Simulation Prediction of Crashworthiness Feature of Advanced Composites

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Abstract. Based on the research of crashworthiness of advanced composites, PAM-Crash simulation software was utilized to predict the crash behavior of thermoset matrix and thermoplastic matrix. The simulation results demonstrated that the thermoset matrix and thermoplastic matrix showed an ideal fragment collapse mode, with a SEA of 63.3 kJ/kg and 50.9 kJ/kg, respectively. Both the SEA values are higher than Aluminum alloy, 17.32 kJ/kg, which means both material systems are promising to replace metal as energy absorption structure in transport applications.

Introduction

The chief concern for crashworthy structure design is to absorb maximum energy within the limited space available, while keeping the peak loads transmitted to occupants to a minimum. Thus the ideal force-displacement curve would have a rectangular shape, as shown in Fig. 1. To approach such behavior with brittle composite structures requires the establishment of a controlled crushing mode of failure, with a localized "crush-front", rather than instability-dominated failure caused by buckling. This is in contrast to metallic energy-absorbing structures, which absorb energy by plastic deformation and folding.
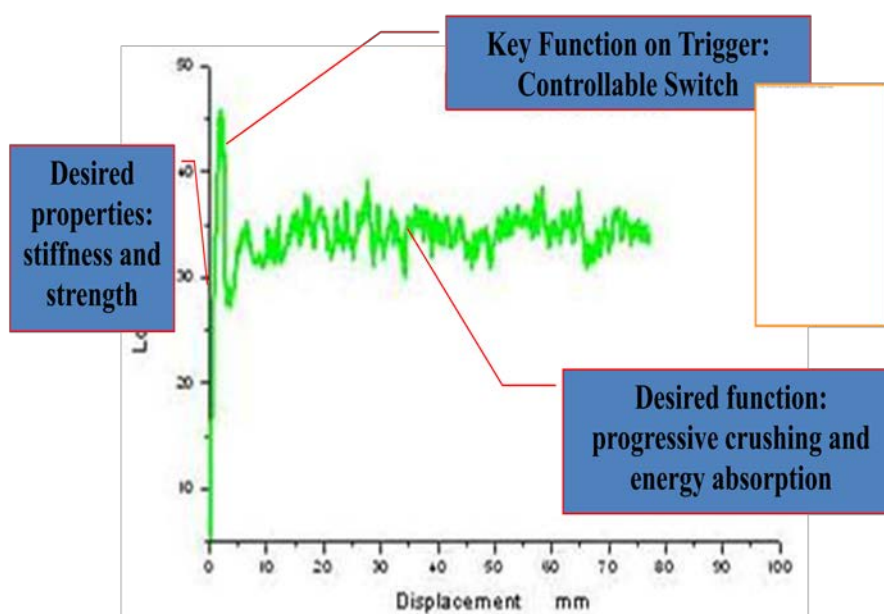

Fig. 1. Typical force-displacement curve of composite crash element.

The research of crash-energy absorption of composite materials and structures began around 1976. Thornton et al. reported the excellent energy absorbing capability of fiber reinforced composites [1, 2] and gave very useful experimental data such as the influences of fiber orientation, fiber architecture, trigger mechanism, experiment constraints et al [3-8]. Experimental results showed that tubes made of glass fiber and carbon fiber has much more specific energy absorption than that made of Kevlar fiber. Carbon and glass reinforcing composites failed in longitudinal delaminates and brittle fracture

mode, whereas Kevlar reinforcing composites often failed in Eular buckling mode. Generally, carbon fiber/epoxy composites have the highest energy absorption capabilities than others. In recent years, metal/composite hybrid structures have been studied and different results were obtained [9]. PAM-CRASH is powerful commercial software to simulate the dynamic crash procedure of energy absorbing structures.

Model Set Up

Reference Frame and Units

According to the space limitation, the maximum crash displacement cannot longer than 110 mm, the typical impact velocity is 16 km/h, and the peak impact force should be lower than 110 kN. For composite crash box, the outer dimensions should be 150mmx65mmx285mm. Based on this industrial requirement, experimental and simulation work has been done by BIAM [10]. And the SEA value of Al alloy (2024-T3) is 17.32kJ/kg, the maximum displacement is 116 mm, and the weight of the box is 1.02 kg.

Model Assumption

Using the experimental observations as a guide, a damage mechanism – based failure model was developed to predict the energy absorption characteristics of the composite tubes. The model consists of two main parts: the material module, which describes the mechanical behavior of the composite; and the tube crushing model, which describes the generous behavior of the tube as it is being crushed.

Load Condition

To verify the material model of the software, 120 kg rigid drop weight at a velocity of 6 m/s was chosen here. Otherwise, the rigid drop weight is 1000 kg and the drop velocity is 4.44 m/s for crash box.

Contact Definition

Contact is the mathematics model during the drop weight affect with the tube. Here, Contact Type 33 was used to define the contact, where drop weight is the slave and crash absorber is the master, as shown in the following. During the crash process, large deformation happened in the structure and the mass of crash box itself impact each other, which was defined as self-contact (Contact Type 36). A self-contact algorithm prevented the elements of the box from passing through each other, and also provided friction between the different parts of the structure.

Composites Manufacturing and Modeling

Composite Tube Specimen Fabrication [11]

The composite tubes were made using T300 carbon fiber and BIAM made epoxy 5288 resin as the thermosetting composite matrix, and AS4/PPS as the thermoplastic composites. The mechanical properties of T300 and AS4 are similar, while thermosetting resin matrix is much higher than the PPS, although PPS has been proved to have good processibility. The basic properties of the fiber and resin matrix, as well as T300/5288 and AS4/PPS composite are showing in Table 1 and Table 2, where the fiber volume fracture is 55%.

The circular cross-section tubes were fabricated using a solid metal mandrel. Composite materials in the form of prepregs were wrapped around the mandrel. The laminate sequence is [+45/-45/0/0/90/0]s and nominal cured ply thickness of the tape prepreg was 0.125mm. The assembly was then placed vertically in an autoclave for curing. After the tube was processed, it was removed from the oven and the mandrel extracted. Individual tube specimens were machined from the long tube. Typically, the tubes were machined to lengths of 100 mm and one end was chamfered at a 45°. The chamfer was incorporated for all composite specimens to limit the initial failure load and initiate the crushing process.

Table 1 Fiber and matrix material mechanical properties

Materials	Modulus	Elongation	Strength	Density
	MPa	%	MPa	cm^2
T300	230	1.8	4210	1.78
AS4	231	1.87	4278	1.80
5288	3.5	4.3	98	1.26
PPS	3.3	4.0	84	1.43

Table 2 Mechanical properties of T300/5288 and AS4/PPS

Mechanical Properties	T300/5288	AS4/PPS
Longitude tensile modulus, GPa	145	114
Longitude compression modulus, GPa	117	128
Longitude tensile strength, MPa	1670	1840
Longitude compression strength, MPa	1260	1002
Poisson ratio	0.317	0.334
Transverse modulus, GPa	9.0	8.8
Transverse tensile strength, MPa	69.4	49
Transverse compression strength, MPa	214	--
Interlaminate shear strength, MPa	94.0	75
Shear strength, MPa	118	103
Shear modulus, GPa	4.82	4.8

Test Equipment and Procedures

The drop testing was carried out with an impact velocity of 6m/s and the impact energy of 2000 J. T300/5288 tubes crushed exhibited in a mixed mode of fragmentation and splaying, which was clearly shown in the microstructure failed zone, as shown in Fig.2. The crushed tubes show observe several fracture and collapse mechanisms: fibre fracture, bundle buckling, matrix cracking, fibre-matrix debonding, delamination and a variety of shear related mechanisms. The resulting force-displacement curve demonstrated the expected uniformly and progressively process (Fig. 3). Here, the specific energy absorption (SEA) is 70.82 kJ/kg.
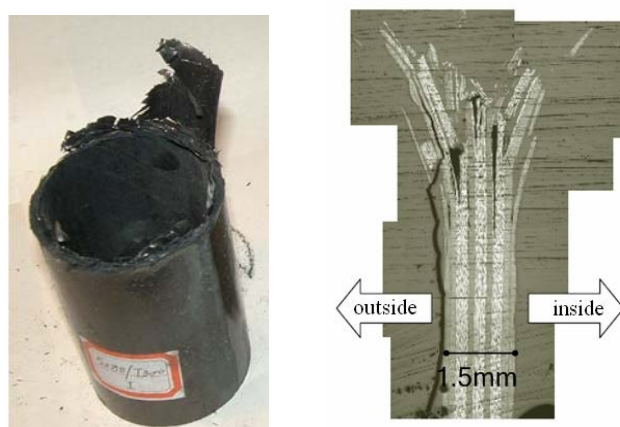

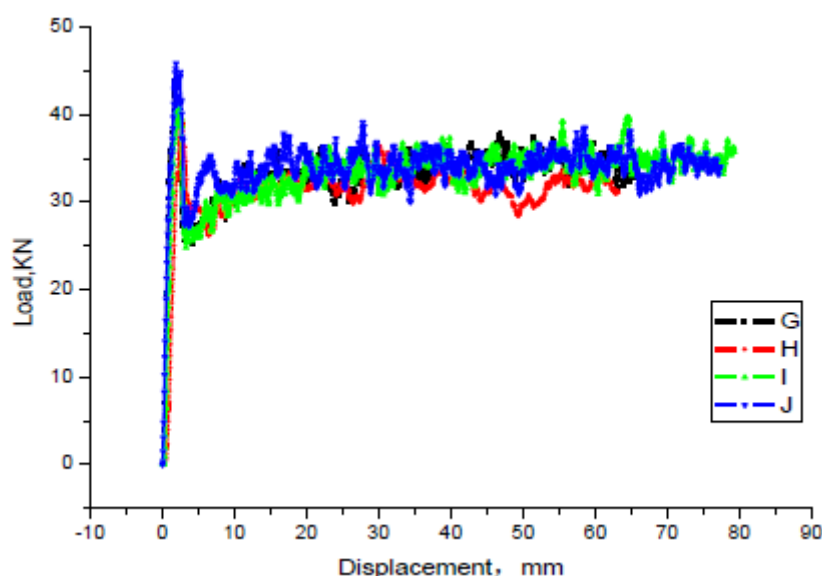Fig. 2 Drop test onto a T300/5288 tube and the microstructure of the specimen.

Fig. 3 The load-displacement result of crash process.

Thermosetting composites, T300/5288, crashed in fragments in a uniform, progressive way. The plies lay-up sequence is [+45/-45/0/0/90/0]s and the trigger angle is 45°. The specific energy absorption is 70.82 kJ/kg when under a drop weight of 120 kg at 6 m/s impact velocity.

Calibration of Composite Model

The performance of the proposed model should be evaluated by comparing the model predictions to experimental data. Here, thermosetting composite tubes, T300/5288, were taken as the calibration reference, and the tube parameters are shown in Table 3. Material 131 of PAM-CRASH was used to simulate the composite structure. There are 12 plies in the circular tube and one plate of shell mesh in each ply. The adjacent layers are connected with bonding element; and also the bonding element could simulate the interlayer strength, because the bonding element has the capable of presenting strength and fracture properties. At the same time, contact pair was taken to avoid penetrating each other and also could simulate the interlayer fabrication effect. And the monolayer failure criterion is PUCK 2000, where G_{IC} and G_{IIC} values were used for the laminate failure criterion.

Table 3. Composite model of T300/5288 tube.

Materials	T300/5288
Shells	144000
Plies layup sequence	(45/-45/0/0/90/0)s
Single ply thickness/mm	0.125
Wall thickness/mm	1.5
Trigger angle/°	45

The maximum displacement is 69.5mm at 22.4ms. The total energy absorption is 2160 J, and the SEA is 71.7 kJ/kg. Good agreements with the experimental results were obtained, as shown in Table 4. Under around impact energy of 2160 J, the SEA is 71.7 kJ/kg, which is in a good agreement with the experimental test result, as shown in Table 4. Thus, the composite model set up, including the bonding definition, contact, loading condition, is well confirmed.

Table 4. Comparison of experimental and simulation results.

Results	Time	Displacement	Energy	SEA
	ms	mm	J	kJ/kg
Experimental	23	72	2000	70.82
Simulation	22.4	69.5	2160	71.7

Design and Simulation of T300/5288 and AS4/PPS Crash Box

Here, the material card was still the same and there are 28 plies in this conical tube and one plate of shell mesh for each ply. This mode was applied to thermoset composite, T300/5288, first. Considering the recycling feature as well as the automatic mass production in the future, thermoplastic composite structure, AS4/PPS, was carried on based on the model of thermoset composite. Table 5 showed the materials parameters and the geometries shown in Fig. 4.

Table 5. Composite model of T300/5288 & AS4/PPS.

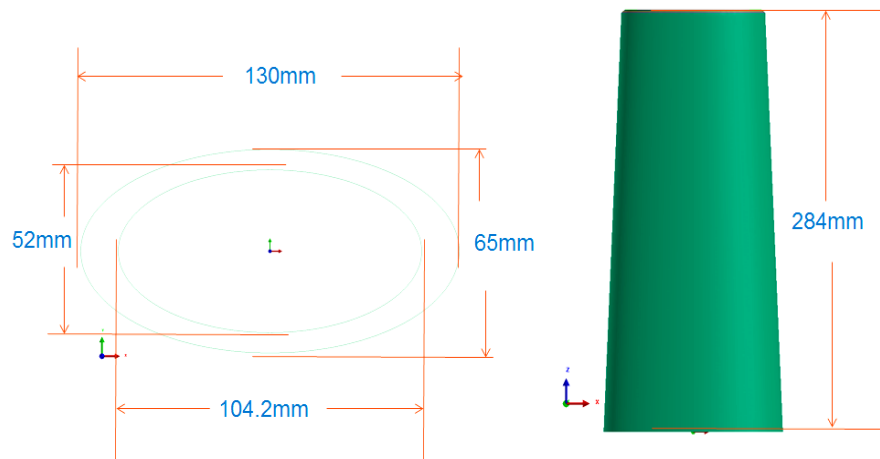| Materials	T300/5288	AS4/PPS
Shells	131712	
Laminate layup sequence	[0/0/45/-45/0/0/90/0/0/90/0/0/-45/45/]s	
Mono ply thickness/mm	0.125	
Wall thickness/mm	3.5	
Trigger angle/°	45	
Density/ kg/m³	1.57×10^3	1.60×10^3
Weight /kg	0.425	0.435

Fig.4 Final elliptical cross-section geometry model of crash box.

Drop weight procedure is an instant process, and the period is normally very short. For T300/5288 thermoset material, the maximum crushing distance was 112.5 mm at 48.8ms and the total energy absorbed is 2160 J and SEA is 63.3 kJ/kg, shown in Fig5 (a) . For AS4/PPS thermoplastic material, the maximum crush distance was 135mm at 47ms, and the SEA was 50.9 kJ/kg. The crash fragments are shown in Fig.6.
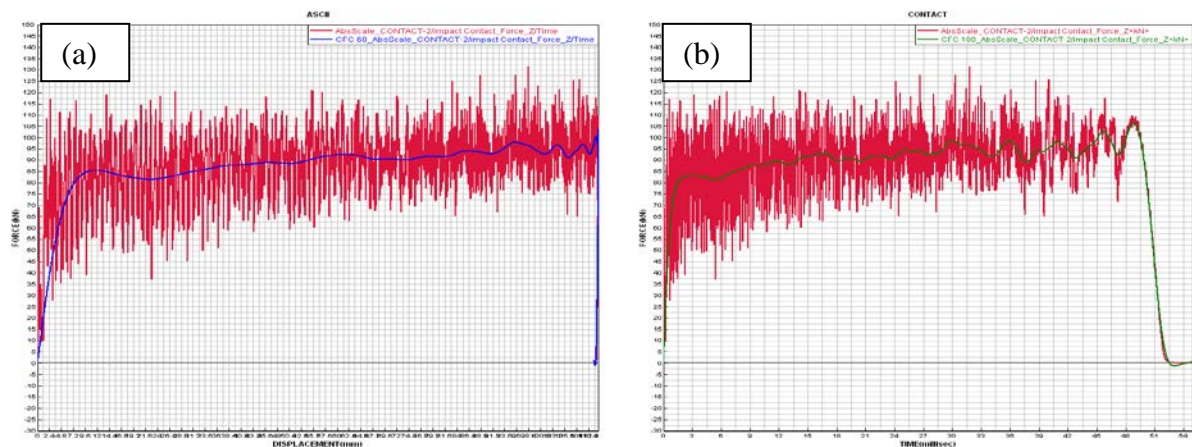

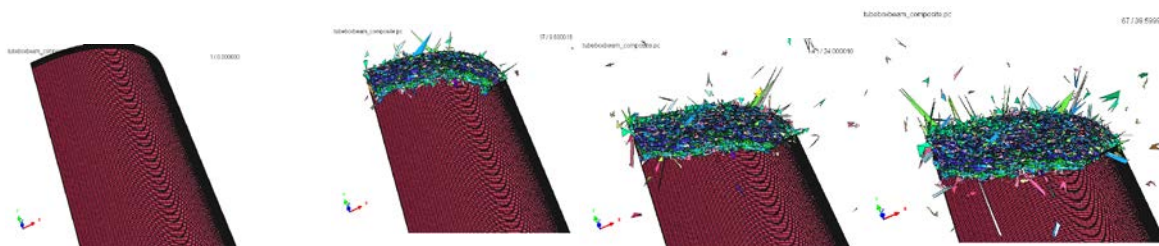Fig. 5 Force vs displacement response for (a)T300/5288 and (b) AS4/PPS.

Fig. 6 Development of failures in FEM simulation of AS4/PPS.

Summary

The simulation work was carried out based on experimental work, and the well matched result demonstrated the model parameters were well set up. Both thermosetting composites and thermoplastic composites can meet the requirement of certain specific application.

1）For thermosetting composite, T300/5288, the maximum crash displacement is 112.5mm, and SEA is 63.3kJ/kg.

2）For thermoplastic composite, AS4/PPS, the maximum crash displacement is 135mm, and SEA is 50.9 kJ/kg.

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