EXPERIMENTAL INVESTIGATION ON THE ENERGY ABSORPTION BEHAVIOUR OF NACRE-INSPIRED COMPOSITE CIRCULAR TUBES UNDER AXIAL COMPRESSION

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ABSTRACT

This study uses a discontinuous and interdigitated strategy which was observed from nacre to improve the specific energy absorption (SEA) of carbon/expoxy composite tubes. Quasi-static axial compression experiment and digital image correlation system is carried out to analysis the failure process of specimens. Four kinds of tubular specimens which include the different ply cut interval and distribution are fabricated and crushed. The load-crushed displacement curves are then investigated and the SEA values are calculated based on these curves. The result shows that the form this regular and discrete ply cuts would cause the fluctuations of compressive force. And yet, the tubes which had helical and discontinuous ply structure can obtain a flatter load-crushed displacement curve. Soon afterwards, this work demonstrates that unidirectional composites with well-designed discontinuities at the ply level can significantly improve the SEA (1.5 times more than UD continuous tube) in the crushed process.

1 INTRODUCTION

Vehicle crashworthiness, which is determined by energy absorption characteristics, is a major requirement for the motorsport and automotive structures. To ensure the passenger compartment to rest without the occupant being subjected to high decelerations, which can cause serious internal injury, particularly brain damage, crashworthy structures should be designed to absorb impact energy in a controlled manner[1].

Composite materials, because of it offer the benefits of high strength-to-weight ratio and high specific energy absorption (SEA) characteristics[2], are generally considered as possible candidates for energy absorbing components to developing improved human safety in an automotive crash[3]. Existing studies have exhibited that although simple tube structures made of composites have exhibited energy absorption greater than similar metal structures[4]. Thus, in order to understanding the crushing process and for the purpose of optimizing the SEA of composite structure, most tests are carried out under quasi-static axial compression loading conditions. Common studies mostly focus on the SEA of material system[5, 6], ply orientation angle[7, 8] and cross-sectional geometric shapes[9, 10], as well as triggering mechanisms[11-13]. Final results showed that in similar design configurations graphite/epoxy (Gr/Ep) had SEA values that were greater than other material systems. The energy absorption of the specimens had increased with increasing number of 0°plies. Comparing with other standard and uniform cross-sectional geometries, the tubular specimens generally had higher SEA values. On the other hand, Siromani et.al[11, 12] proposed that using a external device that they called an inward-folding crush-cap to further enhance the energy absorption effect.

Actually, excepting traditional design and optimization solution as mentioned above, an alternative approach for improving the specific energy absorption is to mimic the structure found in nature, in the case of nacre. Nacre known as mother of pearl is a biological composite material discovered in the iridescent inner shell of some mollusks as observed by Nakahara et al[14]. It is composed of 95 wt% aragonite platelets (a crystallographic form of $CaCO_3$) and 5 wt% thin organic matrix layers (proteins and polysaccharides) and features a multilayered 'brick-and-mortar' architecture[15, 16]. The aragonite

platelets are approximately 0.5μm embedded in the organic matrix being 20-30 nm in thickness. Such highly discontinuous and interdigitated structure deflects cracks around the platelets instead of through them, thereby making nacre easier to exhibit remarkable energy absorption properties. As observed by Barthelat and Espinosa[17], the crack fracture toughness of nacre was already 30 times higher than the toughness of pure aragonite.

So far, the most research has focused on mimicking the nacre structure in submicrometer-scale architectures and achieved appealing results.

Wang et al. [18]designed a laminated Si3N4/BN ceramic composites imitating nacre in structure, which displayed crack deflection and high values of fracture toughness. Sarikaya and Aksay[19] produced another laminated structure of Al-B4C and reported that it was five times tougher than monolithic B4C. The bio-inspired structures of nacre have also been fabricated in other papers[21] as well as exhibiting excellent mechanical properties.

Performing a similar strategy into CFRP composite design is difficult in submicrometer-scale because of most CFRP composite structure, in engineering scale, are fabricated from pre-formed materials, such as pre-preg or non-crimp fabric. However, the core principles of structural bio-inspired design was using design rule deduced from the outstanding biological composites to augment the capability of original structure while retaining their essential features[20].

This research presented herein attempt to enhance or improve the energy absorption properties of circular carbon fiber/epoxy tubes through mimicking the nacre structure in engineering scale by the use of discontinuous FRP systems. Similar design method has already been exploited for the behavior of carbon fiber/epoxy pre-preg composites under uniaxial tensile loading [21] and flexural loading [22]and made remarkable achievements in this field. This work takes a fundamental approach to understanding ply discontinuities and their effect on energy absorption properties in crash process.

2 EXPERIMENT PREPARATIONS

2.1 MATERIALS AND SPECIMEN FABRICATION

The composite material system used in this study was unidirection T300 CFRP pre-preg carbon/epoxy tape (Hengshen CO. Ltd, China) of nominal cured ply thickness 0.135 mm with a 12K tow. The test specimens were fabricated by wrapping the UD pre-preg tape around a circular steel pipe with an outside diameter 25 mm and then inserted into an outer mold which made of Polytetrafluoroethylene (PTFE). Expansion of the inner steel pipe provided compression during fabrication and ensured quality with low void content. All specimens were cured in a heat-oven according to curing cycle provided by manufactures guidelines. The curing cycles consisted of a 2 ℃/min ramp to 80 ℃ then keep it for 30min and a 1.5 ℃/min ramp to 130 ℃ then keep it for 2h. The ply orientation considered in this study is 0 °along the axis. Once the curing process was accomplished, the test specimens were separated from mold parts and then polished using 400 and 800 grade SiC to minimize edge effects and guarantee the plainness of end face. After trimming, the long of the specimens is 50 mm with an inner diameter of 25 mm and the wall thickness is 1.5 mm. The tube t/D ratio was 0.06 to ensure that can fail by progressive fracture mode [23].

2.2 TEST SETUP

All the specimens manufactured were conducted under quasi-static axial compression conditions to study the crushing load-deformation histories. An MTS (SANS) CMT5504 screw driven electromechanical test machine with a 50 kN load cell was applied to carry out all tests. For each the specimens were compressed between two steel cross head at a displacement rate of 1mm/s.

2.3 CRUSH PROCESS AND ENERGY ABSORPTION

An UD continuous tube was tested firstly to acquire the basal experimental data before the design. With the stroke control function of test equipment, the 40 mm crushed length was defined to obtain sufficient crush data because of utilizing the specimen tubes of 50 mm length. Fig.1 shows the load-crushed displacement and SEA results of typical tube with 10 UD continuous plies. It can be seen that the load-crushed displacement curve mainly is comprised by two different stages: linear elasticity and sustained collapse. Clearly, in the linear elasticity stage, there is a very high initial peak load that has emerged, which is disfavored by the researchers because of it will cause the fluctuations of force. The

energy absorption capability of each specimen is evaluated as per unit mass absorbed which commonly known as Specific Energy Absorption (SEA) and defined by:

$$SEA = \frac{4\int_0^s P\mathrm{d}s}{\rho\pi\left(Do^2 - Di^2\right)s} \tag{1}$$

where P is the corresponding force on the specimen, s is the crushing displacement, ρ is the composite material density, and Do and Di are the outside and inside diameters of tube, respectively. Above all, to improve the energy absorption properties it is necessary to reduce the initial peak load and raise the average load in sustained collapse stage.

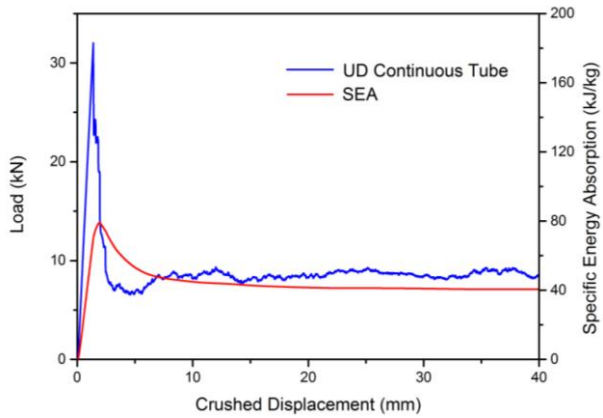


Fig. 1. Load-crushed Displacement curves and specific energy absorption (SEA) value of UD continuous tube

3 COMPRESSION TESTS AND DISCUSSIONS

3.1 NACRE-MIMETIC DESIGN

By observing Fig.1, stable crushed states were kept in space from 0 to 30 mm, so this region was selected to carry out structure design. The design strategy was based on the discontinuous and interdigitated principle which was observed from nacre. Three groups of Nacre-mimetic tubes with different overlap length were designed and produced to evaluate the initial peak load and collapse process. The ply cuts method can be found in the reference [21]. Table1 shows the detailed test matrices and Fig.3 demonstrates the dimensions as well as ply cut locations for design B of Nacre-mimetic tubes (design A and D is exactly the same except for the value of L and S).

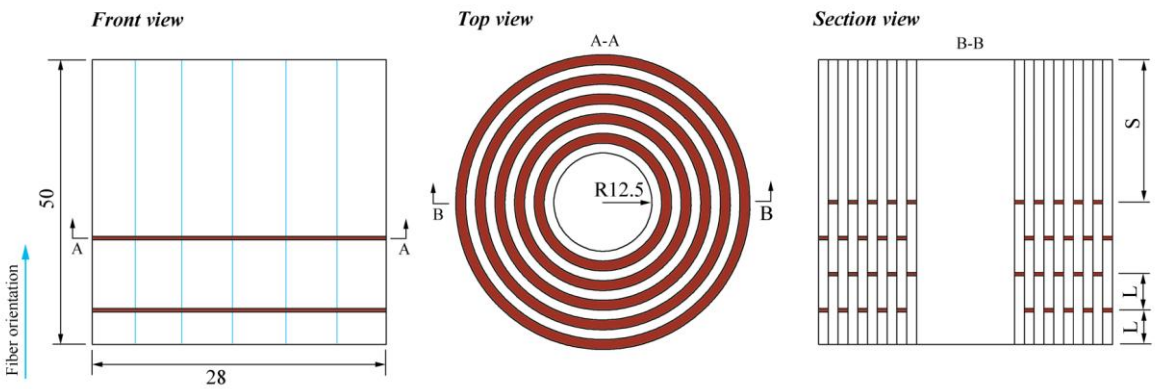


Fig.3. Structure schematic and dimension of nacre-mimetic tube. All view shown the detailed information for design B. Not to scale.

Designations	Length of ply cut interval: L(mm)	Number of discontinuous areas	Length of without design: S(mm)
Design A	2.5	10	25
Design B	5	4	30
Design C	10	2	30

Table 1 Details of each tube A-C

For all designs the physical dimensions were kept constant and the only variable was the overlap length, which refers to the length of ply cut interval into 2.5, 5 and 10mm in this study. At the same time, in order to further demonstrate the experimental effects and repeatability each type of tube with different overlap length was conducted many times. In previous studies, some researchers [6, 11]applied a 45° chamfer one end of tube to reduce the initial load peak. However, all the nacre-mimetic tubes were manufactured with flat end to better explain the effect of this discontinuous structure on peak load and to rule out underlying influence.

3.2 RESULT AND DISCUSSION

3.2.1 Result of design A - C

The load-crushed displacement curve that recorded for three design specimens are shown in Fig.4. The crush load/displacement responses of Fig.4 are a single representative response of the three tests.

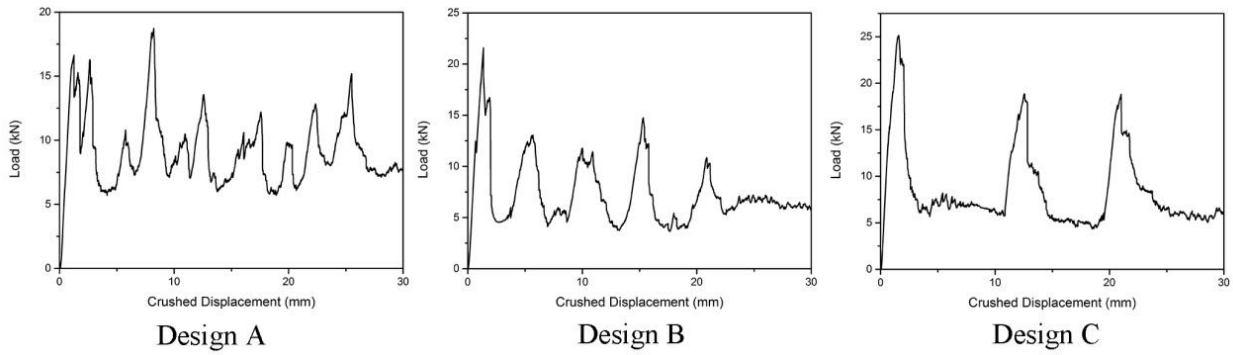


Fig.4. Representative examples of load displacement curves for designs A, B and C

For the experiment results, the average initial peak loads of each group, A-C, were 18, 22 and 25kN respectively. It can be seen that the decrease in the initial loads was 43%, 31% and 21% respectively as compared to the continuous specimen (32kN), shown in Fig. 1. Therefore, this result indicated that during the stage of linear elasticity the discontinuous and interdigitated tubes had a positive impact on the initial peak loads. On the other hand, a much lower average initial peak load (18kN) can be obtained from Design A. It showed a decrease of peak load with a decreasing of the overlap length in discontinuous areas.

In sustained collapse stage, the load-crushed displacement curve of all specimens appeared fluctuation in different degree. The average standard deviation of each group, which has been calculated by the crushed displacement from firstly load drop (A-C by nearly 1.8, 2.7 and 4.3mm) to 30 mm, was 2.4, 2.7 and 4.3kN respectively. Compared with the continuous specimen, 0.4kN, the standard deviation increased to 6, 6.7 and 10.7 times for overlap length of 2.5mm, 5mm and 10mm, respectively. It can be seen that because of the standard deviation reflected the discrete degree of data in each group, the discontinuous tubes designed in a simple scaling can cause the discontinuous failure process. Furthermore, it also discover that the number of waves peaks for design A-C, by nearly 10, 4 and 2, is always the same as the number of ply cut interval. Base on above, we suspected that if the overlap length is short enough or the ply cut keep continuity, the load-crushed displacement curve would be much smoother than before in the sustained collapse stage.

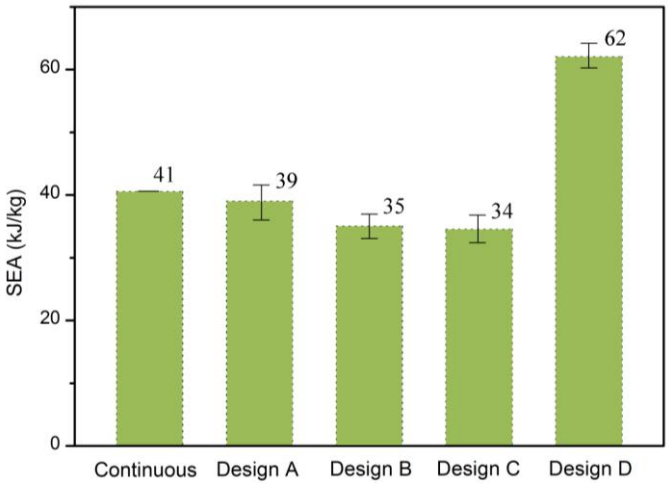


Fig.5. A comparison of SEA for continuous specimen and group A-D

Fig.5. shows the SEA value of each design. It can be seen that the experimental results of all design strategy were contrary to expectation. The SEA value slightly decreased to 5%, 14% and 15% of that of the continuous specimen for overlap length of 2.5 mm, 5 mm, and 10 mm, respectively. Clearly, a simply ply cut design scheme cannot improve the energy absorption properties of circular carbon fiber/epoxy tubes during the crushed process. The load fluctuation in sustained collapse stage contributes to causing the major energy absorption loss. At the same time, it suggests that the overlap length of designed discontinuous tube is directly related to the SEA resulting. The energy absorption properties increased with a decreasing of the overlap length. To reduce the load fluctuation, the SEA values are able to further improvement.

3.2.2 Optimal design and test

Based on the results of the above study, it was established that the overlap length (L) was an important factor in determining the initial peak loads. An overlap length of 5 mm can obtain a much lower initial peak load (15kN) compared to the other two groups. It also indicated that the number of ply cuts was too much in local area thereby creating an adverse effect. This brittle area may sudden fracture to cause the discontinuous failure process in sustained collapse stage. Thus, combining principles learnt from previous design and considering the possible ply cut interactions; an optimal design process was carried out. The feature of optimized structure was: (a) ply cut areas paced 5 mm apart; (b) the orientation of ply cut is tilted 45° relative to the axis of tube; (c) a nacre inspired arrangement of ply cuts. The optimal ply cut locations for nacre-mimetic tube is shown in Fig.8 (a).

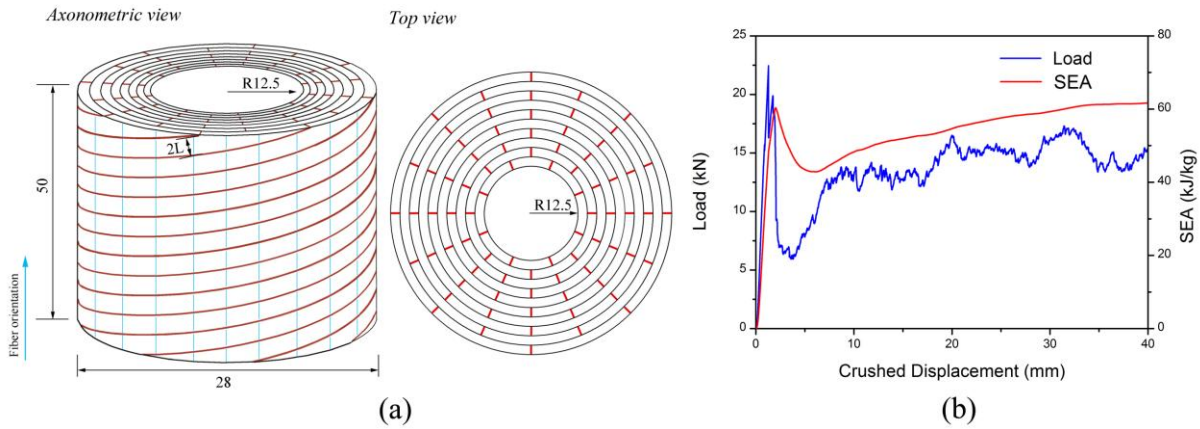
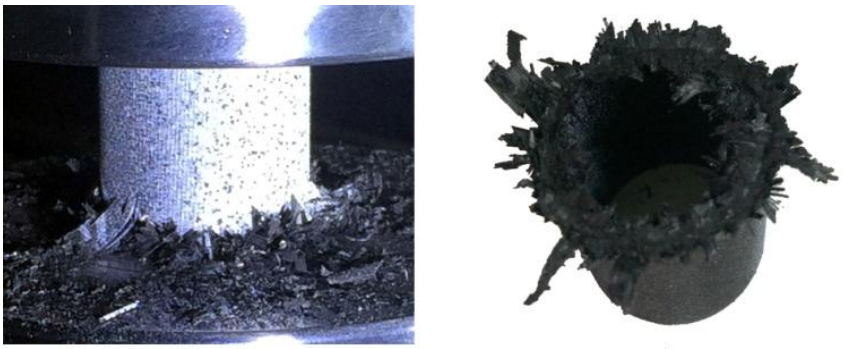


Fig.8. Design strategy and experimental result of new tube: (a) Structure schematic of optimal design strategy, and (b) Load-crushed Displacement curves and SEA value of optimal tube

Fig.8 (b) shows the load-crushed displacement curve and SEA result of the optimized tube. It can been seen that the initial peak load (22kN) was reduced 31% and SEA value (62kJ/kg) was increased 51% as compared to the results of continuous specimen (41kJ/kg), shown in Fig. 2. In contrast to previous design, the crushed process of the optimized specimen was progressive and did not exhibit any large load fluctuation at the sustained collapse stage. This result could help to understand the previous analysis that too much ply cut in one area would cause large load drops. In the case of group A and optimized tube, the obvious difference between them was the distribution of ply cut along the circumference of the specimen, which was related to the crushed property. The discontinuous ply cut along the circumference could increase the SEA value.

However, the failure process of optimal tubes are completely different with the before design A-C (shown in Fig.6(c)). The tube piles are no longer yield similar narrow laminate strips but directly crush into debris of composite. Post-test observation of the specimen revealed that the crushed end is fantastically smooth and lots of fiber nearby failure end could break, which absorb a large number of energy in the process of compression. The failure processes and crushed end of optimal tube are shown in Fig.10.



(a) (b)

Fig.10. Progressive failure of optimal tube: (a) Crushed state during the sustained collapse; (b) post-test view of the crushed end of the specimen

4 CONCLUSIONS

In this study, it was found that the energy absorption ability observed in UD carbon/epoxy tube can be improve by a discontinuous and interdigitated structure which inspired by nacre. Several specimens, which include the groups A - D with different length of ply cut interval and a tube with optimal ply cut, were fabricated and tested under axial quasi-static compression. Based on these results, a new sample D was designed to further improve the SEA value. Results showed that the initial peak load (22kN) was reduced 31% and SEA value (62kJ/kg) was increased 51% as compared to the results of continuous specimen (32KN and 41kJ/kg). This bionics design ideas in engineering scale offered a new method to design next generation composite energy structure for the designer.

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