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Bio-inspired composite structures subjected to underwater impulsive loading

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ABSTRACT

Designing lightweight high-performance materials that can sustain high impulsive loadings is of great interest to marine and civil applications. When designing tough, strong new materials from relatively weak components, mimicking structures from nature can be a highly promising strategy, as illustrated by nacre from red abalone shells. One of nacre's most impressive features is its ability to laterally spread damage and dissipate energy over millimetre length scales at crack tips and other defects. In this work, a composite panel is redesigned to mimic nacre's microstructure. The bio-inspired composite panel and the original composite structure, which have identical areal mass, are subjected to an underwater impulsive loading scenario. Their performances are compared numerically in terms of damage and deflection. A finite element fluid–structure interaction model is developed to capture the water impact on E-glass/vinylester composite facets and to provide insights into the deformation modes and failure mechanisms. Damage and degradation in individual unidirectional composite laminas are simulated using Hashin's composite damage model. The delamination between laminas is modelled by a bilinear cohesive model. Results interpreted from this numerical study will be used as guidance for the future manufacturing and experimental characterisation of bio-inspired composite structures.

1. Introduction

Designing and manufacturing lightweight yet high-performance materials has attracted a lot of attention recently due to fast-growing military and civil applications. In modern warfare, marine's structures could be exposed to extreme impact induced by underwater and in-air blasts that can impose significant damages on their structures. Designing a reliable structures or warships against such extreme threats requires continuous improvements of material systems for better energy absorption, mitigation and fragment penetration resistance. Comprehensive understanding the effects of various factors such as dynamic responses, failure mechanisms and operating environments on the vulnerability and survivability of structures impacted by such threats becomes extremely critical. Development in this area has been discussed in the extensive review-paper by Mouritz et al. [1], Porfiri and Gupta [2] and Hall [3]. In recent years, glass fibre reinforced plastic (GFRP) composite materials are of current interest in naval hull construction [1,4] because they exhibit low weight and low magnetic signature. These advantages are of particular interest to naval engineers, who are interested in designing fast and stealth marine structures. Two different architectures are generally used to build composite hulls: single-skin design and sandwich construction, where a crushable core is encased between fibre-reinforced face skins. Both architectures involve the use of frames, stiffeners and bulkheads that provide the overall structural stiffness and support the GFRP composite hull. The use of sandwich structures in blast mitigation became a favourable choice for designers realizing that the encased crushable core could attenuate the impulse transmitted to the back-side composite face-sheet by which protecting the interior structures or occupants. The two monolithic composite faces (front and back), on the other hand, provide overall structural integrity and penetration proof capability. Extensive designs of sandwich architectures have been studied and showing superior performances compared with single structures of equal areal mass ([5–9]).

Numerous experimental studies of marine composites subjected to impulsive loadings are reported in Porfiri and Gupta [2]. These studies present the performance of different composite panels and the most significant damage modes involved in blast or ballistic resistance of sandwich structures. In these experiments, it has been shown that local degradations can significantly affect the overall structural performance [10]. Localised damage is not representative structural failures observed in larger scale blast studies, where clamping tearing is not the most critical mechanism responsible for structural failure, and deformation and damage are, instead, spread over a large section of the hull. In recent study by Latourte et al. [11] has reported experiments on monolithic and sandwich composite panels subjected to a wide range of impulsive

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loading using a scaled-down FSI apparatus. Post-mortem analysis of composite damages has revealed various damage mechanisms of composite panels such as inter-laminar delamination, fibre and matrix damage in the composite plies over large area. The centre of the front face-sheet composite laminates, which is subjected to water impact, is severely damaged due to the initial impact the following cavitation collapse. These composite failures lead to foam cracking and therefore significantly affects the crushing performance of the polymeric core. As a result, designing a new generation of composite facet which could provide a combination of stiffness and smart energy absorption capability protecting interior structure becomes a promising venture.

While significant efforts have been devoted to improving the impact resistance of composites by either enhancing energy dissipation or preventing fragmentation penetration, efficiently combining both capabilities into a single composite structure is still a huge challenge. Other factors, such as cost, weight, thermal–mechanical reliability and flexibility, also need to be considered as design criteria, which makes the problem even more complicated. One of the ways to overcome such challenges is to learn from nature. Natural materials can exhibit remarkable combinations of stiffness, low weight, strength and toughness, which in many cases outperform man-made materials. Nacre from seashells (see Fig. 1) is a representative example of a biological material mostly made of weak components (a fragile bio-ceramic), but exhibiting surprisingly high levels of strength and toughness in combination. It has been pointed out in many studies that such biological materials are highly organised in a hierarchical manner, from molecular level to nano- and macro-scale, yielding superior mechanical performance from relatively mundane constituents. Nacre, for example, is a ceramic laminated composite comprised of highly structured polygon-shaped aragonite platelet layers with thicknesses of about 0.5 μm separated by 30 nm-thin layers of softer organic biopolymer [12]. This particular microstructure, interestingly, resembles a similar “bricks and mortar” arrangement. The organic interface between the platelet layers with nano-scale roughness are biochemically, structurally and mechanically compatible, providing the overall structural integrity with a combination of strength and flexibility (refer to Fig. 1). Many studies [13–16] have proposed various nanoscale toughening mechanisms of nacre to account for the improved toughness through control of the platelets' interfaces, including: biopolymer stretching, aragonite's asperities and bridges, induced contacts and interlocking, and platelet waviness induced shear resistance.

Considerable efforts from the scientific community have been devoted to understanding, designing and developing biomimetic materials. Special interest is focused on providing simple guidelines to design high performance composite structures. The objective of this research is to develop a numerical model to investigate the performance and failure mechanism of bio-inspired composite facets, which incorporate similar hierarchical architectures to that of nacre, subjected to underwater impulsive loading. This research presents a finite element model to simulate the fluid structure interaction (FSI) and the corresponding failure of monolithic composite panels during the impact event. Performance of a baseline composite panel and the bio-inspired one are compared in terms of total deformation and composite damage.

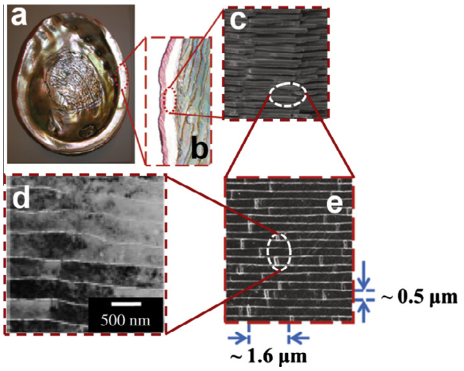

Fig. 1. Hierarchical microstructure of nacre: (a) inner view of a nacre shell, (b) cross-section of red abalone shell, (c) SEM micrograph of fracture plane, (d and e) SEM micrograph showing platelet waviness of nacre shell [12]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Simulation of deformation and failure processes of composite structures in complex and extreme loading conditions still poses significant challenges to the scientific community. Composite panels subjected to blast or impulsive loading typically present not only extensive inter-laminar fracture (delamination), but also matrix micro-cracking and ultimately fibre fracture at severe impact. Regarding the prediction of structural behaviour and the failure of composite panels subjected to impulsive loadings, limited work was reported in the literature [4,17–21]. Significant effort has been devoted to a research initiative called World Wide Failure Exercise [22] to rank and classify the various models available in literature on their capability to predict failure under different loading conditions. In this work, micro-structural damage mechanisms developed in the framework of Hashin's damage mechanics [23] is employed to model the composite failure. A cohesive zone model that couples both normal and shear failure modes is introduced to capture the complex inter-laminar delamination of the composite structures. In recent study [24], Wei and author have developed fluid–structure interaction (FSI) numerical model to simulate the scaled-down FSI experiment [11] and study the failures of composite panel subjected to water impacts.

In this research, we present an FSI numerical model based on the previous author's previous work [24] using the commercial finite element code ABAQUS/Explicit v6.9. This model will allow us to investigate the performance of bio-inspired composite structures subjected to underwater impulsive loading. Numerical results and analysis from this study will give various insights and guidance for our future work on manufacturing bio-inspired composite panels for load protection.

2. Finite element model

2.1. Description of composite panel

The composite solid considered in this study is comprised of quasi-isotropic Devold DBLT850-E10 glass-fibre (0/45/90/-45) non-crimp fabric infiltrated with vinylester Reichhold DION9500, which is similar to system in previous study [24]. Each composite fabric is composed of four laminas comprised of unidirectional E-glass fibres, and is assembled following the sequence: $0^\circ/45^\circ/90^\circ/-45^\circ$. The fibre diameter, lamina and fabric thicknesses are 15, 150 and 600 μm, respectively. The composite fabrics are bonded together with 0.1 μm-thin adhesive layers of vinylester. The total thickness of the panel is about 2.3 mm. Fig. 2 describes the composite monolithic panel geometries tested under the FSI simulation. Optical photography of the cross-section is shown in Fig. 2b and an optical micrograph of an infiltrated fabric is shown in Fig. 2c.

2.2. Numerical model description

A schematic diagram of the scaled underwater impact experiment is shown in Fig. 3. During the underwater blast loading event, the impulsive load is characterised by an exponential decay