EXPERIMENTAL AND NUMERICAL INVESTIGATION OF COMPOSITE ENERGY ABSORBERS USING VARIABLE LOAD CONCEPT

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ABSTRACT

Composite materials have been extensively used in modern helicopters' structures to reduce structural weight. These include energy absorption components to improve crashworthiness performance. Despite composite material can offer higher Specific Energy Absorption (SEA) than traditional metallic materials, there are limitations from the current energy absorbers in a practical helicopter crash scenario, such as under-utilisation of the crushing stroke leading to inefficient material usage and occupants experiencing unnecessarily high deceleration. This paper describes the results of a project to develop the improved system for the crashworthiness. As part of this project, a novel Variable Load Concept (VLC) to improve the performance of the energy absorption has been introduced [1] in which, the crushing force can be controlled through the radius size of trigger mechanism and the use of pressurised composite tubes. As the composite specimens of increasing crush speeds were tested, the concept and the system were developed and further validated. The crush speeds included quasi-static, 2 m/s and 8 m/s load conditions. The validation of the VLC through design and test of the energy absorbing pressurised composite tube system is described in details. The final results showed that the VLC with pressurised composite tube system can be used in crashworthiness applications, and that the improvement in energy absorption has been enabled significantly. Finally, an explicit finite element study was carried out by using finite element (FE) software VPS (formerly known as PAM-CRASH) and the results showed very good agreement between FEA model and experimental work.

1. INTRODUCTION

The crashworthiness performance of rotorcraft structures is very important to the occupants. The main objective of designing crashworthy aerospace structures is to absorb maximum energy with minimum weight, while lowering the peak loads transmitted to occupants to be within human tolerance. Metallic thin-walled structures with different cross-sections have been used since 1970s [2-4]. In recent years, there has been considerable interest in the use of composite materials for the crashworthiness, driven mainly by the increasing use of these materials for primary structures in the aerospace industry. In addition, a composite structure offers vast potential for optimally tailoring a design to the applied loading, which results in an energy absorbing structure with increased strength and stiffness compared to an equivalent traditional metallic construction. Therefore, intensive work has been carried out to examine the energy absorption performance and failure mechanism of open and closed sections made from composite materials [5-12].

Despite significant advances in composite based energy absorbers used, the device crush behaviour is often not in a controlled manner. This includes the energy absorber fails catastrophically at the start of crush resulting in absorbing a negligible amount of energy and the crush behaviour is often unstable with crush load oscillating significantly which are undesirable in the case of a crash. To overcome this issue, energy absorbing composite structures often include a triggering mechanism to cause local stress concentration at a specific location. This high local stress initiates the micro-failure of the structure with a relatively peak load and ensure a process of continuous high energy absorption.

Furthermore, a few design concepts have been developed to improve the energy absorption performance, in which, one of the concepts used to improve the performance of energy absorbing structures is to achieve adaptive energy absorption. For example, a magnetorheological (MR) damper was tested by Crzegorz and Holnicki [13] as an adaptive impact absorber for helicopter landing gear. Although controllable resistant force can be achieved in this type of damper, it can only work at low velocity and there are still many unsolved issues for their application under impact loadings. In a second example, Abosbaia et al. [11] investigated the energy absorption of segmented composite tubes, which consist of three types of fibre epoxy, under quasi-static compressive loading. This segmentation concept integrated in a composite crush tube has shown the potential of variable load behaviour in different crush stages during the test, but the crush force efficiency (defined as steady state crushing stress over peak crushing force) is very poor with these tests. The tested concept showed that a change in the segmentation sequences affects the crush loads significantly and some segmented tubes failed with early bulking and catastrophic failure. The crush tubes without triggering mechanisms led to the crush progressing from both sides of the energy absorber. The design would therefore be incapable of reacting in a controlled manner as a crashworthiness structure. The segmented composite tubes investigated by Abosbaia et al. [11] are therefore less efficient than the integrated radius triggering mechanisms reported in this paper.

The current work in this paper is a contribution from University of New South Wales collaborating with the German Aerospace Center, DLR to form part of the Cooperative Research Centre for Advanced Composite Structures (CRC-ACS) project “Systems for Crashworthiness”. As part of this project, a novel variable load concept to improve the performance of the energy absorption of a crushing composite element was developed for helicopter crashworthiness applications [1]. This variable load concept (VLC) will be presented with details in the next section. With the novel VLC, the energy absorber is designed to crush with a variable load and constant stroke. In this case, the occupant never experiences unduly high decelerations because the energy absorber stroke can be optimally utilised, regardless of the crash scenario. In order to achieve adaptive energy absorption, a system has been developed utilising pressurised air inside a composite crush tube. The validation of the VLC through the design, manufacture and the test of a second generation crushing system demonstrator for impact tests utilising the drop tower at DLR is described in this paper.

2. VARIABLE LOAD CONCEPT

Typically energy absorbers expend crash energy by crushing at a constant load over a variable stroke (crushing distance). The deceleration of the occupants is therefore constant regardless of the crash velocity. The result is under-utilisation of the crushing stroke if the crash speed is too low; leading to inefficient material usage and occupants experiencing unnecessarily high deceleration. Alternatively, if the crash speed is too high, the crushing stroke is exhausted and the tube “bottoms out”, leading to very high peak loads experienced by the occupants, as indicated in Figure 1a.

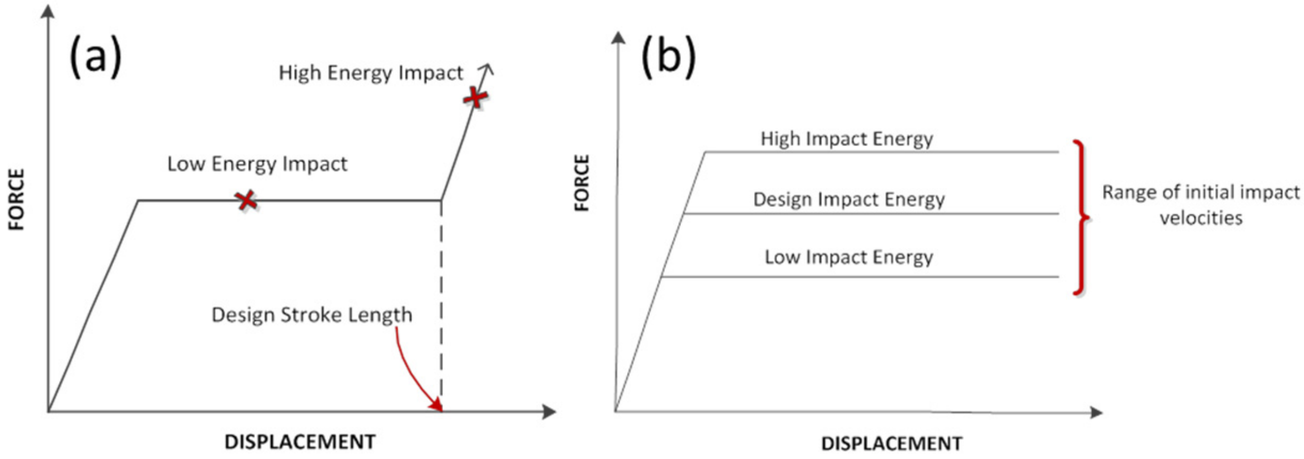

Figure 1: Variable load concept (a) passive design (b) with variable crushing load design [1]

With the novel variable load concept, the energy absorber is designed to crush with a variable load and constant stroke. In this case the occupant never experiences unduly high decelerations because the energy absorber stroke is always optimally utilised, regardless of the crash scenario. The result is minimisation of peak forces experienced by the occupants and the lowest possible risk of injury or death, as shown in Figure 1b.

Two loading types have been included in this investigation. The first is to optimise the tube design for a particular mass and impact velocity. The second type allows a controllable crushing force to achieve an adaptable crushing element that can be fully expended under a range of accident scenarios. In the current work, compressed air is used as the controllable crushing force inside thin-walled cylindrical composite tubes and their energy absorption behaviours under axial crushing are dynamically investigated.

3. VLC CRUSH SYSTEM DEVELOPMENT

3.1 Crush Element

Axis-symmetric cylindrical tubes have been preferred by researchers to carry out experimental work on the energy absorption of composite materials because they are easy to fabricate and also close to the geometry of the actual crash worthy structures [14]. Beside this, cylindrical composite tubes were selected for this work, because it is easier to seal the compressed air inside the device. The non-circular sections can experience leakage from the corners and the pressurisation can cause stress concentration located at the corners.

Composite tubes were initially manufactured by wrapping a woven thermoplastic prepreg material onto a mandrel with a pure $0^{o}/90^{o}$ lay-up and then cured in an autoclave according to the manufacturer's specification. The prepreg material that was used is 'SKY FLEX WSN-3K", a plain-weave fabric that features carbon fibre material and epoxy resin. The specimens were then cut into the geometry shown in Figure 2. The composite tube is 120.0 mm in length, wall thickness 1.0 mm with inner diameter 38.2 mm and a 70^{o} chamfer was machined into one end of each specimen.

In order to achieve a big range of force in the profiles in Figure 1b, the first step is to achieve crushing behaviour as low as possible for the low impact energy crush case. Though the Specific Energy Absorption (SEA) increases with decreasing diameter (D) of the tube, SEA mainly depends on the absolute value of thickness (t), rather than the D/t ratio. For a given value of D, SEA increases with increasing t up to certain value and it starts to decrease above that. Highest specific energy absorption capability has been displayed by tubes of thickness in the range of 2-3mm [15]. To achieve a low force, the lowest thickness of tubes is preferred while avoiding a buckling failure. Gupta et al. [16] reported that the catastrophic failure and global buckling of axially crushed composite cylindrical tubes can be avoided by maintaining the D/t ratio between 15 and 40. Thus the wall thickness of crushing element has been carefully selected to be 1.0 mm with D/t ratio approximately 38. Note that a triggering mechanism is also used to ensure the lower impact energy profile, which will be discussed in the next section.

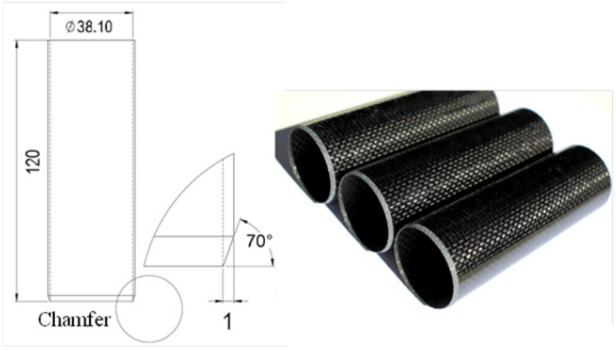

Figure 2: Crush composite tube sample

3.2 Quasi-static Crush System

A crushing test system has been developed in the previous work [17], as shown in Figure 3, to validate the VLC under quasi-static load condition. To overcome the sealing problem, a special plug impactor and crushing base have been designed with triggering mechanism and sealing zone, which can initiate the composite tube into progressive crushing mode and also simultaneously seal the air inside the tube during the crushing process. The internal pressure can be controlled constantly during the test and more details about the quasi-static crush system are described in the paper [17].

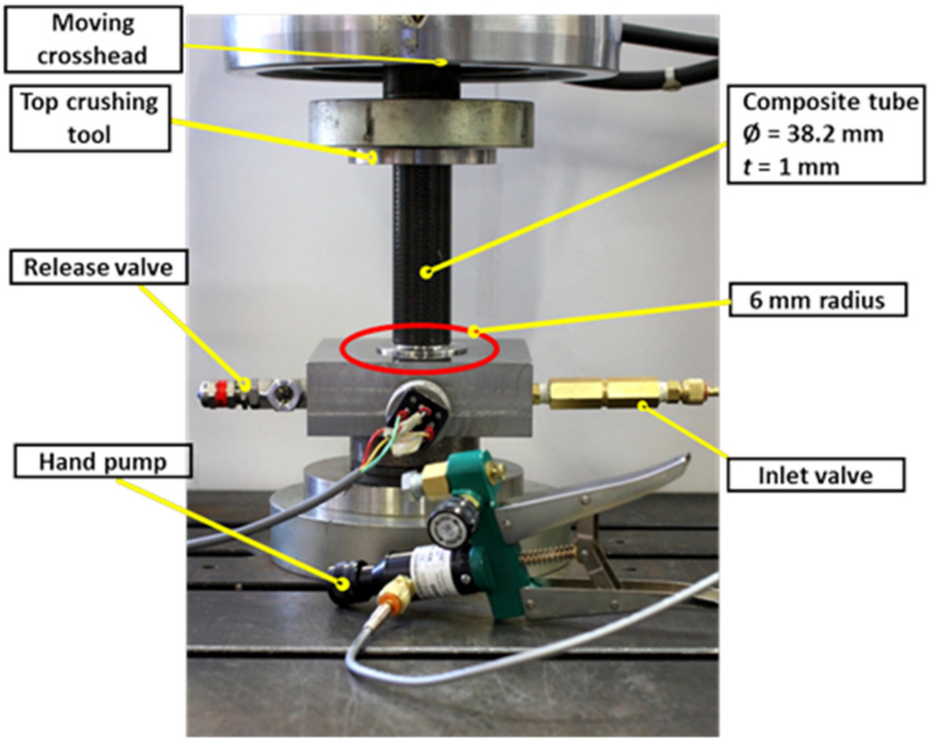

Figure 3: Experiment set-up [17]

3.3 Impact/Dynamic Crush System

The second generation crushing test system was developed for impact tests utilising the drop tower facility at the DLR. In the new VLC system, a major improvement is that the spring operated relief valve was replaced with a pressure control sub-system (B) indicated in Figure 4. It consists of a back pressure regulator using a diaphragm to allow the pressure to be released quickly during the test and a manual set-point to pre-set the pressure to the desired level according to the energy required to be absorbed during each test. This is connected to the main specimen crushing system (A).

To provide a sealed system, a special plug impactor and crushing tool base have been designed incorporating a triggering mechanism and sealing zone. Double O-rings are chosen for sealing on both top and bottom plug-in tools to ensure a good seal and balance the friction between the composite tube and the plugs. A high data rate pressure transducer is connected to the base to monitor the pressure during the test.

4. VALIDATION OF VLC WITH DYNAMIC CRUSH SYSTEM

4.1 Testing Approach

Three test conditions, one quasi-static, 2.0 m/s and 8.0 m/s dynamic, were undertaken. The purpose of the quasi-static test was to establish the baseline performance and energy absorption characteristics of the structure. The purpose of the dynamic testing was to evaluate the crash performance of the system at two different impact speeds.

4.2 Test Setup and Method

The quasi-static tests were conducted at the Solid Lab, UNSW with an Instron 8800 universal 250.0 kN machine at 5.0 mm/min as shown in Figure 3. The dynamic tests were conducted at the DLR Institute of Structures and Design in Stuttgart. The first group of dynamic test was performed in a drop tower shown in Figure 5 at an impact velocity of approximately 2.0 m/s.

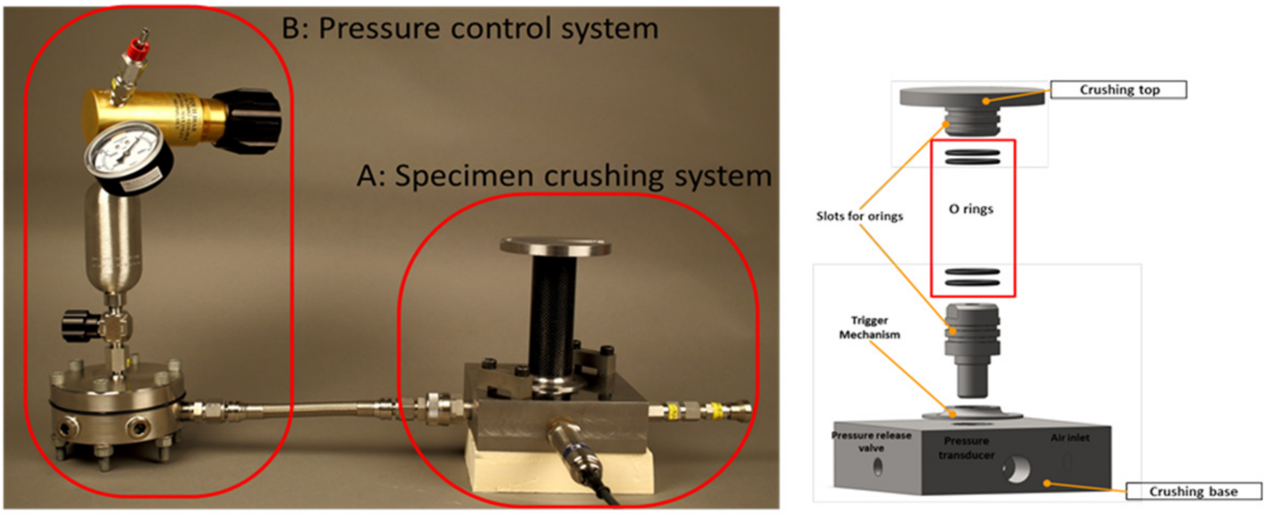

Figure 4: Impact crushing set-up (left) and detailed design for specimen crushing system

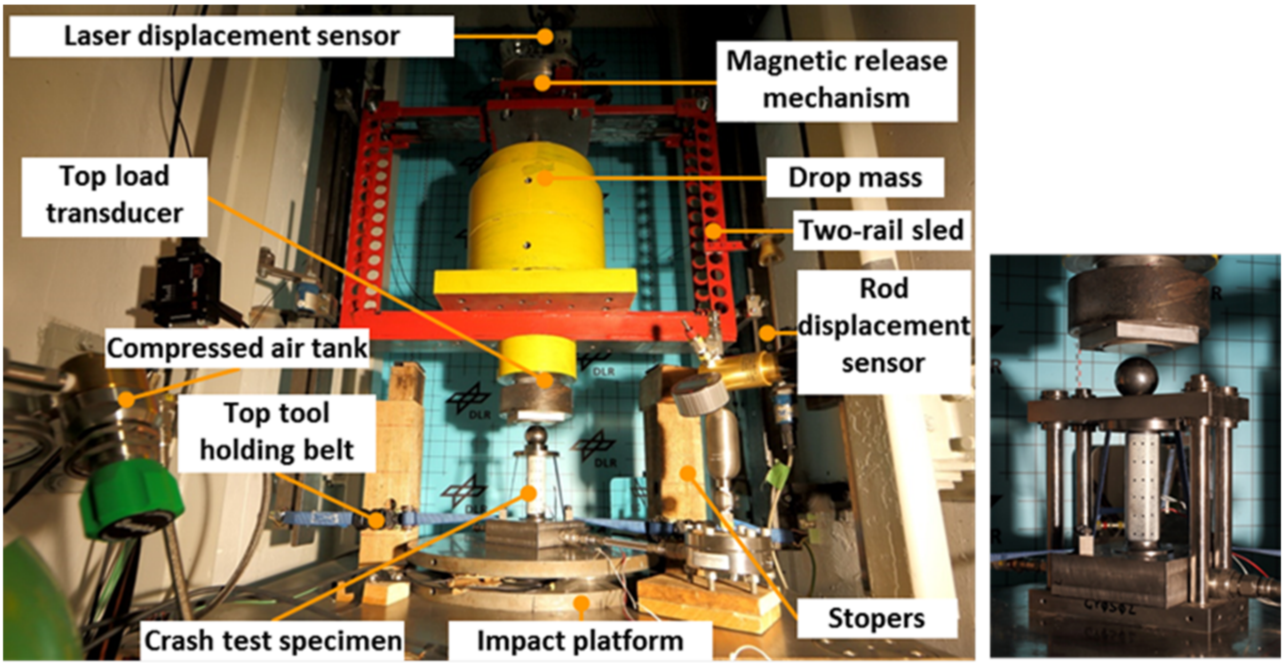

Figure 5: 2.0 m/s impact test set-up (left) and the specially designed guide rail (right)

A novel drop tower, designed and built specifically for the second group of dynamic test is shown in Figure 6. The impact velocity was approximately 8.0 m/s, corresponding to the regulatory requirement for military helicopters [18]. The group 1 and group 2 dynamic tests were conducted with drop mass 293.0 kg and 14.5 kg, respectively. The drop mass were stopped at the end of the stroke required for each test by the stopers to absorb extra energy over the capacity of the structure. The 6.0 mm radius was selected for the triggering mechanism for the tests and three different constant pressure levels were maintained by using the pressure control system (B). In this work, the pressure levels used were 9.0 bar and 18.0 bar and the results were compared with the tubes crushed without any pressurisation. Each of the tubes was crushed to 40.0 mm stroke length to investigate the energy absorbing behaviour. The specimens were instrumented with strain gauges and the tests were recorded using high speed video camera.

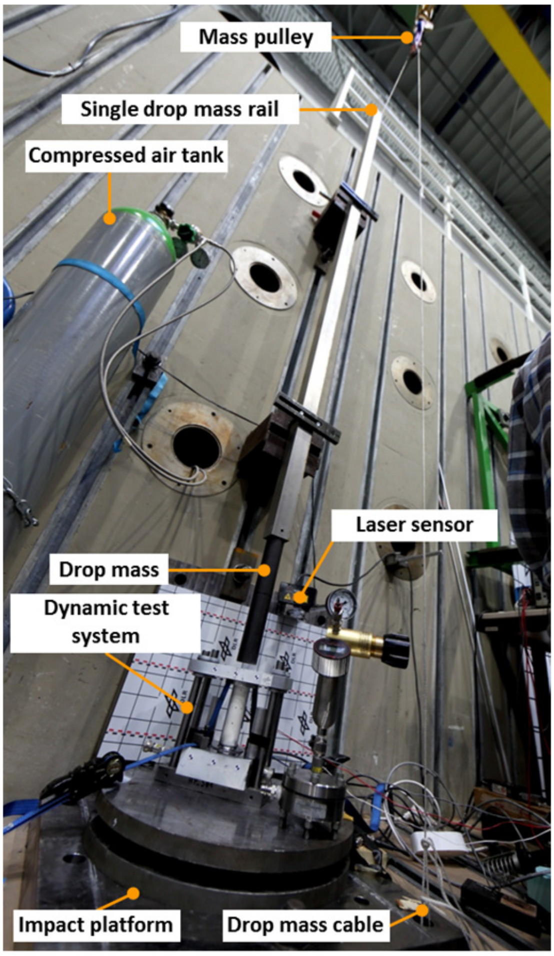

Figure 6: 8.0 m/s Impact test set

4.3 Test Results-Experimental response (Crushing Velocity)

A summary of the test conditions and results (peak load, steady state crush force (SSCF) and SEA) for all the tests inclusive quasi-static tests conducted in previous research work in Ref. [17] and the dynamic tests in this work are detailed in Table 1.

The dynamic crushing velocities were predetermined at 2.0 m/s and 8.0 m/s at the start of drop mass in contact with the specimens and the velocity-displacement curves are presented in Figure 7 and Figure 8. Constant crushing velocity and steady deceleration are observed for 2.0 m/s and 8.0 m/s dynamic tests, respectively.

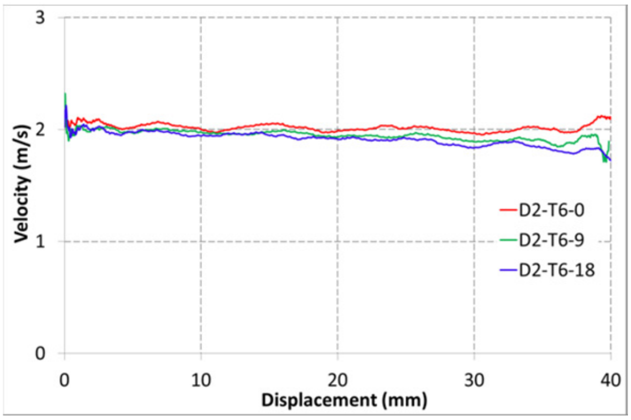

Figure 7: Velocity-displacement responses of 2.0 m/s dynamic test

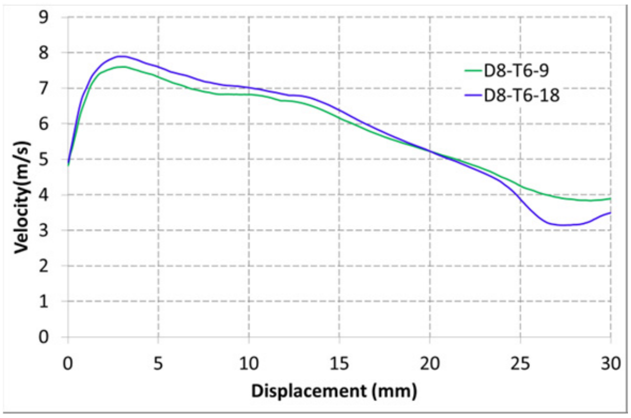

Figure 8: Velocity-displacement responses of 8.0 m/s dynamic test

Specimen Designation	Static/dynamic	Internal pressure	Peak load (kN)	SSCF (kN)	SEA (J/g)
Tubes with 6 mm trigger mechanism					
QS-T6-0	Static	0	3.5	3.3	19.0
QS-T6-9	Static	9	4.8	4.6	26.6
QS-T6-18	Static	18	5.7	5.5	30.3
D2-T6-0	2.0 m/s	0	3.9	3.3	18.8
D2-T6-9	2.0 m/s	9	5.0	4.6	25.5
D2-T6-18	2.0 m/s	18	6.3	5.7	28.9
D8-T6-9	8.0 m/s	9	5.5	4.3	22.1
D8-T6-18	8.0 m/s	18	8.6	6.3	34.8

Table 1. Summary of the experimental results

4.4 Test Results-Experimental Response (Internal Pressure)

Internal pressure was monitored during the test to identify any possible leakage and ensure the effectiveness of the pressure control system effective. The results show that the double O-ring sealing method and the back pressure regulating control system is capable of sealing compressed air dynamically inside composite tubes. Typical pressure profiles are presented for 2.0 m/s and 8.0 m/s dynamic tests in figure 9 and 10, respectively. Although the pressure slightly increased from the start of the test, it decreased back to the desired pressurisation level before the end of the test. The increment and the variation of the internal pressure during the dynamic tests are accepted, considering overall period of the test was only between 8.0 to 25.0 milliseconds.

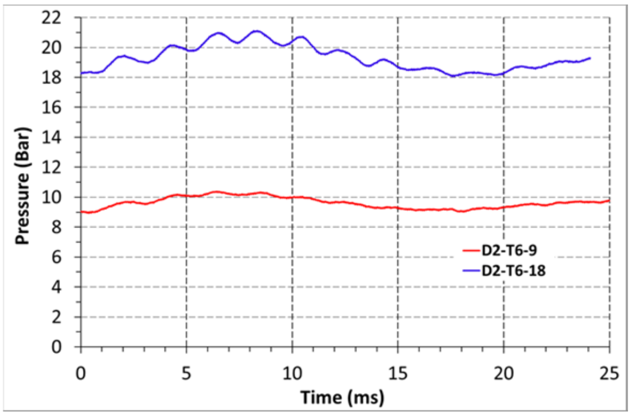

Figure 9: Internal pressure record for 2.0 m/s dynamic test

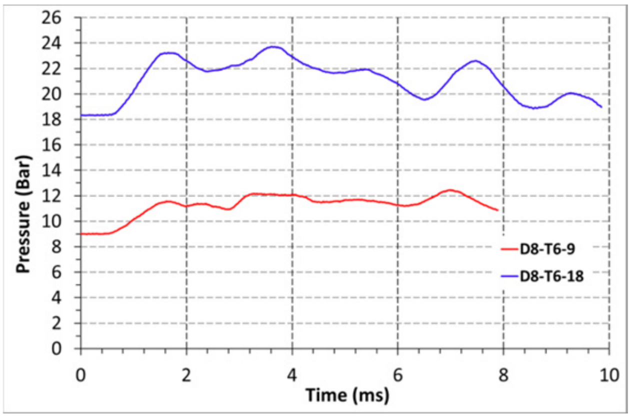

Figure 10: Internal pressure record for 8.0 m/s dynamic test

4.5 Test Results-Experimental Response (Force-displacement)

For each of the tested configuration, two composite tubes were tested. At the end of crushing test, the fixture was removed and the specimen was analysed. The crushed tubes were firmly held outside the plug-ins of the crushing system due to the friction between the specimens and the O-rings. Due to the consistency of the test results, only one curve for each test configuration is shown in subsequent graphs in order to improve clarity. The measured load-displacement curves from Quasi-static [1], 2.0 m/s and 8.0 m/s dynamic tests are presented in Figure 11-13. During the test program, the results for two unpressurised specimens under 8.0 m/s dynamic loading condition were not recorded on the data log. Thus these results are not included in this paper. It shows that stable, progressive crushing was initiated and sustained for both quasi-static and dynamic tests. Typically, the load increased linearly over the first 4-6 mm of vertical displacement to a certain value, after which the crushing load stabilised in a progressive manner until the end of the test. The response of the specimens in all three test conditions was similar, although the measured force from 8.0 m/s dynamic test oscillated more than quasi-static and 2.0 m/s dynamic test.

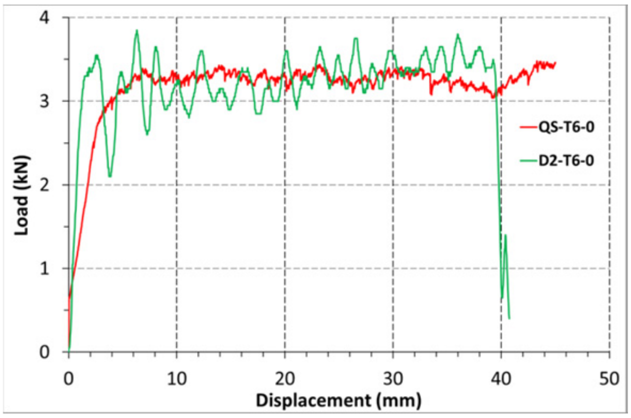

Figure 11: Comparison of force-displacement responses between unpressurised quasi-static and dynamic test

The plots of the three different pressurisation levels (unpressurised, 9 bar, and 18 bar) for 2.0 m/s and 8.0 m/s dynamic loading conditions are shown in Figure 14 and 15, respectively. The excellent agreement has been achieved between the dynamic loading condition and the VLC demonstrated in Figure 1b. A significant increment in energy absorption has been observed in the specimens crushed at 18.0 bar pressurisation on the 6.0 mm trigger radius mechanism with approximately 60% improvement. This wide range of the steady state crushing force can be potentially utilised to achieve effective crushing system with VLC in crashworthiness applications.

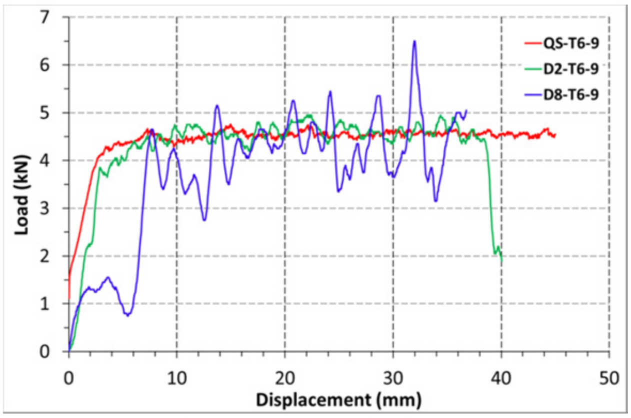

Figure 12: Comparison of force-displacement responses between static and dynamic tests under 9 bar pressurisation

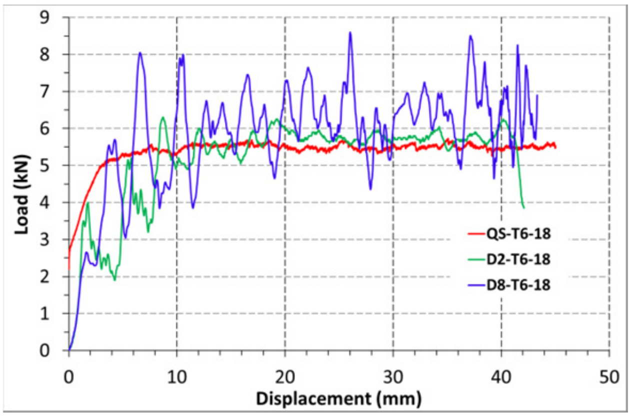

Figure 13: Comparison of force-displacement responses between static and dynamic tests under 18 bar pressurisation

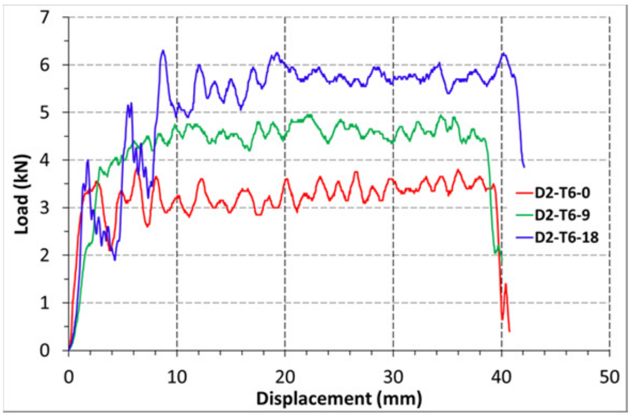

Figure 14: Force-displacement responses of 2.0 m/s dynamic tests

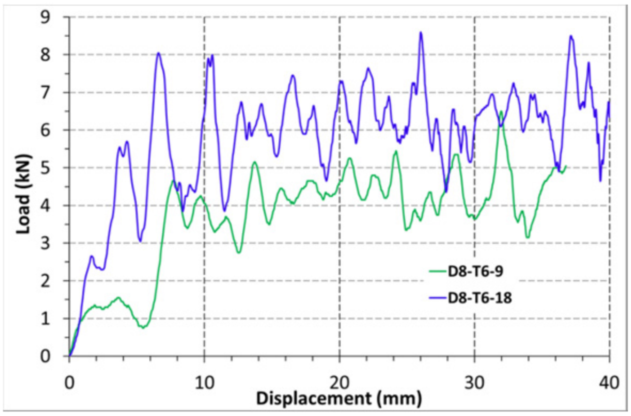

Figure 15: Force-displacement responses of 8.0 m/s dynamic tests

4.6 Test Results-Video Images

Photron Fastcam APX RS model 250K was used to record the response of the crush system during each test. The test tubes were spray painted with a light coat of white to improve the contrast of the video and highlight any possible crack during the test. Figure 16 present a set of images extracted from the video camera for the quasi-static, 2.0 m/s and 8.0 m/s dynamic loading condition tests, from left to right, respectively. From analysing the crushing process, all specimens failed in the splaying failure mode where axial splitting occurs, forming fronds of crushed material which splay outwards at the crushing surface against the crushing base trigger mechanism. It was identified that the petal size formed due to splitting in dynamic tests are smaller than those crushed quasi-statically.

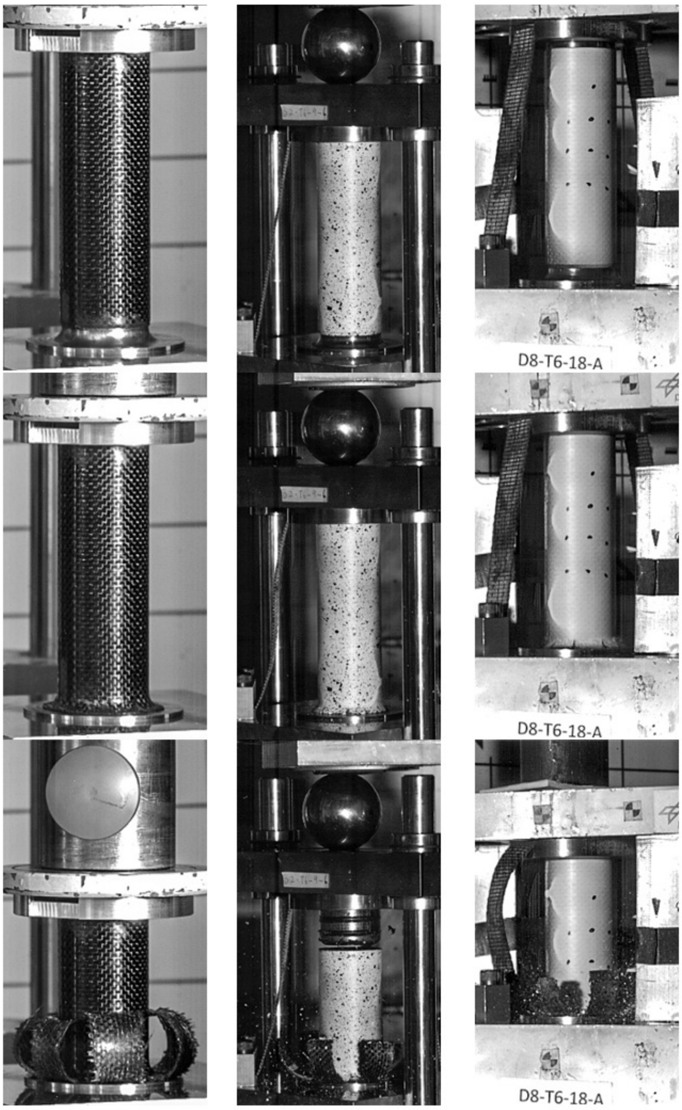

Figure 16: Video images from the (left) quasi-static, (centre) 2.0 m/s and (right) 8.0 m/s dynamic loading condition tests

5. NUMERICAL INVESTIGATION OF THE COMPOSITE CRUSH TUBE

Based on the experimental investigation, numerical modelling techniques were developed in VPS an explicit finite element (FE) software to predict the crushing behaviour of the composite energy absorbing elements. The modelling method builds on previous work [19] and uses a meso-scale composite damage model [20] in which the composite laminate is represented by stacked shell elements (incorporating an appropriate composite material degradation model) connected through interfaces that can fail via a cohesive fracture law [21]. In the vicinity of the bottom plug, different zones were defined to represent the varying levels of friction forces present during crushing, as shown in Figure 17. The predicted failure mode of the energy absorber compared very well with the test, as shown in Figure 18 and was shown to be able to capture the pedalling failure mode and varied energy absorption mechanisms observed in the experimental tests. The friction forces in-between the composite tube and the O-rings and the plug were obtained from the quasi-static test and used to calibrate the numerical model. A comparison of the numerically predicted and experimental response for the composite crush tube is shown in Figure 19. Phase A show that the friction force between the composite tube and the crushing tools has been excellently simulated in the numerical model. It is identified that the numerical model slightly under-predicts the axial stiffness in the initiation phase B and the steady state crushing phase C. A summary of the comparison between the experiment and the numerical study is provided in Table 2. The results show that the numerical simulations using the detailed modelling approach yielded very good correlation with the experiments.

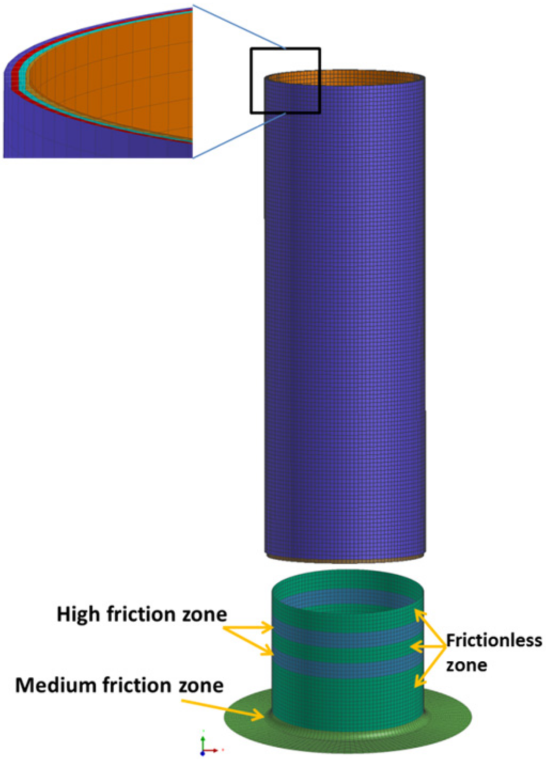

Figure 17: Detailed FE model of the composite crush tube

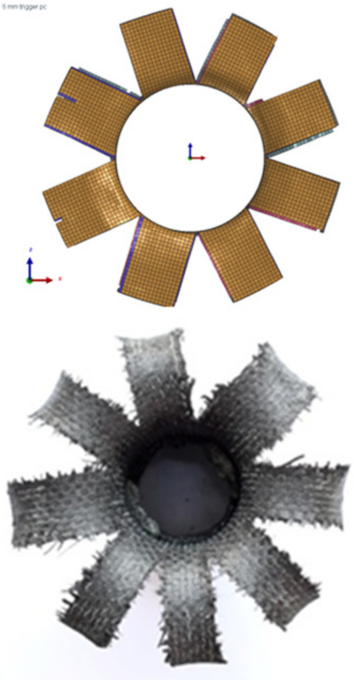

Figure 18: Comparison of the numerical and experimental crushing modes for a composite crush tube

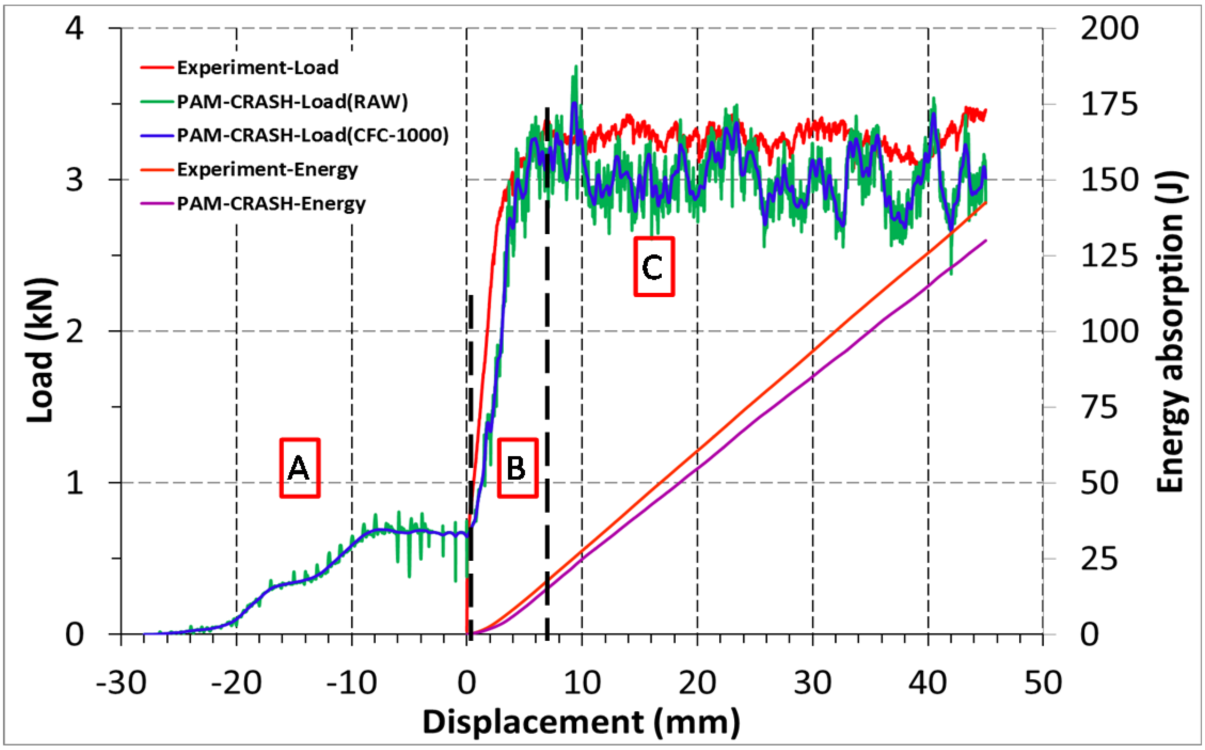

Figure 19: Comparison of predicted and experimental response of composite crush tube test

Peak load (kN)			SSCF (kN)			SEA (J/g)		
Experiment	PAM-CRASH	% error	Experiment	PAM-CRASH	% error	Experiment	PAM-CRASH	% error
3.5	3.5	0	3.3	3	9.1%	19	17.3	8.9%

Table 2. Summary of results from experiment and simulation

6. CONCLUSION

A novel Variable Load Concept (VLC) to improve the performance of energy absorption in crashworthiness application has been developed and validated. To validate the VLC, an experimental investigation using energy absorbing pressurised composite tubes has been developed and tested dynamically in this work.

Through the experimental investigation, the results showed that the internal pressure was maintained constantly during the dynamic test without leakage. With the success of the dynamic crushing system design for VLC, it showed feasibility of using pressurised composite tubes as variable load energy absorbers. The specimens with 18.0 bar pressurisation delivered 60% energy absorption enhancement compared to an unpressurised tube, which indicates that the forces transmitted to the occupants can be minimized subject to achieving desired energy absorption, thus significantly improving the survivability.

Based on the concept and design, a numerical study was carried out using a FE software, VPS (formerly known as PAM-CRASH) and the results showed very good agreement between FEA model and the experimental work. This model can be used to design and optimise pressurised composite tube system in energy absorbing structures, while significantly reducing the demands for expensive physical experiments.

7. ACKNOWLEDGEMENTS

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