EXPERIMENTAL DEVELOPMENT AND ANALYSIS OF AN ACTIVE CRUSHING ELEMENT USING PRESSURIZED COMPOSITE TUBES

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Abstract

In this paper, a novel concept with variable crushing loads has been proposed to improve helicopter crashworthiness. Quasi-static crush testing of carbon-fibre/epoxy specimens representative of elements in an energy absorbing subfloor structure was designed and tested. The results showed the significant improvement in energy absorption and crushing stroke has potential to be fully expended under all accident scenarios. Finally, an explicit finite element study was carried out by using software PAM-CRASH and the results showed very good agreement between FEA model and experimental work.

1 Introduction

The Cooperative Research Centre for Advanced Composite Structures (CRC-ACS) is investigating retrofit solutions for improving helicopter crashworthiness. As part of this program, a novel concept to improve the performance of the energy absorption of a crushing element has been being undertaken. The underlying aim of the present project was to develop a crushing element that can be fully expended under all accident scenarios. This required a controllable crushing force, so that the full stroke of the crushing element was used independent of the initial impact velocity, as indicated in Fig. 1.

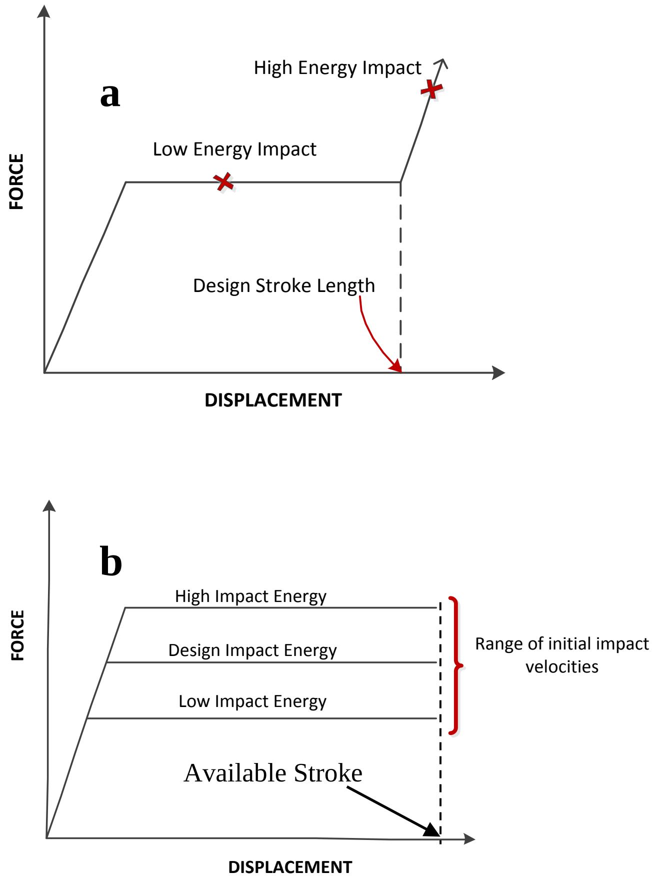

Fig. 1. Load-displacement curves for an energy absorber (a) passive design (b) with variable crushing load

Typically, helicopter energy absorbers are designed as passive devices with characteristics satisfying pre-defined impact condition according to a crashworthy requirement. However, in the majority of crashing cases, the initial impact velocity is either lower or higher than the design condition. The crushing stroke will not be fully utilised in a low impact velocity accident, but the load produced and transferred to an occupant is the same as that in a pre-defined condition (Fig. 1) On the other hand, load will dramatically increase after reaching the maximum stroke in a higher initial impact velocity crash, which will result in extremely low survivability for the occupants. In order to overcome the drawback of constant or fixed load energy absorbing systems, the variable load concept was developed. This concept requires a controllable crushing force, so that the full stroke of the crushing element can be used independent of the initial impact velocity.

In order to achieve adaptive energy absorption, Zhang and Yu [1] investigated the energy absorbing behaviour of pressurized metallic thin-walled circular tubes under compression crushing. Their work showed that the mean force and energy absorption of the same tube can be enhanced by more than twice after filling with a compressed gas. In addition, the adaptive energy absorption of the pressurized metal tube can be achieved by controlling the initial internal pressure and the releasing speed of the internal gas. Composite structures absorbing energy through micro-fracture can provide very high specific energy absorption [2, 3]. This makes them attractive as advanced material for energy dissipation and suitable for helicopter crashworthy structures. In the present study, the composite material will be used together with pressurized air simultaneously to achieve significant improvement of energy absorbing performance.

2 Experimental Details

2.1 Testing Specimens and Devices

Specimens were made from SKY FLEX WSN-3K plain weave carbon/epoxy fabric. The specimens were cut from autoclave cured mandrel wound tubes with a $0^o/90^o$ layup. Two different lengths of carbon tubes were cut, 100 mm for preliminary testing of the crushing top, base and sealing, and 200 mm for in quasi-static testing to validate the variable loading concept. The wall thickness were both 2mm with inner diameter 38mm and a 60 degrees chamfer was machined into the bottom edge of all specimens to promote stable progressive crushing, shown in Fig. 2.

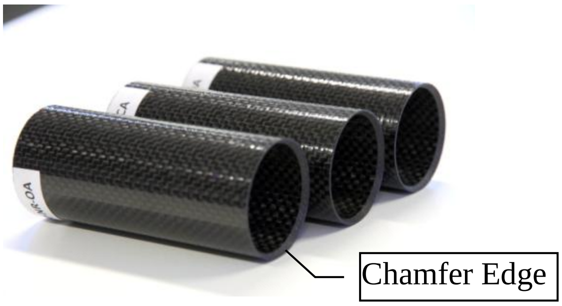

Fig. 2. 100 mm Testing specimens

Top and base testing devices were designed and manufactured as shown in Fig. 3. To overcome the sealing problem, a special plug impactor and crushing base have been designed with trigger 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. Two channels were also introduced at the base, one was used to connect to a pressure sensor to monitor the internal pressure and the other one had the function of blocking and releasing the air in different tests.

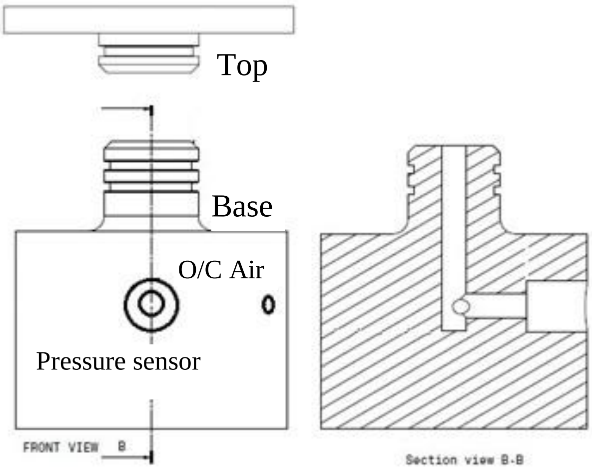

Fig. 3. Crushing top and base

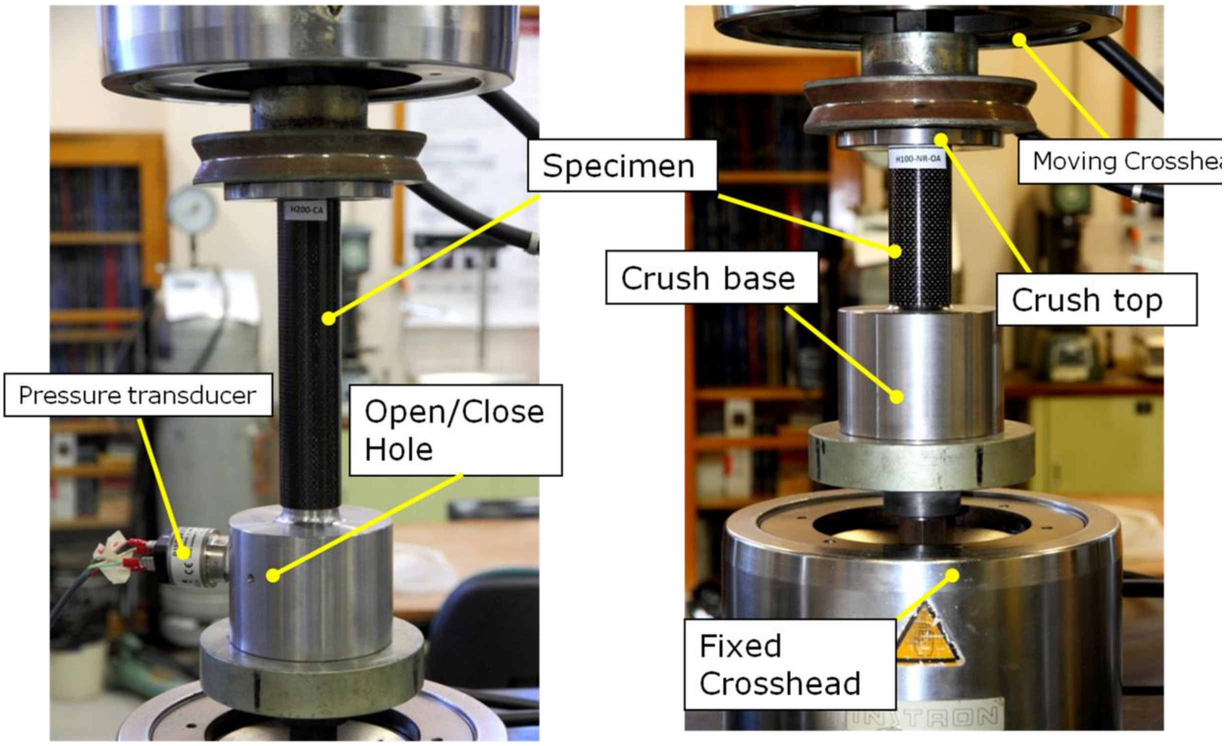

Fig. 4. Quasi-static 200 mm (left) and 100 mm (right) specimen test configuration

2.2 Experimental procedure

Quasi-static testing was performed in an Instron universal test machine at 10 mm/min for the first group of 100 mm specimens with 50 mm of crush displacement to investigate the effect of using rubber O-rings, then for the 200 mm specimens with 100 mm of crush displacement to validate the feasibility of the variable loading concept when the air was sealed internally. The experiment set up is shown in Fig. 4.

2.3 Preliminary Analytical Results

A simple analytical model was studied to verify the variable loading concept. The initial volume of the tube can be calculated as, $V_0 = (L_l + L_e)A_0$; After the tube has crushed by a stroke, the volume becomes, $V = (L_l + L_e - x)A_0$

Where,

A_0	Cross section area of the tube
V_0	Initial volume
V	Instantaneous volume during crushing
V_f	Final internal volume at the end of test
L_1	Original length of pressurized tube
L_e	Equivalent tube length taking account of the channels
P_0	Initial internal pressure
P	Instantaneous pressure
P_f	Final internal pressure at the end of test

It should be pointed out that in the testing system it was difficult to achieve ideal sealing. Therefore, the response of the pressurized tube depended not only on the initial internal pressure, but also the efficiency of the seal. If the final volume and the internal pressure after the compression are V_f and P_f , the leakage of the internal air can be obtained as follows:

$$P_oV_o - \eta P_oV_o = P_fV_f$$

$$\eta = 1 - \frac{P_fV_f}{P_oV_o}$$

Consider the releasing of the internal air and assume the speed of the leakage is uniform with the assumption that the process is isothermal. Then, $PV = P_0V_0(1-\eta\frac{X}{X_f})$, which gives $P = P_0\frac{L_l+L_3}{L_l+L_3-x}(1-\eta\frac{X}{X_f})$.

Therefore total crushing force will be,

$$F_T(x) = F_{crush} + F_{Pressure} = F_{crush} + PA_o$$

$$F_T(x) = F_{crush} + P_o\frac{L_1+L_e}{L_1+L_e-x}(1-\eta\frac{x}{x_f})A_o$$

Equation 1

Where, F_{Crush} can be obtained from the experiment.

Based on the parameters of the experimental set up, for a tube with length 200 mm, radius 19 mm and wall thickness 1 mm, the mean crushing force without pressurization is preliminary assumed to be 5 kN. This value can also be confirmed with author's previous study in a drop tower testing on certain composite tube. Assuming that the tube is closed, the overall crushing force behaviour was calculated by using the previous analytical model based on three initial internal pressure conditions atmospheric, 5 MPa and 10 MPa, respectively. The load-displacement curves with three initial pressure conditions shown in Fig. 5. demonstrate the proposed variable loading concept (Fig. 1. b) very well. Beside this demonstration of the variable loading concept, another example is given here to show how much percentage of crushing force increment can be enhanced with only 5 bar pressure applied initially. The results from the calculation are shown in Table 1. It shows 19% of average increment of crushing force has been achieved without any extra weight introduced to the existing energy absorber, which is significant and attractive for crashworthy design.

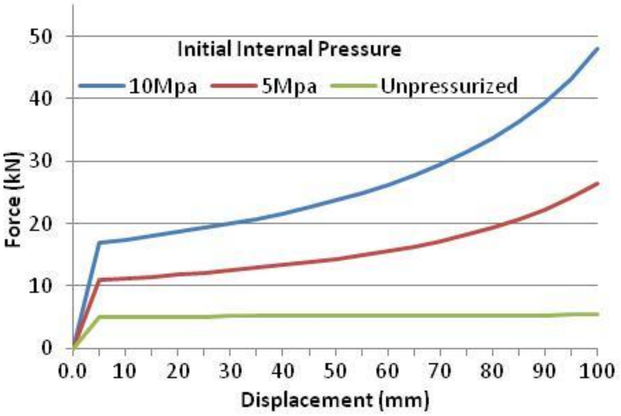

Fig. 5. Load-displacement curves for different levels of pressurization.

Table. 1. Results of analytical model with 5 bar initial pressure

	Initial Pressure 5 Bar (0.5Mpa)		
Stroke (mm)	**Internal Pressure (Kpa)**	**Pressure Force (KN)**	**Fraction of Total Crushing force**
0	506.55	0.46	9%
10	550.27	0.51	10%
20	601.45	0.57	11%
30	662.09	0.64	13%
40	734.95	0.72	14%
50	824.01	0.82	16%
60	935.06	0.95	19%
70	1077.02	1.11	22%
80	1264.2	1.32	26%
90	1521.07	1.61	32%
100	1893.08	2.03	41%
Average Increment			**19%**

2.4 Experimental Results and Discussion

Before interpreting the results of the composite tube crushing, it is necessary to visualize and understand the different stages of the tube crush phenomenon[4]. Based on the proposed concept of crushing energy absorbing system, the entire event is separated into three stages. Stage I describes the slipping of the plug into tube and ends with the crushing of the chamfered end. Stage II describes axial cracking of the material around the tube circumference and the

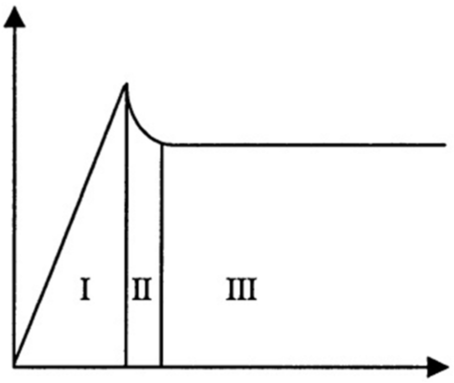

Fig. 6. Representation of the three crush stages

formation of a 'damage zone' near the crush initiator end. Stage II is a transient stage culminating in the formation of a well-defined damage zone. Stage III describes the steady-state portion of the tube crush event, in which a damage zone of near constant axial length propagates down the tube. The axial load-displacement curve corresponding to each stage is shown in Fig. 6.

In this study, 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. During the crush, energy was absorbed through different fracture mechanisms such as intra-laminar delamination, mixed mode fracture, fibre breakage and micro-cracking. A typical test specimen after crushing is shown in Fig. 8.

The results of both 100 mm and 200 mm specimens tested quasi-statically are provided in Table. 2. Stable, progressive crushing was initiated and sustained in all the tests. The load - displacement curves are shown in Fig. 7 and Fig. 9, and internal pressure was also recorded during the entire test of 200 mm specimen. The specimens with O-ring (H100-WR) provided significantly lower peak load and higher steady crushing force than the specimens without O-ring sealing (H100-NR), which eventually gives 25% load ratio improvement in the crushing test. The main reason is the peak load can be damped down and more resistance was produced from rubber O-rings in the crush. However, more experiment data is required to fully confirm the statement above. From the internal pressure results of the 200 mm specimen with closed air (H200-CA), it showed good demonstration of the proposed variable loading concept and confirmed the prediction from the analytical model of the internal air as shown in Fig. 5. The total absorbed energy was calculated by integrating the test data for the entire test period (0 to 50 mm for H 100-WR/NR, and 0 to 100 mm displacement for H200-CA). This was then divided by the weight of the crushed portion of the absorbing tube to give Specific Energy Absorption (SEA) for each crushing specimen.

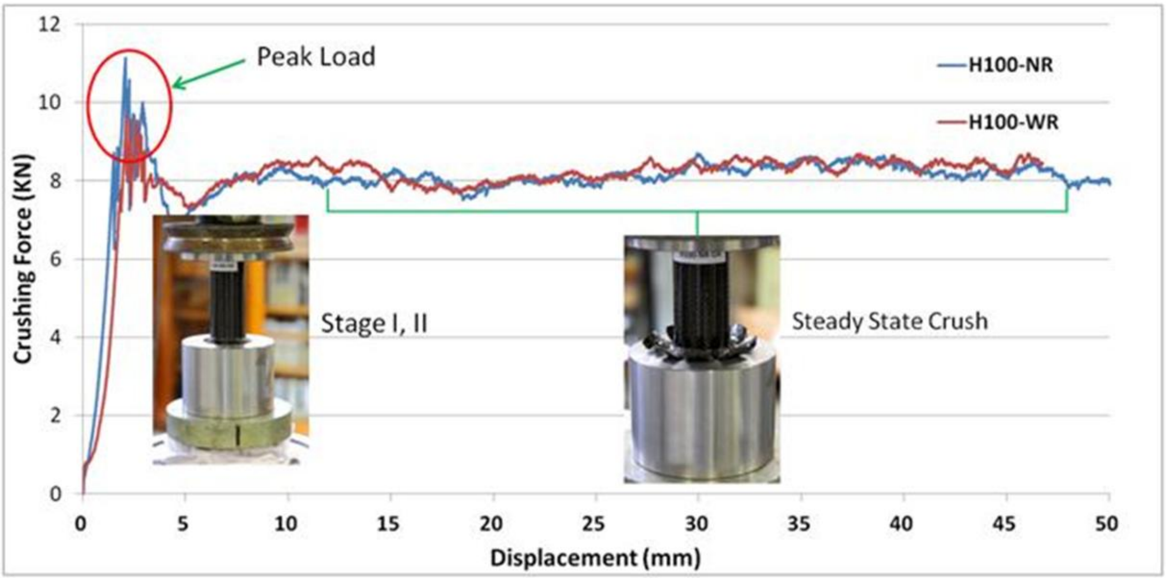

Fig. 7. Load-displacement curves of 100 mm specimens.

The mass of the crushed portion of the specimen was attained by multiplying the total crush distance by the mass per length of each specimen which was determined from pre-test measurements. Steady State Crush Force (SSCF) was calculated as the mean value of the force from 8mm to 50mm and 12mm to 100mm with H100 and H200 specimens respectively. As expected, the specimen with O-ring sealing the air (H200-CA) showed highest crushing load and best SEA performance.

Table. 2. Test summary of crushing tubes

Quantity	H100-NR	H100-WR	H200-CA
Crush Distance (mm)	50	50	100
Maximum Load (kN)	11.12	9.2	9.78
Stead Crush Load (kN)	7.98	8.18	8.57
Load Ratio	1.4	1.12	1.14
Absorbed Energy (J)	404	411	873
SEA (kJ/kg)	46.2	47.00	49.9

3 Finite Element Studies

The crushing composite tube was modelled with stacked-shell approach using finite element software PAM-CRASH [7, 8]. The crushing base was modelled in accordance with the experiments with a trigger mechanism radius of 6 mm. The entire model was meshed using shell element and the size of an element was 3 × 3 mm. For each shell layer the material properties, thickness and fibre orientation were defined. To simulate the quasi-static condition, a constant velocity of 10 m/s was applied to the crushing top since the real crushing speed was too slow for the numerical simulation.

Unfortunately, no manufacturer data sheet was available for the woven fabric WSN-3K. Several publications use specimens of the same material, but list varying properties. Most values for the model were taken from Chung's research [5] and the coupon tests in [6]. All material parameters that could not be found in the sources mentioned above were set to reasonable values (mostly based on publications about other composite material types) and/or calibrated to match this behaviour by carrying out the repetitive single element test. The results showed very good agreement of final deformed shapes between FEA model and experimental work. However, the predicted mean crushing load is over 30% than the experiment, which requires more FE work to reproduce the crushing behaviour in the future.

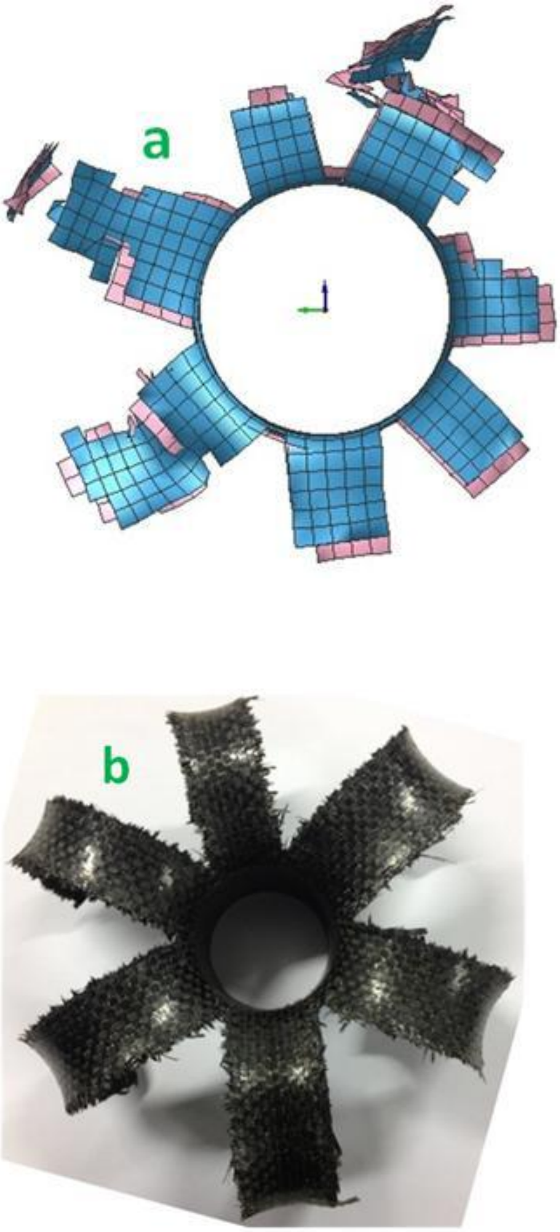

Fig. 8. Comparison of final deformed shape of the crushing tube in top view (a) FEA result and (b) experiment.

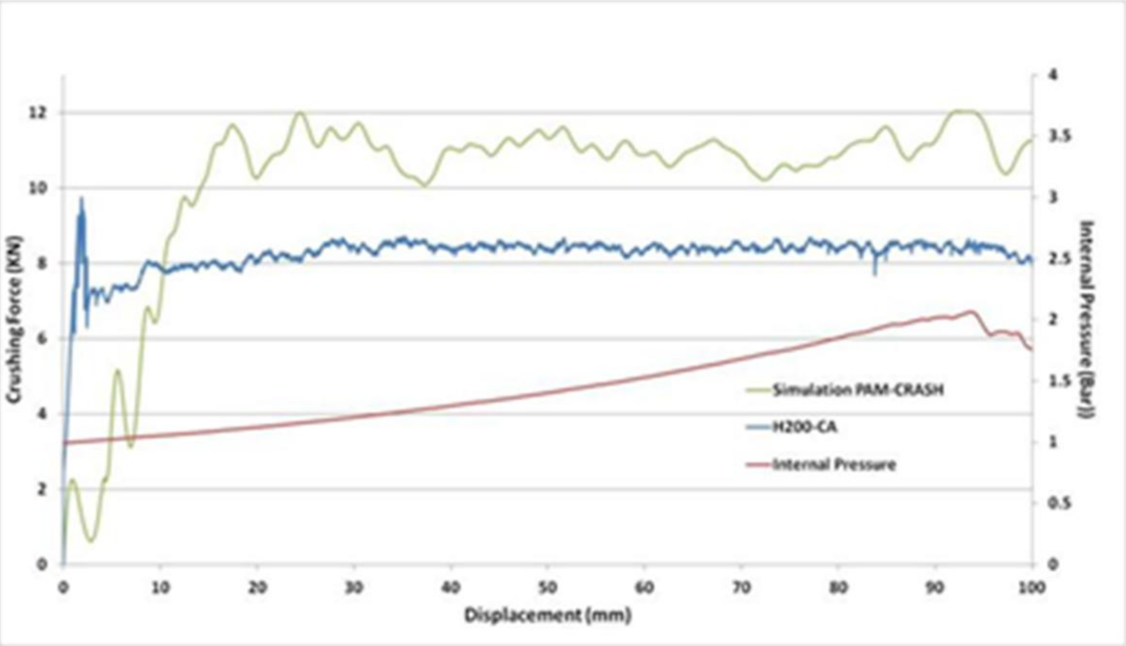

Fig. 9. Comparison of experimental and simulation Load-displacement curves of 200 mm specimen

4 Conclusion

The work presented in this paper showed a contribution to the experimental development of crushing element using pressurized composite tubes. In order to overcome the drawback of existing constant or fixed load energy absorbing systems, a novel concept to improve the performance of the energy absorption of crushing element was introduced. Base on the variable loading concept, a crushing system was designed and tested to verify the feasibility of the concept.

The internal pressure results of 200 mm specimen test have given a very good demonstration and the feasibility of the proposed variable loading concept and confirmed the prediction from the internal air analytical model. As expected, the specimen with O-ring sealing the air (H200-CA) showed the highest crushing load and best SEA performance. An explicit finite element study was carried out by using software PAM-CRASH. The results showed very good agreement of final deformed shapes between FEA model and experimental work.

5 Future Work

For further development and improvement of crushing performance of active crushing energy absorber, it is necessary to increase initial pressure to a certain level and utilise more components to control the crushing force of from high internal pressure air. The experiment map is shown in Fig. 10 for the next stage of investigation. The numerical model with stacked shell approach will be improved to predict crushing behaviour more accurately.

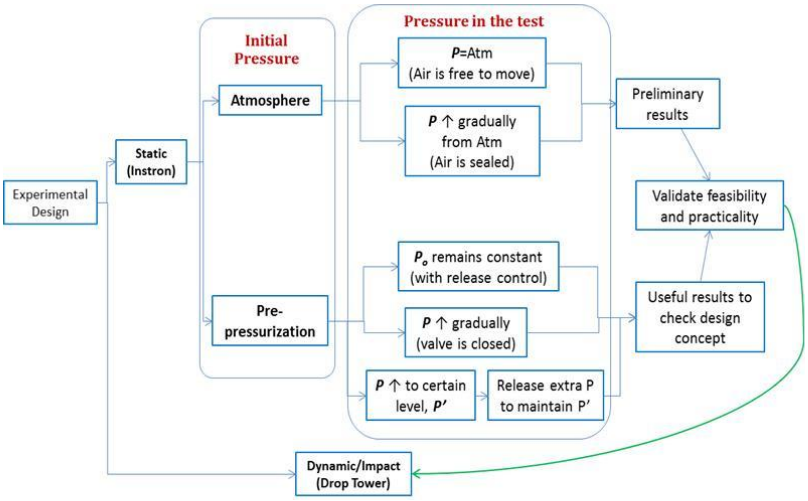

Fig. 10. Proposed future experiment plan

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