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LARGE-SCALE BLAST LOADING OF A COMPOSITE TUBE ARRAY FOR PROTECTION OF CIVIL ENGINEERING STRUCTURES

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Abstract

Crushing of composite tubes under impact loading has been studied very intensively over the last few decades. On the contrary, the energy absorption of composite tubes under blast loading is much less studied, and very limited public literature is available. This paper presents the experimental testing of a sacrificial cladding structure, composed of glass/polyester tubes, under blast loading. The composite tubes show stable and progressive crushing and considerably lower the peak force transferred to the non-sacrifical structure.

1 Introduction

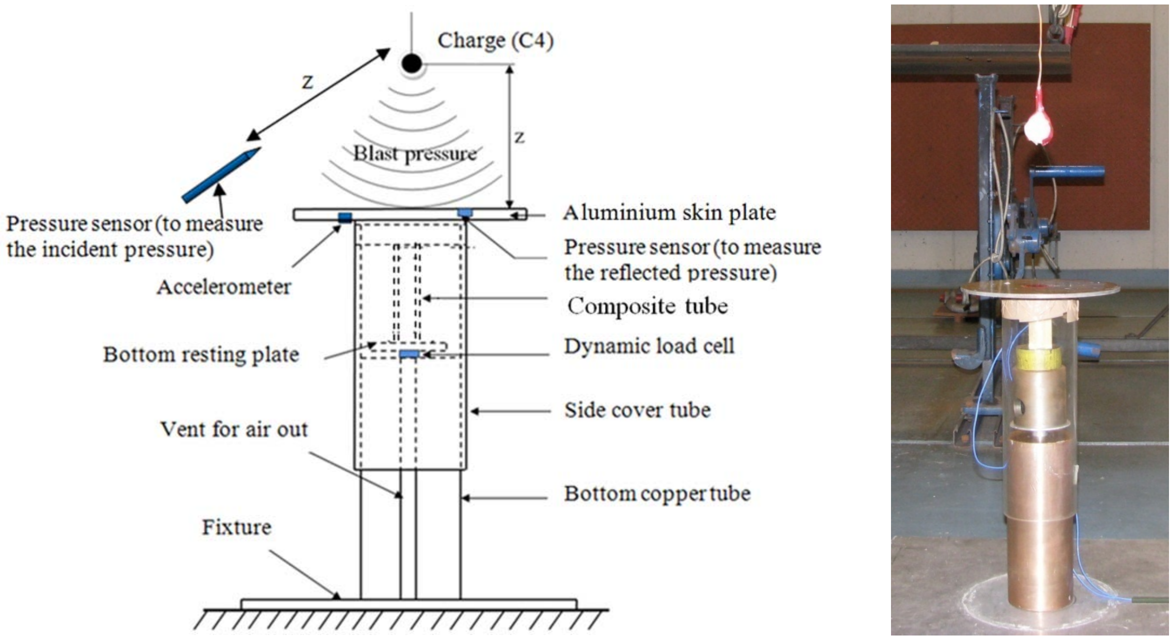
When civil engineering structures are subjected to blast loading, the failure of the critical load bearing members such as beams, pillars, columns etc., and its debris cause major human casualties. Hence a preventive solution is needed to safeguard those civil engineering structures. Out of many proposed solutions, the concept of sacrificial claddings has attracted a lot of attention. Any sacrificial cladding structure can have two layers (an inner core and an outer skin plate). The function of the skin plate is to distribute the blast pressure more evenly to the inner core which deforms progressively and absorbs most of the energy from the blast load, so that the main load bearing members will be safeguarded.

This contribution focuses on a sacrificial cladding structure with the core consisting of an array of composite tubes which should be responsible for the major energy absorption from the blast. Over the past years, the authors have studied the energy absorption of a single composite tube under axial impact and air blast loading [1-6]. Those models for crushing have been thoroughly validated by small-scale drop weight tests and blast tests in a bunker. The purpose of the research presented here, is to validate the proof-of-concept with large-scale air blast tests on a representative sacrificial cladding structure, composed of glass/polyester composite tubes as core material and sandwich composite skin plates.

Before discussing those results, the next paragraph discusses the observed strain rate insensitivity of the pultruded glass/polyester tubes. This observation is very important, because many insights from quasi-static and impact loading can be transferred directly to the blast loading tests. The authors are well aware that this strain rate insensitivity cannot be generalised, but is mainly due to the unidirectional fibre alignment in the pultruded tubes.

2 Strain rate insensitivity of pultruded glass/polyester tubes

The material, architecture and dimensional parameters of the composite tubes for the blast loading are the same as for the quasi-static testing, previously conducted by the authors [1-4]. To conduct such close-range free air blast tests on a single composite tube, a special laboratory test set-up was designed and manufactured (Figure 1). Tests have been conducted for varying different parameters such as **spherical explosive (C4) mass, stand-off distance, area of skin plate and mass of the skin plate. The incident angle for all tests is zero.**



(a) (b)

Figure 1. (a) - Schematic view (b) - Small-scale air blast test set-up.

To show an example for progressive crushing from free air blast tests, the deformation patterns of the circular cross sectional composite tubes are shown in Figure 2. It can be noticed that the crushing failure mechanisms of these tubes are the same as quasi-static testing results. Similar results were also observed for commercially available pultruded glass polyester composite tubes (M/s Exel composites, Belgium). The deformation patterns of these tubes are also presented in Figure 3.

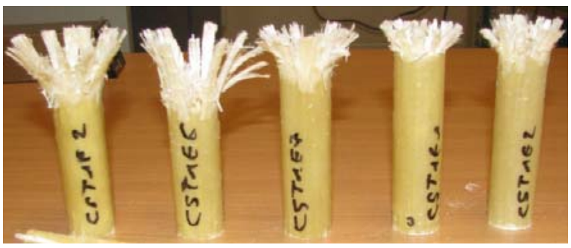
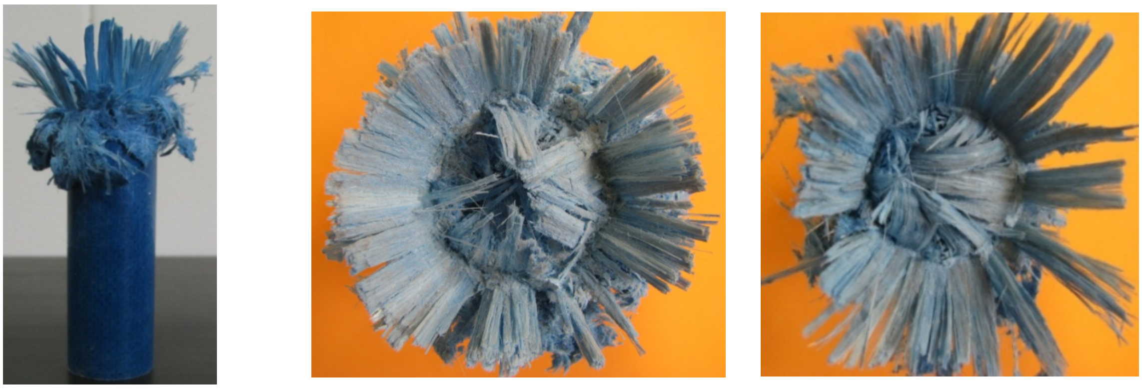


Figure 2. Uniform progressive crushing of the circular cross sectional glass polyester composite tubes (1 mm wall thickness) for different charge mass and stand-off distances (20g and 30g with 30 cm stand-off distance).



(a) Deformation pattern of commercially available pultruded GFRP composite tube (2 mm wall thickness) with triggering type 2 for 40g of C4 with 15 cm stand-off distance.

(b) Deformation pattern of commercially available pultruded GFRP composite tube (2 mm wall thickness) with triggering type 1 for 40g of C4 with 15 cm stand-off distance.

(c) Deformation pattern of commercially available pultruded GFRP composite tube (2 mm wall thickness) with triggering type 2 for 40g of C4 with 15 cm stand-off distance.

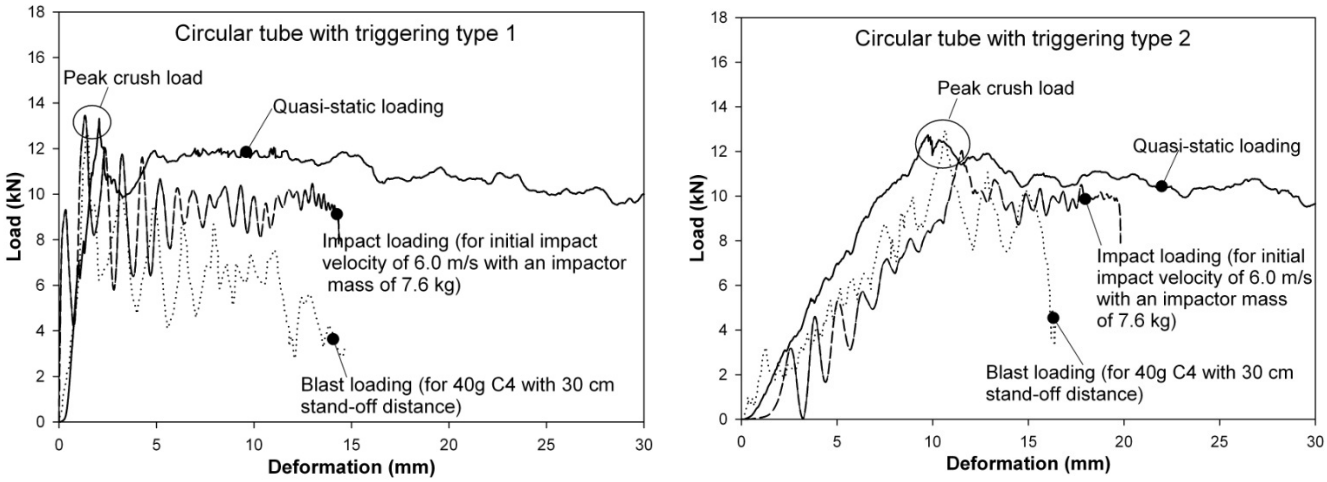
Figure 3. Progressive deformation patterns of commercially available pultruded GFRP composite tubes for free air blast loading**.**

Furthermore, the same finding was also validated for **contact blast loading** using a suspended pendulum test set-up which was developed in collaboration with Prof. Gerald Nurick from University of Cape town, South Africa (Figure 4(a)). Tests have been conducted on this pendulum set-up with different sizes of **cylindrical charge masses and with different striker masses**. As an example, the deformation patterns of the tubes subjected to contact blast loading are given in Figure 4(b). The failure mechanism and the patterns of these tubes are the same when compared to quasi-static experimental results. Hence, it can be concluded that the failure mechanisms and the failure patterns of these tubes (unidirectional glass polyester composite tubes) seems to remain identical irrespective of the strain rate.

(a) (b)

Figure 4. (a) Pendulum set-up for contact blast loading, (b) progressive deformation patterns of GFRP composite tubes subjected to contact blast loading condition.

Further, the authors would like to show a comparison of force-deformation curves of composite tubes with triggering type 1 (45° chamfering) and triggering type 2 (tulip triggering) for quasi-static, impact and blast loading conditions. Figure 5(a) shows the average force-deformation curves (from 4 tests of each type) of circular cross sectional composite tubes with triggering type 1. The quasi-static tests were performed for the cross head displacement of 10 mm/min; impact tests were performed for an initial impact velocity of 6.0 m/s with an impactor mass of 7.6 kg; and the free air blast tests were performed for 40g of C4 with stand-off distance of 30 cm. It can be noticed that the average peak crush load of these cases is very close to each other. A similar result was also observed for triggering type 2 (refer Figure 5(b)). Hence, it can be concluded that for uni-directional fibre orientation the effect of strain-rate on the peak crush load is negligible. Similar results have been also reported for glass polyester pultruded composite tubes in ref [7].



(a) Triggering type 1 (b) Triggering type 2

Figure 5. Comparison of force-deformation curves for different loading conditions (quasi-static, impact and blast loading).

3 Materials and methods for large-scale blast tests

The global view of the experimental test set-up is shown in Figure 6. The glass/polyester tubes were mounted on a (rear) sandwich composite skin plate behind which three dynamic force sensors were connected to a concrete wall to measure the transferred impulse to the concrete structure. All the skin plates used for the large-scale blast tests were manufactured by M/s Acrosoma, Belgium. The sandwich composite skin plates were made of three materials. The outer face sheets (top and bottom) are made of bi-axially balanced glass fibre with polyester resin; the core structure made of divinycell P foam. The outer face sheets are sewn together straight through the foam with aramid fibres. This prevents the delamination between the face sheets and the core structure. The locations of the force sensors are equidistant from the centre and the angle between these sensors is 120°. Another skin plate was assembled on the front side of the glass/polyester tubes (test specimens). The diameter of both front and rear skin plates was 1 m. The front skin panel was instrumented with three pressure sensors and two accelerometers to measure the reflected pressure and the acceleration of the skin plate respectively (refer Figure 6). The crushing face of the front sandwich skin panel was in-line with the end of the concrete tube which was close to the concrete wall. The C4 charge was placed at the other end of the concrete pipe (stand-off distance was 4.2 m - refer Figure 6). Blast experiments have been conducted on two configurations of the composite tubes (25 and 37 tubes) with different charge masses (100g and 150g of C4). Two high speed cameras were used to capture the crushing behaviour of the glass/polyester tubes during the blast loading.

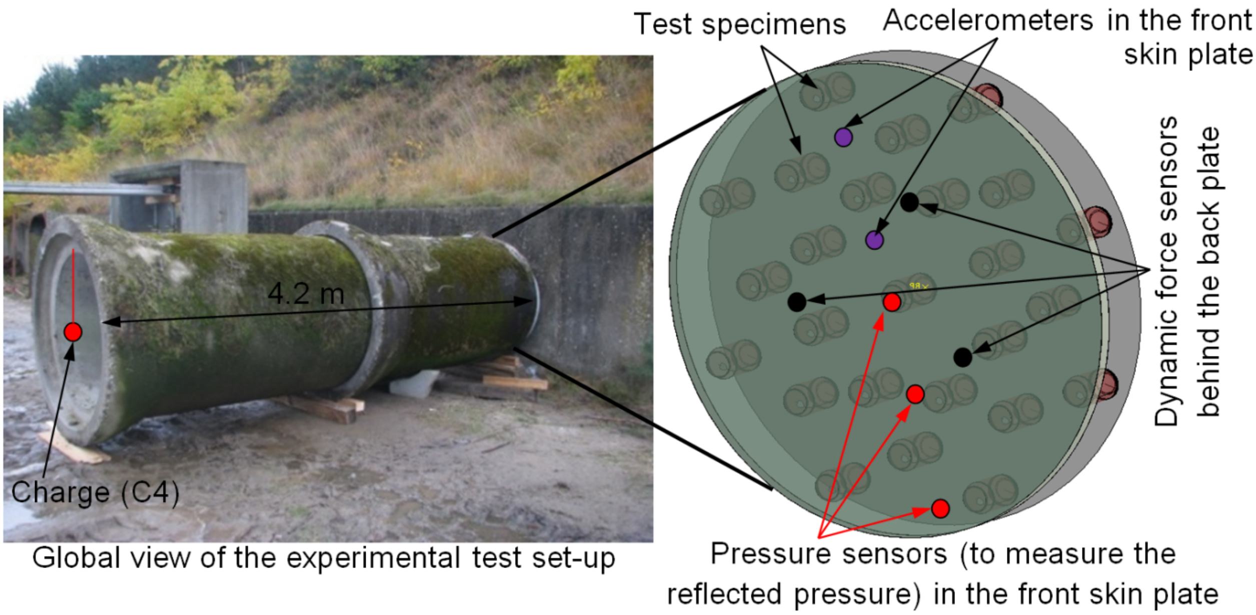


Figure 6. Schematic representation of the experimental set-up.

Simulations have been conducted for different charge masses and with different lengths of concrete sewage pipes to identify the length which was required to have a perfectly plane shock wave. The commercially available code Autodyn v12.1 was used. As an example, the simulated propagation of the pressure wave inside the concrete sewage pipes for 150g C4 with 4.2 m stand-off distance is shown in Figure 7. It can be noticed from the same figure that that a perfectly plane shock wave was formed at the other end of the tube.

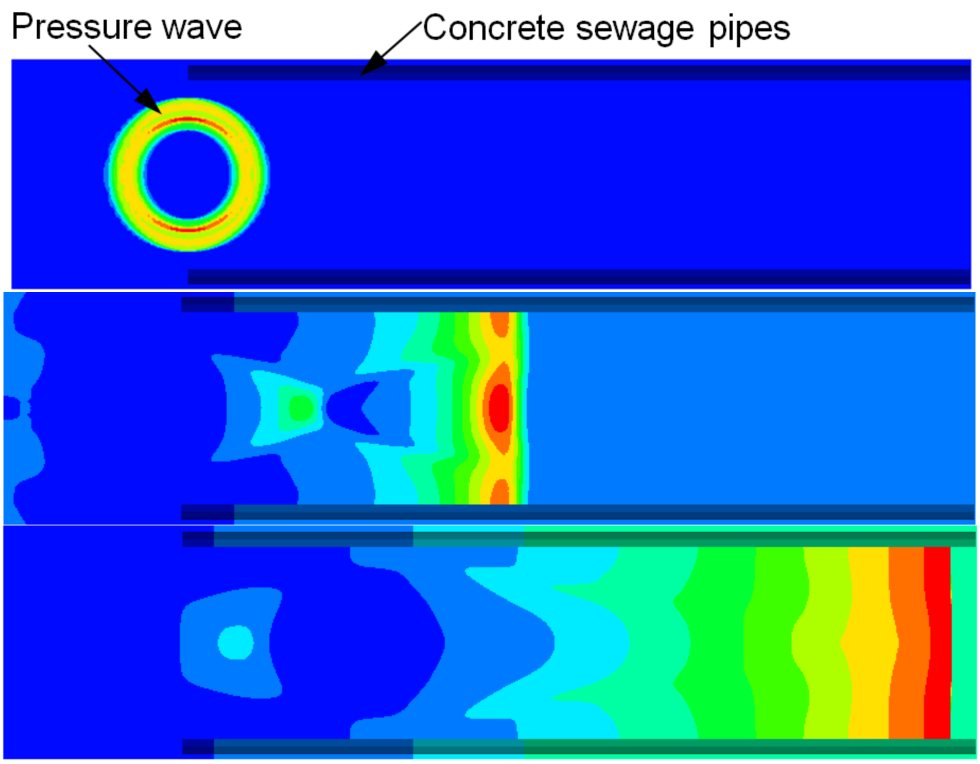


Figure 7. Propagation of blast pressure wave inside the concrete sewage pipes.

Also, the comparison of the experimentally measured and numerically calculated (Autodyn simulation) reflected pressure-time histories showed a very good correlation for peak reflected pressure and the positive duration of the blast.

All pultruded small-scale composite tubes used for the large-scale blast testing were reinforced with 18 streams of 4800 tex glass roving (P192 type from M/s OCV). The volume fraction of the fibre was approximately 50%. The POLYLITE® 413-010 resin (un-accelerated, non-thixotropic, medium reactive orthophthalic polyester resin) was used to manufacture the composite tubes. In order to achieve a uniform and progressive deformation pattern the t/D ratio of 0.045 was chosen. The dimensional and material details of the composite tubes are given in Table 1. The composite tubes have been cut for 100 mm length. To induce the failure at lower force, the 45° chamfering (triggering mechanism) was introduced at one end of the composite tubes. Preliminary quasi-static and impact investigations have been performed to check the progressive crushing deformation patterns of these tubes.

Cross-section	Fibre	Resin	Dimensions (mm)	ρ_{linear} (g/mm)	Volume fraction (%)
Circular	Glass	Polyester	$\phi = 22$ $t = 1$ $L = 100$	0.14 without foam 0.15 with foam	$V_m = \sim 50$ $V_f = \sim 50$
ϕ - Outer diameter; t – thickness; L – length of tube; V_m – volume fraction of matrix; V_f – volume fraction of fibre.					

Table 1. Dimensional and material details of the composite tube series.

4 Results

For all tests the composite tubes showed uniform and progressive crushing failure modes such as delamination, axial cracks, lamina bending, fibre fracturing and compression of polyurethane foam. As an example, the progressive crushing stages for configuration 1 (25 composite tubes) from one of the high speed cameras are shown in Figure 8 for 150 g C4. For all these tests both the front and rear skin panels experienced local and global bending modes. This effect can be noticed from the same figure. This was due to a high stiffness of the composite tubes and the corresponding effective contact area with the front and rear skin panels.

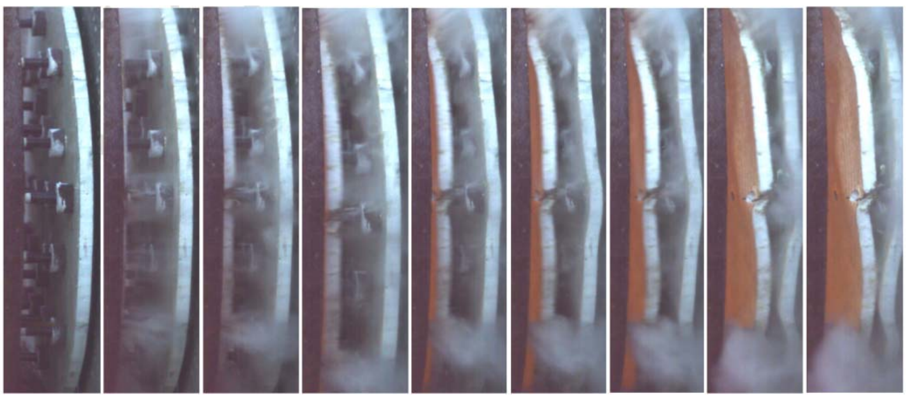


Figure 8. Progressive crushing stages of the 25 composite tubes (25 numbers) for 150 g of C4.

Due to the small contact area the skin panels were highly stressed during the crushing process. After each test the front and rear skin panels were checked. The mounting locations of the rear skin panels showed a noticeable deformation at the mounting locations.
As an example, the final deformation patterns of two composite tubes from each case are shown in Figure 9(a-d). It can be noticed from these figures that the deformation patterns of the composite tubes are consistent; and all typical failure modes are clearly evident. The average deformation length for configuration 1 was higher (55.7 mm) than for configuration 2 (33.7 mm).
Similar to the quasi-static and impact tests, the presence of the polyurethane foam prevented the axial splitting of the tube wall. In addition to that the low density of the polyurethane foam did not affect the continuous delamination and subsequent fibre fracturing failure modes which are very good irreversible energy dissipation mechanisms.

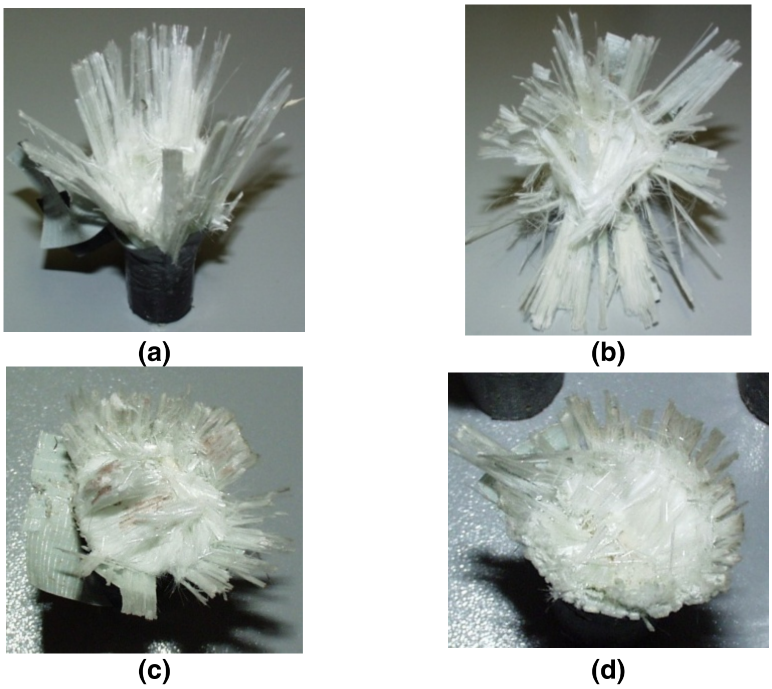


Figure 9. Final deformation patterns of composite tubes (a-b) for 150 g of C4 with configuration 1 (25 composite tubes). (c-d) for 150 g of C4 with configuration 2 (37 composite tubes).

5 Conclusions

Large-scale blast tests have been conducted to understand the blast mitigation performance of the pultruded small-scale glass polyester composite tubes. Tests have been conducted on two configurations of the composite tubes (25 and 37) with two charge masses of C4 (100 g and 150 g). From the conducted experimental tests the following conclusions can be made.

- For thin-walled composite tubes, in addition to several parameters such as t/D ratio, linear density and triggering mechanisms, the uniform distribution of the wall thickness plays a significant role to achieve progressive deformation patterns. A non-uniform distribution of the wall thickness can result into catastrophic failure modes. For the chosen composite tubes (pultruded small-scale glass polyester composite tubes) the catastrophic failure modes were avoided by the polyurethane foam-filling on the outer surface of the composite tubes.
- The conducted axial quasi-static, impact and large-scale blast experiments have showed that the deformation patterns of these composite tubes remain the same. The

typical brittle composite tube failure modes such as delamination, axial cracks, lamina bending and fibre fracturing were clearly evident.

- The failure pattern of a foam-filled composite tube highly depends upon the density of the filled foam material. A high density of the foam can suppress few failure modes and associated energy absorption. However, a low density foam material can improve the wall strength and stability of the composite tube during crushing; furthermore it can allow to achieve the typical failure modes of the composite tubes and the corresponding energy absorption.
- The average peak crush load of the configuration 1 and 2 (25 and 37 composite tubes respectively) was 86.5 kN and 103.1 kN respectively. Progressive crushing was achieved for all tests.

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