central wall crack propagation[9]. The author attributed the higher energy absorption to the addition of the mode I failure mechanism observed during the chamfer tests.

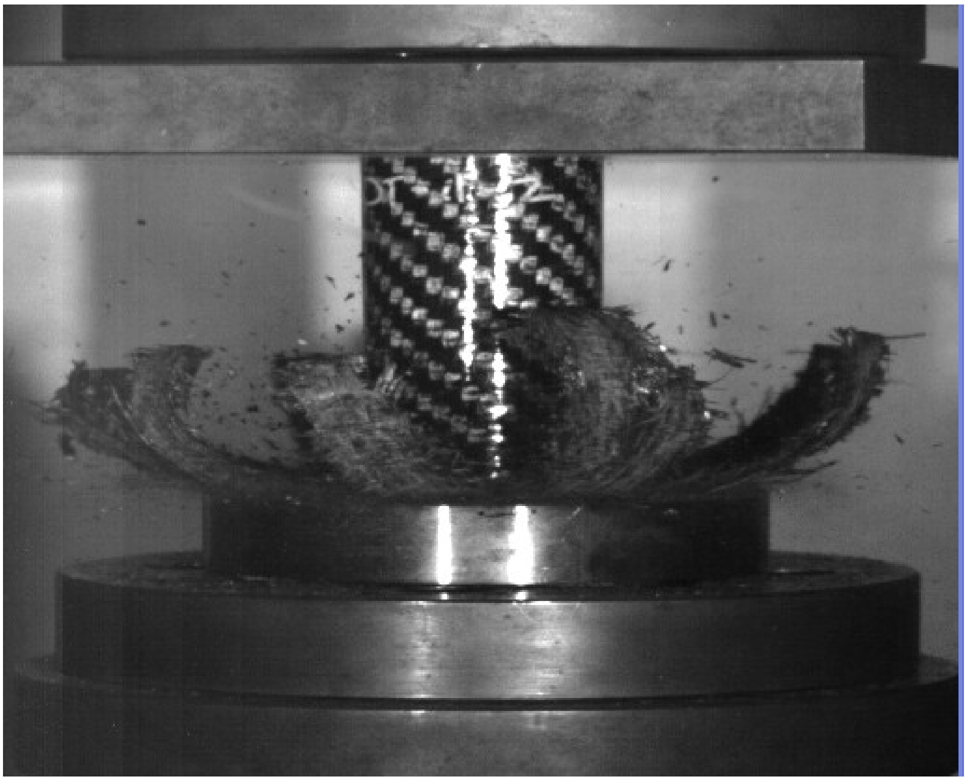

Figure 3 Frond development during 2.5mm plug initiated test at 4m/s

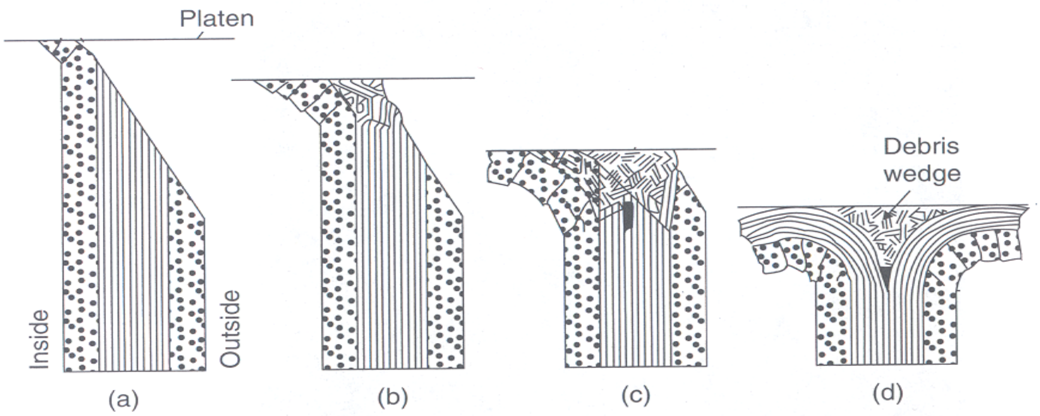

Figure 4 Showing the lamina splaying and formation of debris wedge at the beginning of a chamfer initiated test[9].

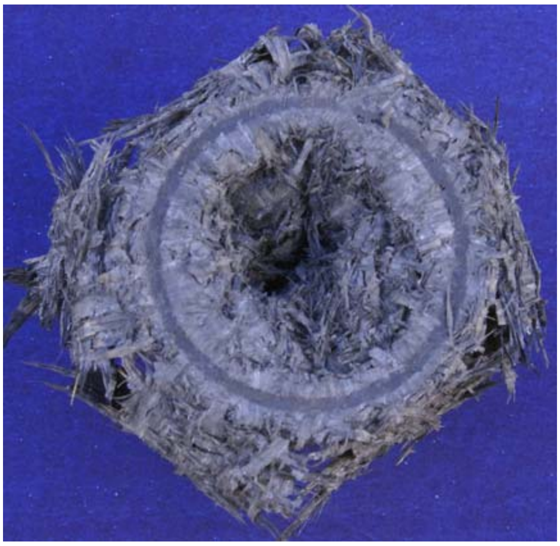

Figure 5 Showing the debris wedge formed during 45 chamfer tests

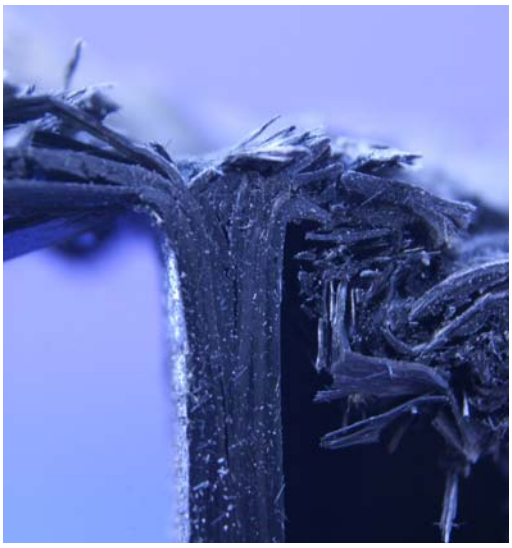

Figure 6 Fracture zone showing failed material and debris wedge

As the speed of the 2.5mm plug tests was increased from 0.5m/s to 4m/s, the behaviour of the fronds was seen to change. During the quasi-static tests the fronds were found to have a tight radius of curvature (Fig. 7), however, at higher crush rates the radius of curvature decreased (Fig. 8) until the 4m/s test in which the fronds were not observed to curl much at all (Fig. 9).

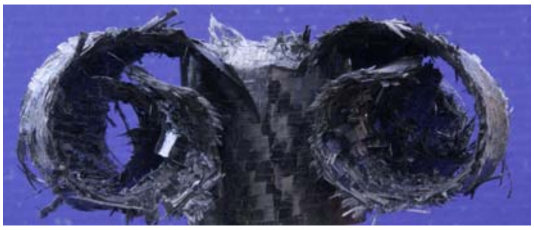

Figure 7 Tight fronds developed at 0.5m/s impact speeds

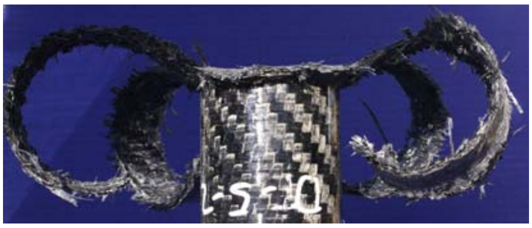

Figure 8 Separated fronds developed at 2m/s impact speed

Figure 9 Unwound fronds developed at 4m/s impact speed.

Glass/Polypropylene Tubes

During quasi-static testing a similar trend was observed with the carbon tubes, as the radius of plug initiator approached the wall thickness, the energy absorbed increased. This can be seen in fig 10.

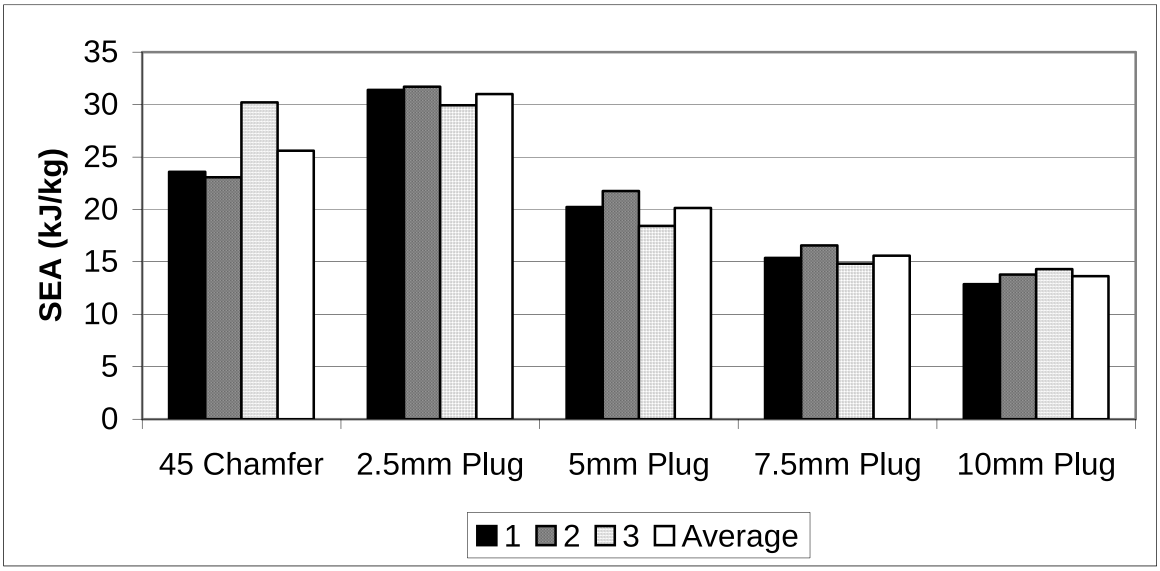

Figure 10 SEA values using different forms of initiation at quasi-static rates showing an increase as the radius of the plug initiator is decreased.

During the quasi-static tests it was observed that the Glass/Polypropylene tubes failed by progressive folding in a combination of concertina and diamond folding. However, due to the high strain to failure of the polypropylene matrix the Twintex tubes failed by external inversion Fig 11. This inversion took place for half the length of the original tube until the inverting tube came in contact with the crushing head at which point, either fronds develop or the remaining material failed in a concertina manner. This was a similar failure mode as experience during testing of a hybrid CF/AF-EP crash element for the Audi A8 [10]. Although the 45° chamfer resulted in slightly higher SEA values, the author attributed this to higher frictional effects of the flat platen.

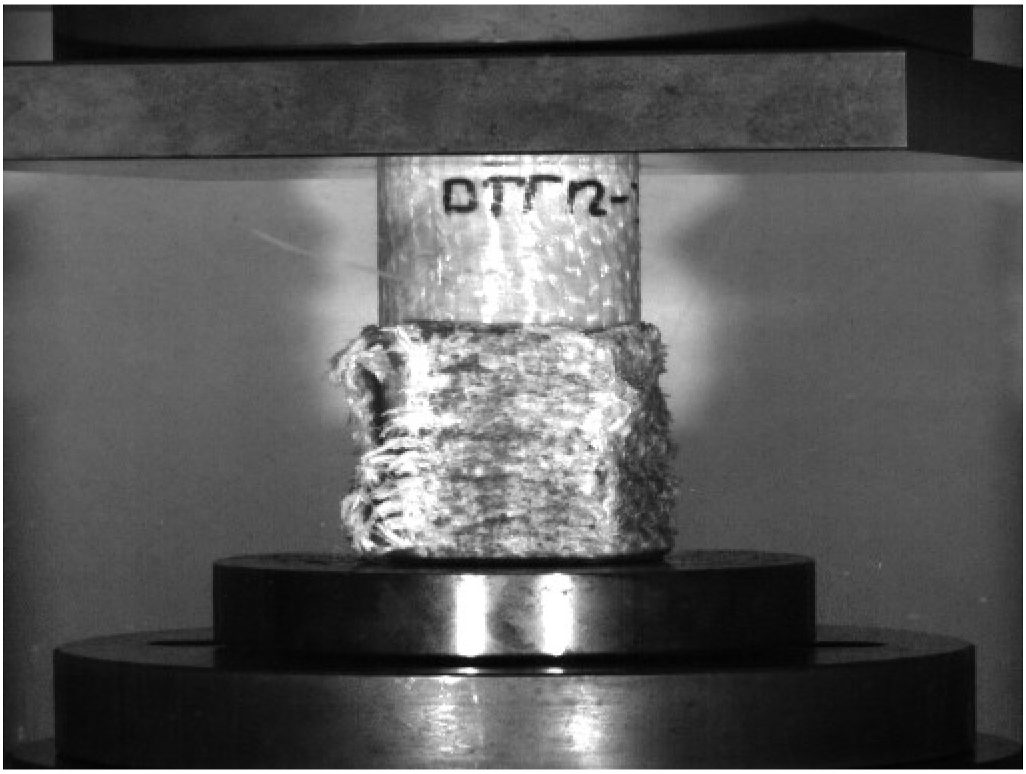

Figure 11 Twintex tube undergoing inversion during plug-initiated test at 0.5m/s

By observing the high-speed photography of the crush events it was seen that the failure modes experienced using both the 45° chamfer and the 2.5mm plug appeared to be similar, however the behaviour when using the 2.5mm plug were more repeatable. While the same behaviour was observed in the 45° chamfer initiated tests it took some time before these failure modes appeared. The tests that did not exhibit this failure mode were the tests that included wall shear failure. This reduction in force at the initial failure point meant that the test did not have the time to develop or continue the inversion process.

Strain Rate Behaviour

Carbon/Epoxy Tubes

SEA values obtained from dynamic testing showed that carbon tubes had a slight dependence on rate. During 45° chamfer testing it was found that there was a 15% drop in load across testing speeds. It was also seen that 2.5mm plug tests showed a 22% drop in load across the testing speeds, Fig 12 and Fig 13. Each set of tests produced SEA values within a range of 3kJ/kg for the chamfer tests and 12kJ/kg for the plug initiated tests. This represented very repeatable testing results.

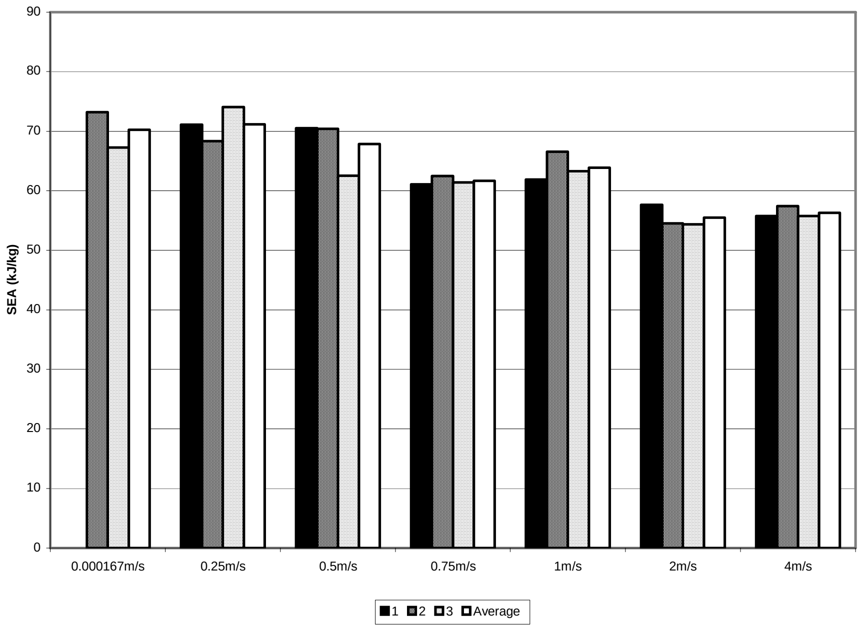

Figure 12 SEA vs. Test speed for carbon tubes using a 2.5mm Plug initiator.

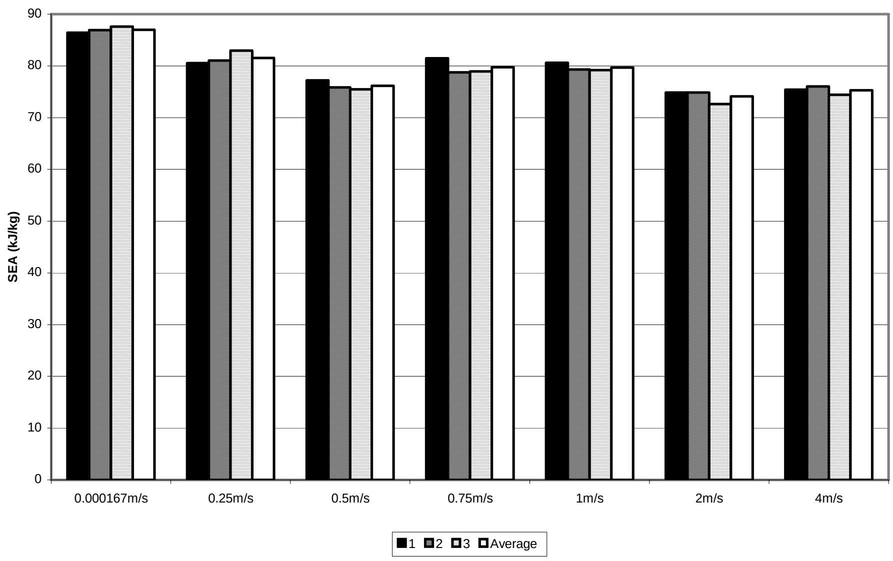

Figure 13 SEA vs. Test speed for carbon tubes using a) 45° chamfer.

Glass/Polypropylene Tubes

The difference between testing speeds with the Twintex tubes showed a large range in SEA values. Twintex tests with the 45° chamfer demonstrated a 39%

variation between the highest and lowest values. This was attributed to the difference in failure modes as discussed earlier. At 0.5m/s the inversion failure mode became evident, after this the average SEA values fell rapidly to approximately 44kJ/kg where it plateaued (Fig 14). While using the 2.5mm plug a 40% difference between the highest and lowest was evident (Fig 15). Using the 2.5mm plug as an initiator the peak in SEA did not occur until the 1m/s tests, the energy absorption capacity then dropped off as test speeds increased. However there was a large amount of variation within each set of test conditions, some tests exhibited up to a 40% difference.

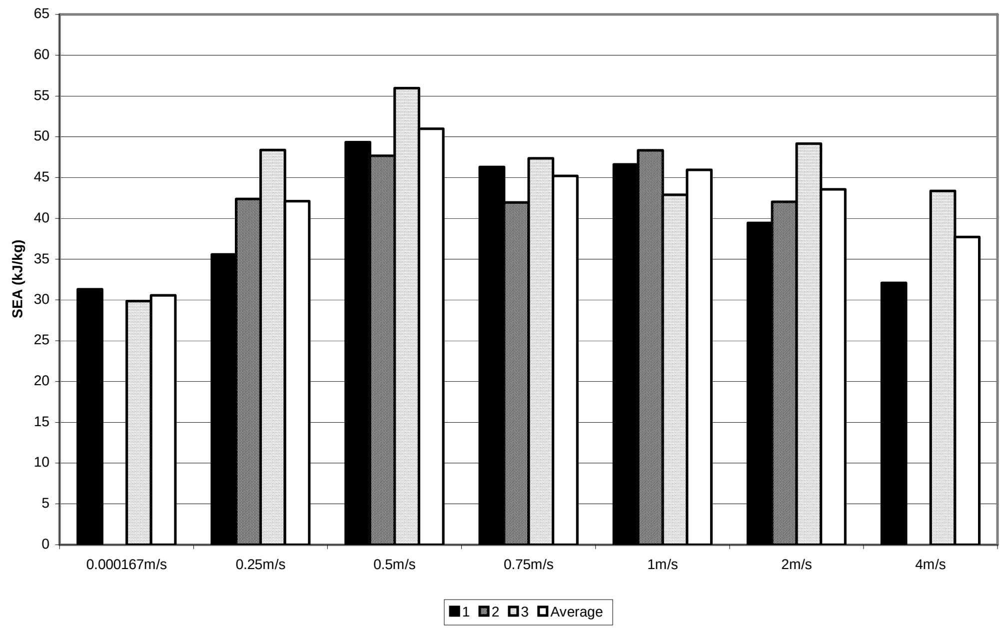

Figure 14 SEA vs Test speed for Glass/polypropylene tubes using a 2.5mm plug

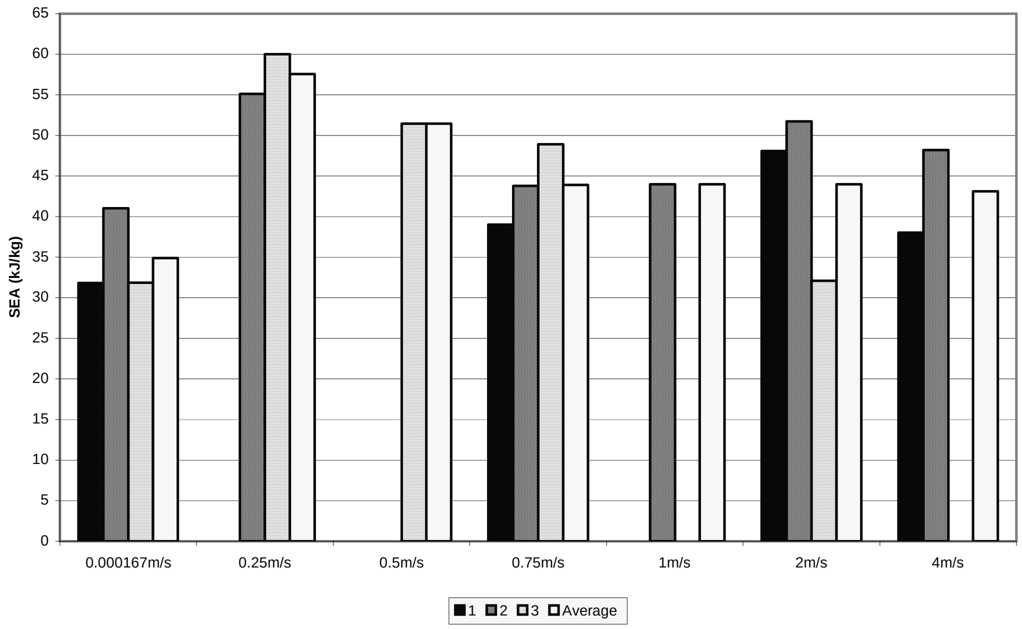

Figure 15 SEA vs Test speed for Glass/Polypropylene tubes using a 45° chamfer

Conclusion:

Carbon/Epoxy and Glass/Polypropylene tubes were crushed at speeds ranging from 1.67×10^{-4}m/s to 4m/s to determine the energy absorption capability. Quasi-static testing showed that the 45° chamfer and 2.5mm plug initiator produced the highest SEA values. It was found that as testing speed increased, SEA values for Carbon/Epoxy tubes decreased for both the 45° chamfer and 2.5mm plug initiated tests. These tubes exhibited up to a 22% decrease in energy absorption capability.

Impact tests involving the Twintex tubes were not found to reach their peak SEA values until speeds of 0.25m/s for the 45° chamfer and 0.5m/s for the 2.5mm plug initiated tests were achieved. Once the inversion failure mechanism developed, the energy absorption dropped by up to 40% across the test speed range.

Both matrix systems had a strain rate response, however the polypropylene matrix showed a greater dependence on impacting speed. The 45° chamfer Carbon/Epoxy tests showed the highest SEA and the least dependence on speed.

"Research sponsored by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of FreedomCAR and Vehicle Technologies, as part of the Automotive Lightweighting Materials Program and the High Temperature Materials Laboratory User Program, Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract number DE-AC05-00OR22725."

References:

1. NoAuthor, *2004 escaped shoppers study*. 2004, J.D. Power and associates.
2. Zhu, B. and C. Grundstrom. *Needs, Demands and Requirements in The Vehicle Safety Product Realization Process*. in *International Engineering Management Conference*. 2004. Portland.
3. Brosius, D., *Carbon Fiber Gains Traction with Automakers*, in *Composites Technology*. 2003.
4. Jambor, A. and M. Beyer, *New cars-New materials.* Materials &Design, 1997. **18**(4/6): p. 203-209.
5. Farley, G.L., *The Effects of Crushing Speed on the Energy-Absorption Capability of Composite Tubes.* Journal of Composite Materials, 1991. **35**: p. 1314-1329.
6. Carruthers, J., A.P. Kettle, and A.M. Robinson, *Energy Absorption Capability and Crashworthiness of Composite Material Structures.* Applied Mechanical Review, 1988. **51**(10): p. 635-649.
7. Fernie, R., *Loading Rate Effects on the Energy Absorption of Lightweight Tubular*

Crash Structures: , in *School of Mechanical, Material, Manufacturing Engineering and Management.* 2002, University of Nottingham: Nottingham.
8. Silcock, M.D., et al., *A Novel Method of Tube Manufacture for Vehicle Crashworthiness Utilising the Quickstep Process.* 2004.
9. Silcock, M.D., *Composite Crashworthy Structures Manufacturing and Modelling*, in *CMFI* 2007, Deakin University: Geelong.
10. Dyckhoff, J. and H.-G. Haldenwanger, *Fibre-reinforced Composite Plastic Side member with Crash Compatibility*, in *Business Breifing,Global Automotive Manurfacturing & Technology*. 2003.