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Low velocity impact resistance of bio-inspired building ceramic composites with nacre-like structure

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HIGHLIGHTS

- Nacre-like layered and staggered structural building ceramic composite was prepared.
- Impact resistance of the composite was investigated by drop weight test.
- The bio-inspired composite had higher multiple-impact resistance than the layered composites.
- The bio-inspired composite with soft interlayer showed superior structural integrity at failure.

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ABSTRACT

Nacre in abalone shell exhibits prominently high toughness and remarkable inelasticity when subjected to the external loads, despite the brittle nature of its main constituent. Aiming to improve the impact resistance of the building composite materials, inspired from nacre, a layered and staggered structural system based on the building ceramic mosaic tiles joined with soft adhesive was designed and fabricated. Then, the ACI 544 drop weight test was performed on the above bio-inspired building ceramic composites, and the effects of partitioned tile layer, impact location, stagger mode, tile shape and size, adhesive type, as well as fiberglass mesh were experimentally assessed. The experimental results show high impact resistance of the proposed bio-inspired building ceramic composites under low velocity drop weight impact, and a design approach is proposed. The obtained conclusions could provide some helpful references for the design of protective structures.

1. Introduction

Current world events highlighted the need to develop economical civil infrastructure resilient to impact and blast loading to enhance public safety. This can be gained by utilizing the common building materials with improved mechanical and dynamical properties. Clay-based building ceramic tiles is a cost-effective decoration material often used in building floors and walls, their main component is the silicate compound. Although the building ceramic tiles can possess relatively high hardness and strength [1], they are susceptible to catastrophic failure when subjected to impact loading due to their inherent brittleness.

Abalone nacre is the internal layer of abalone shell. It consists of at least 95 wt-% of orthorhombic aragonite (a form of $CaCO_3$) and less than 5 wt-% of organic material but exhibits prominently high toughness and remarkable inelasticity. For example, the toughness of abalone nacre can reach 1.5 $kJ\cdot m^{-2}$, which is generally twice that of the high-tech ceramics, 1000 times that of the aragonite and 3000 times that of the calcite [2,3]. Also, the inelastic strain of abalone nacre can reach up to 15% in shear and at least 1% in tension [4,5]. These outstanding mechanical properties make nacre becoming perfect natural produced armor, thus nacre can maintain the integrity of the shell under external aggressions and protect the soft body of the mollusk. The mechanical behaviors of nacre have been studied for many years, and the hierarchical microstructure of nacre has been widely accepted as a main contributor to its high toughness and inelasticity. During the past few decades, the specific structural features of nacre have been served as the guidelines for the designs of tough ceramics and glass [6–9]. However, limited attention has been paid to the development of bio-inspired building materials.

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The building ceramic tiles that have relatively high hardness and strength may be fabricated into the nacre-like structural composites that combine strength and toughness, these composites are prospective to use on the structural surface and subsurface as a cladding panel or a shield layer to resist the accidental and deliberate impact. In the present paper, the building ceramic mosaic tiles and adhesive based composite material with a nacre-like layered and staggered structure was designed and fabricated. Then, the low-velocity impact resistance of the above composites was assessed through a drop weight impact test. The effects of tile size and shape, stagger ratio, adhesive type and impact location on the failure behaviors of the composites were also experimentally studied. Finally, a design approach was proposed, which can be referred for the protection of the critical structures or components.

2. Bio-inspired design and experimental program

2.1. Abalone nacre

Fig. 1 shows the scanning electron microscope image of the abalone nacre. It illustrates that the abalone nacre is a material of hierarchical structure with brick and mortar-like shape. The 'brick' refers to the polygonal aragonite tablets that are connected and separated by the 'mortar' which is a biological organic material. The aragonite tablets in abalone nacre are slightly staggered rather than stacked exactly as those in mussel and oyster nacre [10]. Moreover, optical microscopy shows that the arrangement and size of the tablets are highly uniform within the plane of an individual layer, and the tablets are not flat but significantly wavy on the cross section [4].

The well-formed microstructure of nacre is the main factor contributing to the superior mechanical performance of nacre. As shown in Fig. 2(a), when nacre is subjected to shear or tensile loadings along the tablet planes, the organic material around aragonite tablets yields firstly, then the tablets sliding occurs. The microscale waviness of the tablets may act as the obstacles against the tablets sliding, which is conducive to initiating new sliding sites and distributing inelastic strains over large volumes. Correspondingly, as shown in Fig. 2(b), when nacre is compressed perpendicularly to the tablet plane, cracks attempting to pass through the nacre are likely to deflect along the weak organic interlayer rather than propagate rapidly through the relatively stiffer tablets. The tortuous crack path formed in a broad region will alleviate stress concentrations and lead to graceful failure of nacre [11]. Therefore, by introducing weak interfaces in the monolithic material which can deflect a growing crack and lead to multiplying layer cracking, abalone nacre shows a way to toughen the brittle material.

2.2. Material used

Three types of building ceramic mosaic tiles were used to mimic the stiff tablets of abalone nacre, which were respectively assembled into the layered and staggered specimens. For comparison, large-size building ceramic tiles were stacked orderly into simple layered control specimens, as illustrated in Fig. 3. The specific information of the tiles and specimens is given in Table 1. In the column of "Specimen", the initial letters B, L, S, H of the specimen designations represent large-size building ceramic tiles, the larger-size square mosaic tiles, the smaller-size square mosaic tiles and the hexagon mosaic tiles, respectively. The second letters E and S of the specimen designations represent the epoxy adhesive and silicone sealant, respectively. The letters M and D denote the interlayers being reinforced by the fiberglass mesh and the hexagonal tiles staggering along the diagonal direction.

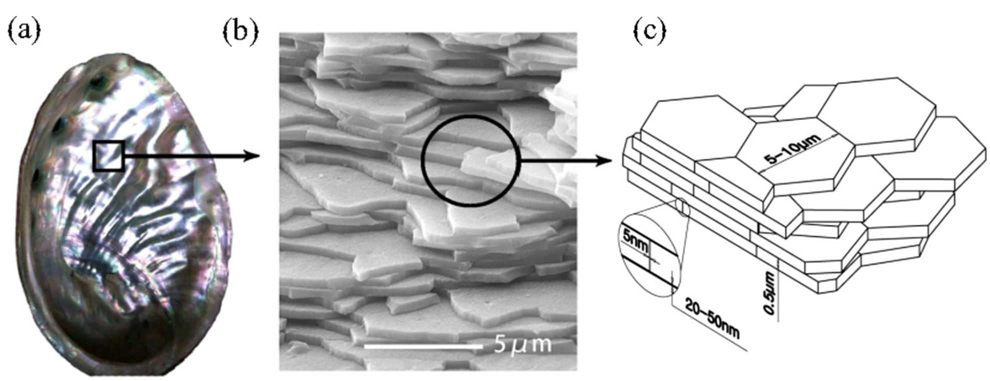

Fig. 1. Abalone nacre (a) inside view (b) hierarchical microstructure (c) dimensions and arrangement.

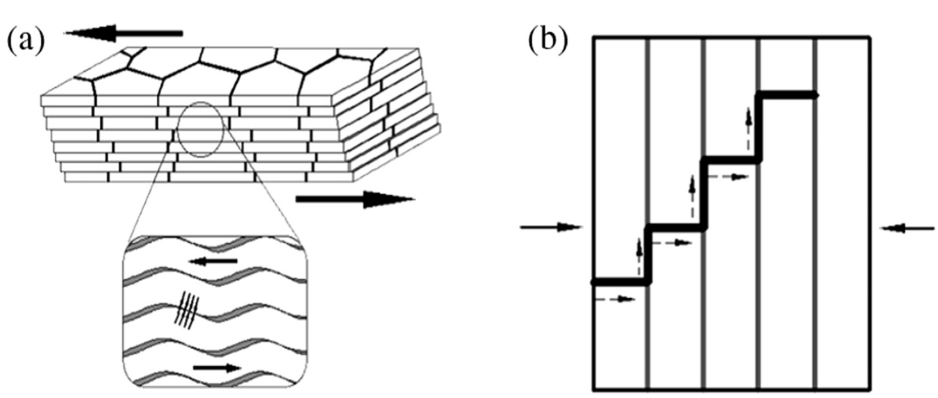

Fig. 2. Schematic illustrations of nacre (a) tablets sliding under shear (b) crack deflecting along the weak interfaces between tablets under compression.