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Review Article

Bioinspired Design of Building Materials for Blast and Ballistic Protection

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Nacre in abalone shell exhibits high toughness despite the brittle nature of its major constituent (i.e., aragonite). Its specific structure is a major contributor to the energy absorption capacity of nacre. This paper reviews the mechanisms behind the performance of nacre under shear, uniaxial tension, compression, and bending conditions. The remarkable combination of stiffness and toughness on nacre can motivate the development of bioinspired building materials for impact resistance applications, and the possible toughness designs of cement-based and clay-based composite materials with a layered and staggered structure were discussed.

1. Introduction

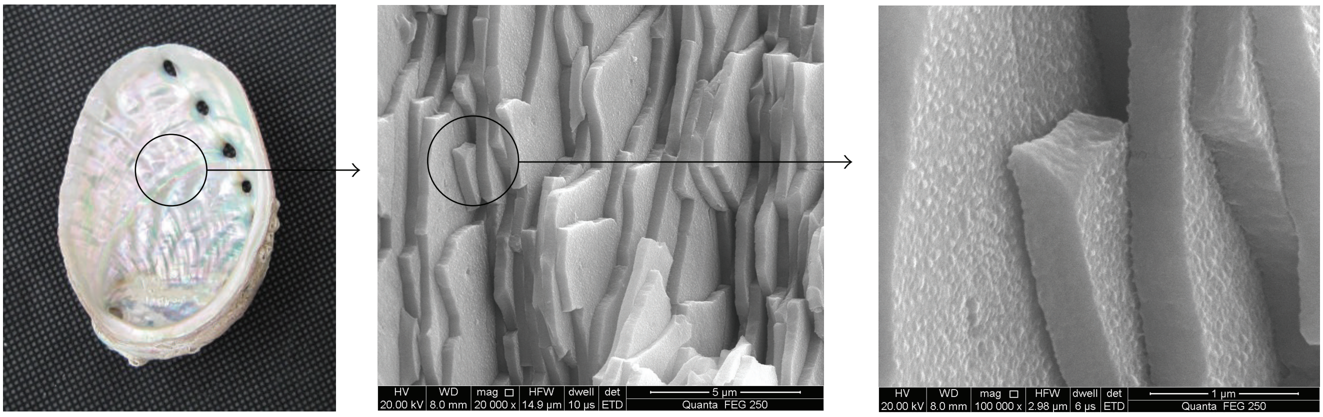
Abalone nacre is the inner layer of abalone shell, which can help to maintain the integrity of the shell under external loads and thus protect the mollusk. Although composed of at least 95% of aragonite by weight, nacre exhibits high toughness which is 1000 times that of the aragonite without compromising strength [1]. Moreover, the ratio of compressive strength to tensile strength of nacre ranges from 1.5 to 3, which is much smaller than those of the conventional monolithic ceramics (range: 8–15) and plain concrete (range: 9–15) [2]. The outstanding mechanical performance of nacre is generally considered to be due to the hierarchical structure of nacre at the nano- and microlevels. Inspired by the structure of nacre, man-made composite materials have been developed with enhanced toughness, such as bioinspired glass and technical ceramic [3–7]. However, very limited work has been carried out to apply this natural principle to the toughness design of building materials such as cement-based and clay-based materials.

This paper discussed the effects of the hierarchical structure on the mechanical behavior of nacre based on the existing publications. Learning the underlying mechanisms of the performance of abalone nacre would help to design nacre-like building materials that combine strength and toughness. When the building was subjected to seismic, impact, or blast loading, these materials can help reduce the incidences of failures and enhance public safety.

2. Abalone Nacre

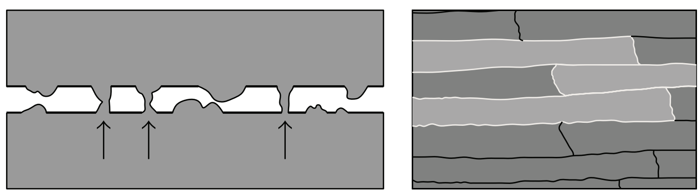
2.1. Structure Features. Abalone nacre is a material of hierarchical structure formed by aragonite tablet layers and thin biological organic interlayers, as shown in Figure 1. Each tablet layer consists of polygonal aragonite tablets which are about 5–8 μm in diameter and 0.5 μm in thickness; the spacing between the neighboring tablets is about 5 nm [2]. Moreover, tablets in adjacent layers are slightly staggered rather than stacked randomly or exactly [8]. Transmission electron microscopy (TEM) shows that the surfaces of the aragonite tablets are not flat but significantly wavy, their roughness can reach amplitudes exceeding 200 nm when the average thickness of the tablets was 450 nm, and the waviness of the tablets is highly conformal so that the tablets of adjacent layers fit perfectly together [9].

At the nanoscale, the organic interlayer is about 20–50 nm thick, which is porous and possesses holes of about 50 nm in diameter [2]. Aragonite bridges (Figure 2(a)) connect the aragonite tablet layers through the interlayer [10], and aragonite asperities on the surface of the tablets (Figure 1(c)) form nanoscale islands that are around 30–100 nm in diameter, 10 nm in amplitude, and 60–120 nm apart [11]. Moreover, at the periphery of some tablets, dovetail-like features



(a) (b) (c)

Figure 1: The structure of abalone nacre at different length scales: (a) the inside view of an abalone shell, (b) SEM image showing the fractured surface of nacre, and (c) the asperities on the surface of aragonite tablets.



(a) (b)

Figure 2: Schematic illustrations of (a) aragonite bridges (marked by arrows) between tablets and (b) dovetail-like features at the periphery of tablets.

(Figure 2(b)) generated by the waviness of the interface can be observed in two-dimensional cross sections of nacre [8]. Furthermore, rotated nanograins with an average grain size of 32 nm within the aragonite tablets were found by Li et al. [12] using in situ dynamic atomic force microscope (AFM).

2.2. Mechanical Responses. The outstanding mechanical properties of nacre were first demonstrated by Currey [13] and have been intensively studied over the past two decades. Sarikaya [14] conducted bending tests on red abalone nacre and obtained a fracture toughness of $8 \pm 3\,\mathrm{MPa{\cdot}m^{1/2}}$, which is eightfold higher than that of monolithic $CaCO_3$ and much higher than that of concrete (about $0.2\,\mathrm{MPa{\cdot}m^{1/2}}$ [15]). Some experimental data obtained from mechanical tests (e.g., tension, compression, shear, and bending) are collected based on the available references and shown in Table 1. Although the values among different references in Table 1 are slightly or even significantly different probably due to the diversity of lab equipment or specimens, some consistence can still be found: (i) the mechanical response of nacre is anisotropic, depending on the orientation of the imposed forces relative to the surface of the aragonite tablets; (ii) under tension and shear loadings, abalone nacre exhibits relatively large inelastic deformation prior to rupture; (iii) the linear elastic response (E = 10–80 GPa) is remarkable, considering low Young's modulus (2.84 ± 0.27 GPa [16]) of the soft interlayer. Moreover, Table 1 also shows that the dynamic compressive strength of nacre is about 50% higher than its quasi-static compressive strength.

2.3. Underlying Mechanisms

2.3.1. Shear. Table 1 shows that the shear strength of abalone nacre is much lower than the compressive and tensile strengths but accompanied by a relatively large inelastic deformation. It appears that the shearing of interfaces between tablets dominates the shear resistance and deformation mechanism of nacre. When subjected to shear loading, the interfaces yield first followed by the relative sliding of tablet layers [18]. The microscale waviness of the tablets may act as obstacles to the tablets sliding, and a transverse expansion of the tablets is generated due to the compression (Figure 3(a)), which can further hinder the tablets sliding. These mechanisms are favorable for nacre to initiate new sliding sites, uniformly distribute inelastic strains, and mitigate damage localization.

Wang et al. [11] reported that the asperities on the surface of the tablet were the principal source of the shear resistance of nacre and also a major contributor to its initial strain hardening. However, the significance of the asperities was not supported by Barthelat et al. [16], since the sliding distance attributed to the asperities (20–25 nm) is much smaller than the observed tablet sliding distance (100–200 nm) under shear loading.

The thin porous organic material in nacre is traditionally regarded as glue to maintain the cohesion of the tablets over a large separation distance [11, 19]. However, Meyers et al. [2] reported that the primary role of the organic layer on the mechanical behavior of nacre was to subdivide the aragonite matrix into tablets, and the glue effect was not significant.

Table 1: Some experimental data collected from literature on abalone nacre.

Reference	Test	σ_1/MPa	σ_2/MPa	ε_t/%	E/GPa
[17]	Quasi-static compression	540	235	···	···
	Dynamic compression	735	548	···	···
	Shear	···	30	45	···
	Three-point bending	197	177	···	···
[11]	Shear-compression*	73	···	8	···
	Three-point bending	223 ± 7	194 ± 8	···	69 ± 7
	Four-point bending				
	Compressive	370	···	···	70
	Tensile	105	···	1	60
[12]	Tension	···	···	1–5	···
[9]	Shear	···	50	15	10
	Shear-compression*	60	···	1.5	···
[1]	Tension	···	90	1	80

σ_1 and σ_2: the strength obtained from loading perpendicular and parallel to the tablets surface plane, respectively.
E: Young's modulus.
ε_t: inelastic strain.
*The strength obtained with the boundaries at 45° to the load axis.

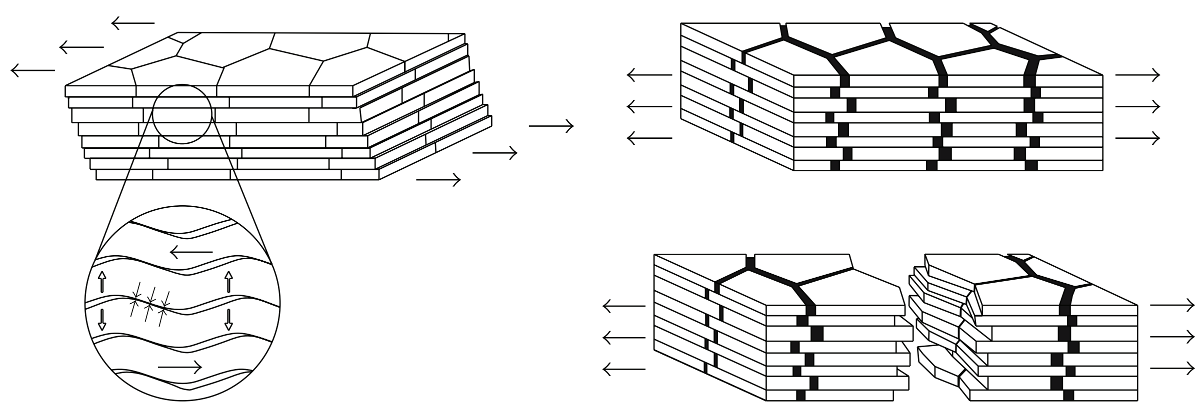


Figure 3: (a) Deformation mechanism of nacre under shear stresses; (b) deformation mode of nacre under tensile stresses.

2.3.2. Tension. The response of abalone nacre to tension is critical to prevention of pullout failure. Under tensile loading applied along the tablet plane (Figure 3(b)), the strain hardening rate and observed tablet sliding distance are both less than those in shear, as in tension the shearing interfaces (overlap areas) account for only 30% of the interface area. The inelastic deformation spreads over large volumes around cracks and defects, which generates many "white tension lines" [11].

The dovetail-like feature at the end of some tablets is generally considered as a key contributor to nacre's performance in tension, as it can generate progressive interlocking and lead to a triaxial state of stress in the sliding region to impede the tablet separation [8]. However, Barthelat and Espinosa [1] reported that the angle of the dovetails was rather small (about 1–5°), so that the locking and hardening functions were weak.

Song et al. [20] reported that the mineral bridges between tablet layers significantly reinforced the weak organic interlayers and consequently enhanced the tensile strength of nacre. However, Lin and Meyers [21] disapproved of the existence of such mineral bridges, and Katti et al. [22] concluded that the mineral bridges had marginal effect on both linear and nonlinear responses in nacre, as the mineral contacts broke long before yield initiated in nacre.

The results of tension test conducted by Li et al. [12] showed that the rotation and deformation of nanograins significantly benefitted the energy dissipation in nacre. However, Barthelat et al. [9] pointed out that the primary role of the nanograins was to preserve the tablet integrity in the deformation process rather than directly influence the overall deformation in nacre.

2.3.3. Compression. When nacre is subjected to compressive loading that is perpendicular to the tablet surface plane, the failure occurs gradually due to crack deflection along the organic interlayer [17]. The mechanism is that if a crack occurs and attempts to pass through the nacre, its direction

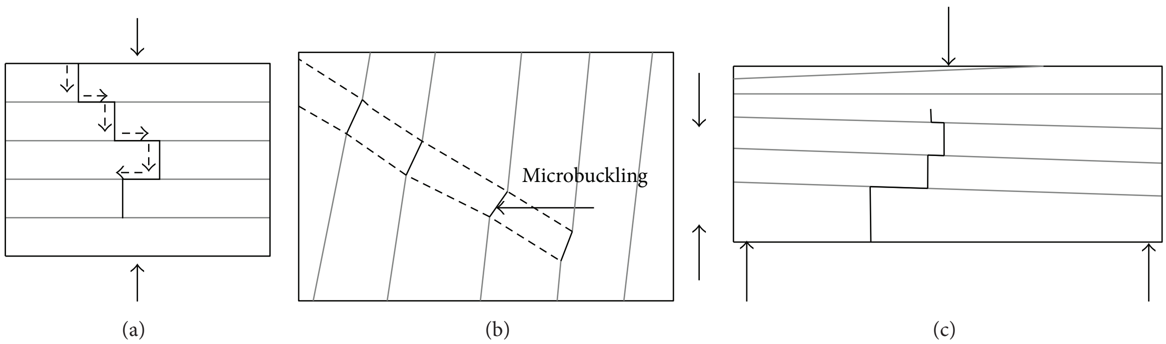


Figure 4: Schematic illustrations of (a) crack deflection along organic layers of nacre under compression, (b) microbuckling in nacre under compression (parallel), and (c) crack deflection in an abalone shell under three-point bending.

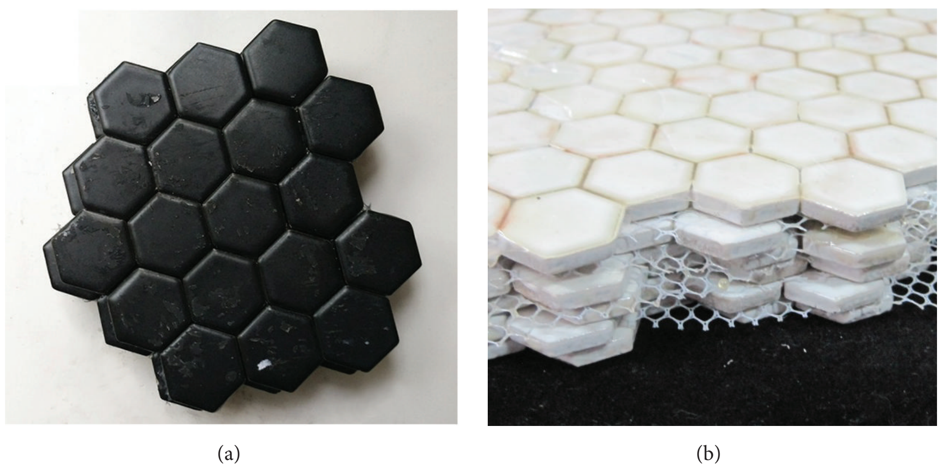


Figure 5: (a) A building ceramic composite sample with a layered and staggered structure; (b) the side view of a composite sample.

will be forced to change along the weak protein layers rather than develop rapidly through the relatively stiff tablets. As such, a tortuous path will be formed, and a single sharp crack will be replaced by a large number of small cracks within a broad region (Figure 4(a)), which disperses the imposed force and alleviates stress concentrations. When the compressive loading is parallel to the tablets surface plane, the value of compressive strength is lower than that in perpendicular condition, which can be explained by the microplastic buckling (Figure 4(b)).

2.3.4. Bending. When an abalone shell is subjected to a localized pressure normal to the outer shell surface, the overall shell can be idealized as experiencing bending stress. In this situation, the hard outer layer of the shell is in compression and the inside nacreous layer is in tension (Figure 4(c)); thus the damage mechanisms for abalone shell in bending may involve the compressive and tensile strengths of outer and inner shells, respectively.

3. Toughness Design for Building Materials

Cement-based and clay-based materials such as concrete and building ceramic tiles are commonly used as construction materials in civil engineering. Although they can possess high compressive strength, they are susceptible to catastrophic failure due to their inherent brittleness. Inspired by the fracture mechanisms of nacre, we suggest that cement-based and clay-based building composites having a layered and staggered structure like nacre may have improved fracture toughness. To achieve this structure, thin and weak interlayers should be introduced in the building composite to facilitate layer sliding and deflect growing cracks, and the hard layers should be partitioned into multiple tiles to prevent fracture surfaces crossing the entire layer. Besides, the ratio of length to thickness of an individual tile should be high enough to enhance interlayer cohesion but not too high to cause premature tile failure.

Authors of this paper have recently studied the impact response of the building ceramic composite with a nacre-like structure by drop weight test and also explored the potential use of this ceramic composite as protective covering on concrete against high-speed projectile impact [23]. The layered and staggered structure of the composite consisted of building ceramic mosaic tiles (CMTs) and soft adhesive, which mimic the stiff aragonite tablets and the organic material in nacre, respectively (see Figure 5). The experimental results showed that this ceramic composite exhibited significantly improved impact resistance compared with the simple layered ceramic composite consisting of nonpartitioned tile layers and concrete targets with the protective

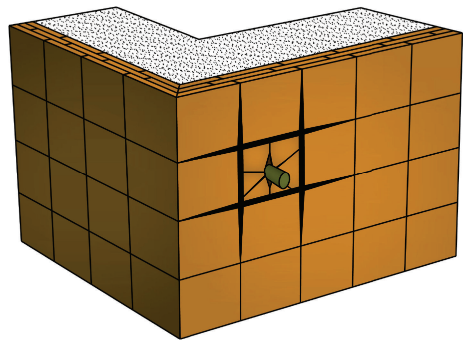
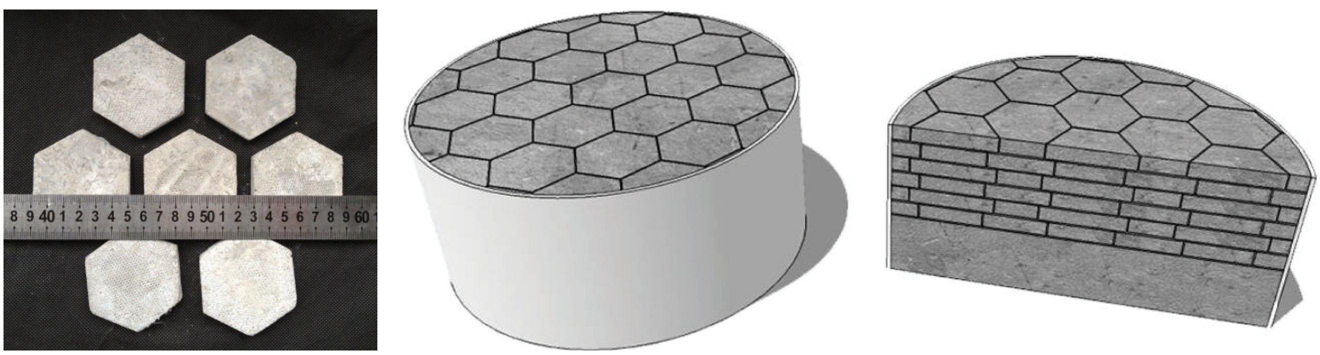


Figure 6: The protective covering on concrete member can confine the crater damage within the impacted tile.



(a) (b)

Figure 7: (a) Concrete tiles of hexagonal shape; (b) schematic illustrations of concrete target with cement-based composite protective covering.

covering displayed superior integrity and highly reduced penetration depth compared with those without protective covering. Since the CMTs in the building materials market have various sizes, shapes, and thicknesses, they will favor the future experimental studies on the optimal polygon shape, aspect ratio, and overlap length of the tiles in the layered and staggered structural composites.

According to the ballistic test results in [23], the penetration depth of the projectile in concrete can be reduced by up to 77.3% in the presence of the protective covering. That means the design thickness of the concrete member under protection can be greatly decreased, which will help to lower the costs of the concrete material. Besides, as the crushed tile can be separated from the adjacent tiles while confining the radial cracks within the impacted tile when the adhesive possesses a relative large elongation at break (see Figure 6), the repair costs in war time will be decreased. However, the selling price of CMTs is about 70 RMB/m^2, which is higher than that of concrete; although only a small amount of adhesive material is required to prepare the building ceramic composite, the unit prices of both epoxy adhesive and silicone sealant are relatively high; additionally, the production procedures of the building ceramic composite are complex; therefore, the material and construction costs may limit the application of the composite. To reduce the material costs, it is necessary to find alternative materials, and the cement-based material is a good choice due to its relatively low cost and high strength.

The impact resistance of multilayer cement-based composites has been studied in recent years [24, 25]. It was reported that the layered or functionally graded cement-based composites showed better performance against high velocity impact compared with the monoblock cement-based materials. However, the layered structure was not sufficient to provide inelastic deformation. Learning from nacre, cement-based composite can be designed into a layered and staggered structure by using concrete or mortar tiles (Figure 7(a)), and such composite may also be used as a protective covering on concrete against impact loading (Figure 7(b)). Moreover, properties of the thin interlayer materials can affect the failure behaviors of the composites: rigid interlayers (such as cement mortar with high elastic modulus) can facilitate energy transmission but reduce the multihit capability of the composites; elastic interlayer (such as rubberized mortar with low elastic modulus) is able to support large deformation but at a cost of decreased stiffness of the composite. Therefore, the choice of the interlayer material should depend on the loading condition and service requirements of the composite. The efficacy of the cement-based composite protective covering needs to be investigated in the further studies.

4. Conclusion

Nacre in abalone shell, consisting mainly of brittle aragonite, shows high toughness and remarkable inelasticity. Mechanisms at distinct length scales contribute to the overall mechanical responses of nacre. At the microlevel, the well-formed hierarchical structure of nacre can deflect cracks and prolong the crack propagation, which consumes a significant amount of energy; at the nanoscale, tablet sliding is considered the prominent inelastic deformation mechanism.

The structure of nacre can serve as a biomimetic model for the toughness design of cement-based and clay-based building composite materials. This structure can lead to deflection of cracks and delay failure of the composite. The building ceramic composite with a nacre-like structure showed improved impact resistance, and it also has the potential to be used on structural surface and subsurface for blast and ballistic protection. The efficacy of concrete with a layered and staggered structure for impact resistance application needs further investigation.

Competing Interests

The authors declare that they have no competing interests.

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