



Nacre-inspired design of CFRP composite for improved energy absorption properties



Zhibo Xin^a, Xiaohui Zhang^a, Yugang Duan^{a,*}, Wu Xu^b

^a School of Mechanical Engineering, State Key Lab for Manufacturing Systems Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China

^b School of Aeronautics and Astronautics, Shanghai Jiao Tong University, Wuhan, Shanghai 200240, China

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ABSTRACT

Discontinuous unidirectional fiber-reinforced composites are shown to possibly exhibit pseudo-ductile failure that is lacking in continuous fiber composites. The aim of this paper is to use a discontinuous and interdigitated design strategy which mimicks the nacre structure to improve the specific energy absorption (SEA) of a carbon/expoxy composite tube. Quasi-static axial compressive experiment is combined with a digital image correlation system to analyze the failure process of the specimens. Four kinds of tubular specimens which are based on different ply cut intervals and distributions are fabricated and crushed. The load-crushed displacement curves and the SEA values are obtained showing that circular shaped continuous ply cuts result is the highest fluctuation of the compressive force. Moreover, the tubes with helical and nacre mimicking ply cut structures result in a flatter load-crushed displacement curve. This work demonstrates that in a crush process, unidirectional composites with a well-designed discontinuity at the ply level can improve the SEA over 51% as compared to the unidirectional continuous tubes.

1. Introduction

Mechanical energy-absorbing components can protect the security of passengers or equipment in crushes occurring in catastrophic events. At present, due to the constraints of lightweight design cost, traditional metal materials can hardly meet the market needs of the present transport applications. Composite materials offer beneficial properties thanks to high strength-to-weight ratio and high specific energy absorption (SEA) characteristics [1]; composite materials are thus promising candidates for energy absorbing structural components which could accelerate the development of passive safety systems in different fields including aviation, spaceflight [2], national defense facilities [3] and automotive industry [4].

Recent studies have revealed that simple tube structures made of composites exhibit a higher energy absorption respect to similar metal structures [5], however, the complex energy absorption mechanism hinders further practical applications. In order to further understand the crushing process and optimize the SEA of different composite structures, extensive experiment have been carried out under quasi-static axial compression loading conditions. Typical studies mainly focus on the SEA measurement of the material system [6,7], on systematic studies on the ply orientation angle [8,9], or on the cross-sectional geometric shapes [10,11], as well as the triggering mechanisms

[12–14]. These researches successfully revealed some engineering rules, which are valuable for the energy absorbing structure design. To design energy absorbing structures, researchers mainly used traditional composite design methods, which were developed from isotropic metallic structures. According to the traditional design method, continuous fiber reinforced composites have been applied to engineering area extensively because of their high mechanical performance.

Actually, besides the traditional design and optimization, an alternative approach for improving the SEA is to mimic natural structural designs as the one found in nacre. Nacre, also known as mother-of-pearl is a biological composite material found in the iridescent inner-shell of some mollusks. As observed by Nakahara et al. [15], it is composed of 95 wt% aragonite platelets (a crystallographic form of CaCO_3) and 5 wt % of thin organic matrix layers (proteins and polysaccharides) and features a multilayered *brick-and-mortar* architecture [16,17]. The aragonite platelets size is approximately $0.5\ \mu\text{m}$ and plates are embedded in the organic matrix being 20–30 nm in thickness, shown in Fig. 1 (adapted from [18]). Such highly discontinuous and interdigitated structural deflects around the platelets (instead of being through them) confer to nacre its remarkable energy absorption properties. As observed by Barthelat and Espinosa [19], the crack fracture toughness of nacre was already 30 times higher than the toughness of pure aragonite.

* Corresponding author.

E-mail address: ygduan@mail.xjtu.edu.cn (Y. Duan).

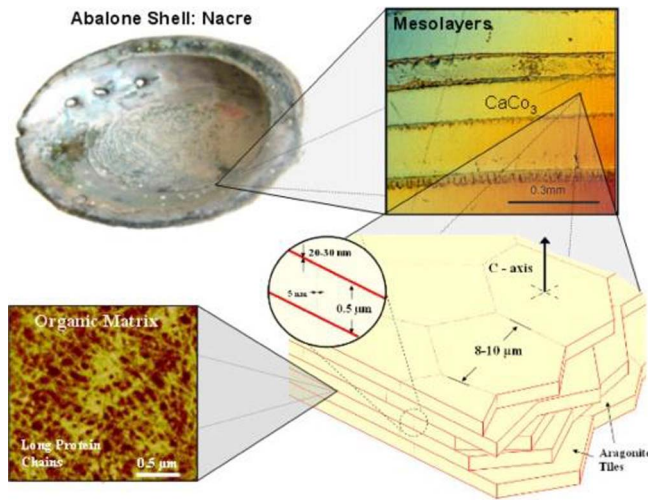


Fig. 1. Hierarchy of abalone structure shown the nacre was composed of highly discontinuous and interdigitated aragonite platelets (adapted from [18]).

The mechanical property of nacre, derived from its structural features can inspire the design of efficient energy absorbing structures; however, so far, most researches were focused on mimicking the nacre structure in sub-micrometer-scale architectures, while only few studies focused on nacre-mimetic design strategies in composite material systems.

Malkin et al. [20] introduced a simple concept of discrete material sections which was inspired by the architecture of nacre into design a laminated composite. They introduced regularly dispersed ply cuts within the laminate to successfully convert the catastrophic flexural failure in unidirectional (UD) laminates to a progressive failure process.

Czél et al. [21] formulated the discontinuous UD carbon/epoxy prepreg composite with *brick-and-mortar* architecture to create a significantly non-linear material response under a quasi-static tension. Meanwhile in their study, the generalized shear-lag model proposed by Pimenta and Robinson [22] was used to predict and optimize the discontinuous ply configuration within the specimen. Their work also demonstrated that a brittle composite material system could possibly exhibit pseudo-ductile properties through a nacre-mimetic design.

Previous studies also demonstrated that discontinuous UD fiber reinforced composites (FRP) could exhibit pseudo-ductile failure that can't be achieved in a continuous FRP. In this work we have engineered the energy absorption properties through mimicking the nacre structure at different scales by using a discontinuous FRP system. In order to achieve this goal, we have applied structural design methods for integrating discontinuous and interdigitated plies into the carbon fiber/epoxy tubes. Four different kinds of tubular specimens are fabricated and crushed. The load-crushed displacement curves are investigated and the SEA values are derived from these curves. Finally, these experimental results are applied to evaluate how the selected nacre-mimetic feature design influences the energy absorption behavior.

2. Experimental section

2.1. Materials and specimen fabrication

The composite material system used in this study is the unidirectional T300 CFRP pre-preg carbon/epoxy tape (Hengshen CO. Ltd, China) of nominal cured ply thickness 0.135 mm and with a 12 K tow. The test specimens are fabricated by wrapping the UD pre-preg tape around a circular steel pipe with an outside diameter of 25 mm and then insert it into an outer mold made of polytetrafluoroethylene (PTFE). The expansion of the inner steel pipe provides for the compression during fabrication process and ensured a high sample quality

as testified by the low void content. All specimens are cured in a heat-oven according to curing cycle provided by manufactures' guidelines. The curing cycles consist of a 2 °C/min ramp to 80 °C kept for 30 min, then a second heat ramp at 1.5 °C/min is performed up to 130 °C kept for 2 h. The ply orientation considered in this study is 0° along the tube axis. Once the curing process is completed, the specimens are separated from mold parts and then polished using 400 and 800 grade SiC to minimize edge effects and guarantee the plainness of the end face. After trimming, the length of the specimens is fixed to 50 mm with an inner diameter of 25 mm and a wall thickness of 1.5 mm. The tube t/D ratio is 0.06 to ensure that can fail following a progressive fracture mode [23].

2.2. Compression test setup

All the specimens manufactured are tested under quasi-static axial compression conditions to follow their crushing load-deformation evolution. An MTS (SANS) CMT5504 screw driven electromechanical test machine with a 50 kN load cell is used to carry out all tests. The specimens are compressed between two steel cross head at a displacement rate of 1 mm/s.

In order to capture the overall deformational characteristics and the strain field, a XTDIC (digital image correlation, XT is an abbreviation of company) system is adopted, which was developed by Xi'an Jiaotong University. The system is integrated with a digital image correlation, including a binocular stereo vision and close-range photogrammetry which allows realizing three-dimensional, measurements of the deformation and strain through the analysis of speckled images taken at the surface. The capacity of measuring strains ranges from 0.01 to over 100% with a precision within 5 με. The camera shoots at 4.1 megapixels.

2.3. Crush process and energy absorption

An UD continuous tube is tested firstly to acquire the basic experimental data for comparison purpose. With the stroke control function of the test equipment, since the specimen tubes length is 50 mm, a crush length of 40 mm is defined to obtain sufficient crush data. Fig. 2 shows the load-crushed displacement and SEA results typically obtained on a tube with 10 UD continuous plies. The load-crushed displacement behavior results to be mainly comprised of two different stages: a linear elasticity and a sustained collapse. The linear elasticity stage is characterized by a very high initial peak load which is clearly not desirable as it will cause the fluctuations of the compression force. The energy absorption capability of each specimen is evaluated from the Specific Energy Absorption (SEA) defined by:

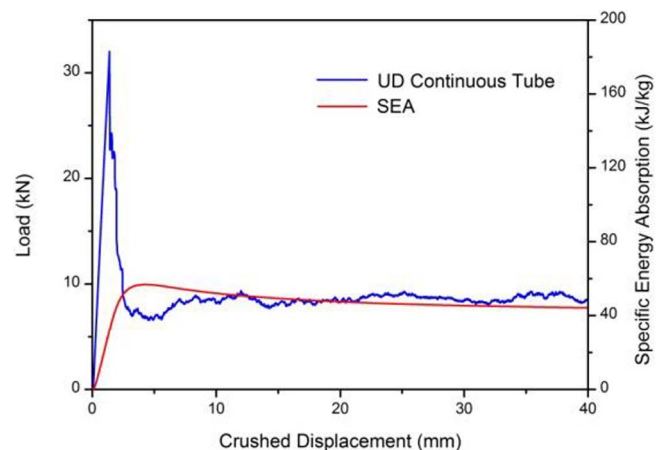


Fig. 2. Typical load-crushed displacement curves and specific energy absorption (SEA) value obtained on a UD continuous tube.

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