Numerical analysis for impact resistance of nacre-like composites

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ABSTRACT

Inspired by the micro layered structure of nacre, a 3D Voronoi model of an Aluminum AA7075-T651/toughened epoxy resin composite was established in Abaqus/Explicit, which is similar to the microstructure of multilayer nacre-like tablets. Cohesive layers are inserted between the tablets to simulate the soft layer of nacre observed under the microstructure, and blunt bullets are used as research object of impact load. According to the morphological changes of nacre-like composites during impact, the mechanism analysis and stage division for the resistant deformation of nacre-like composites were carried out. In addition, the effects of the number of layers and polygons on the energy dissipation and deformation characteristics of composites are analyzed. The results show that increasing the number of layers and decreasing the number of polygons in the layers can increase the energy absorption performance of composite tablets, which is mainly due to the effective improvement of the interlayer interlocking mechanism and the promotion of global energy absorption.

**keywords:** Nacre-like composites; interlayer interlocking; Voronoi; finite element analysis; dissipation energy.

1. Introduction

In the process of evolution, nature has developed ingenious biological armor, which can adapt to the living environment of creatures and make them resist natural disasters and predators [1]. Among them, nacre has attracted the attention of scholars because of its lightweight and high-strength structural characteristics. For nacre, although
it is composed of 95% aragonite and 5% organic matrix, its fracture toughness is about 3-9 times higher than aragonite [2-4]. The coexistence of toughening mechanisms of hard tablets and organic matrix makes the nacre have three main toughening mechanisms: crack deflection, fiber pull-out and organic matrix [5, 6]. These toughening mechanisms make nacre-like composites have greater impact resistance potential than traditional laminated composites [7]. Impact resistance studies of nacre-like composites have been carried out, including drop hammer impact [8-12] and ballistic impact [4, 7, 13]. From the results, the structural damage forms and structural resistance modes caused by different impact forms are different[14], different resistance properties should be considered during the development of nacre-like composite, but the research on the high-speed impact of blunt bullet is ignored.

In addition to the research on the toughening mechanism of the existing nacre, the different forms of nacre-like composites have been developed [15-22]. If the research only focuses on the design of the geometric form of the composite and ignores the influence of the length scale on the structural performance, this design is obviously not feasible [23]. Tablets and organic matrix form a tiny multiphase structure, which will produce a gradient resistance when bearing external loads. Due to the structural coupling between hard materials and soft materials, the nacre-like structure has significant crack suppression and fatigue resistance performance [6, 24], so it is not feasible to ignore the number of layers in the thickness direction. In addition, the failure mode of nacre-like composite is affected by a variety of mixed modes, including the pulling out of the tablets, the failure of the cohesive layer and the damage of the tablets, and the plastic deformation of the tablets is the main form of energy absorption under impact load [5]. During the process of resisting deformation, the tablets will rotate and crack internally [25], and the deformation mode of the tablets will affect the stepped failure mode. Therefore, when designing nacre-like composites, the geometric form and aspect ratio of the tablets must be considered.

In general, nacre is a micro randomly arranged layered structure, and the number of layers and tablets is very
large, so nacre can show complex toughening characteristics when facing impact load. However, due to factors such as the equipment and computer performance, the previous mechanical studies on the nacre-like composite set a smaller number of layers and tablets compared with real nacre, so there is still great development potential in the research on the number of layers and tablets of nacre-like composites. In addition, in the previous impact study of nacre-like composites, round bullet was usually selected as the impact object, while the impact of blunt bullet was ignored. In this paper, on the premise of ensuring the reliability, the number of layers and tablets be increased as much as possible, and the large deformation of the hard tablets under the impact of blunt bullet be studied. The aluminum AA7075-T651/reinforced epoxy nacre-like composite model was established based on Voronoi polygon structure, and the impact resistance performance of the model was studied. In addition, we analyzed the deformation characteristics of composites in the impact stage, and focused on the analysis of energy absorption by two parameters: (a) number of tablets layers; (b) polygon counts.

2. Nacre-like Voronoi diagram structure

2.1. Microstructure of nacre.

Sample made of the nacre of Hyriopsis cumingii (bivalvia class), which cultivated in Zhejiang Province of China was selected as the observation object. The keratin and prismatic layers of the shell are removed by grinding, wash the nacre of the shell with distilled water and air dry it at room temperature. As shown in Figure 1, nacre is sprayed with gold by Ion sputtering instrument (JEC-3000FC, Tokyo Japan) and examined with the scanning electron microscope (JSM-7100, Tokyo, Japan) at an operating voltage of 5 kV.

The cross sections of nacre were observed by SEM, and the morphologies of nacre revealed a brick-mortar arrangement. The length of aragonite tablets is 3-7µm, and the thickness is 500-700nm. It can be seen from Figure 1 that the cracks in the nacre are mainly caused by the destruction of the organic matrix and the pulling out of the tablets, and small amounts of tablets are destroyed along the crack development plane. The random arrangement
of the tablets promotes the crack of the nacre to diffuse along the inclined plane, and the destruction along the slope will increase the energy absorption of the nacre, which is an important toughening mechanism of the nacre—crack deflection [26].

It can be seen from the fault surface of nacre in Figure 1, the tablets are randomly distributed by an approximate irregular hexagon in the plane, which is similar to the Voronoi diagram. The tablets of the upper and lower layers are staggered, which is the interlaminar interlocking mechanism between the tablets. When the nacre bears external impact load, the staggered tablets will transfer the load to a larger area to resist the impact. The organic matrix between the tablets provides a certain buffer for the deformation of the tablets, and improves the toughness of the nacre. The thickness of organic matrix is 20-30nm, which is about 5% of the volume fraction of nacre.

2.2. Generation of the nacre-like Voronoi structure.

Voronoi diagram is a method of dividing the plane of space, and this method is famous in geometric calculation. The characteristic of the Voronoi diagram is that each polygon contains only one sample point, and the distance from any position inside the polygon to the sample point is smaller than other sample points, it can be expressed by the following equation [16]:

\[ R_k = \{ x \in X | d(x, P_k) \leq d(x, P_j) \forall j \neq k \} \]  (1)

where \( R_k \) is the set of all points in the Voronoi diagram \( X \), the distance \( d(x, P_k) \) between each point \( x \) and a site \( P_k \) is less than or equal to the distance \( d(x, P_j) \) between that point and any other site. In short, the connection lines of any two adjacent points are vertically divided by their common boundary line, as shown in Figure 1.

This article uses the Grasshopper function sector inside Rhino 7.0 to achieve the generation of Voronoi diagram, and export it into ABAQUS software for model settings and solve analysis.

2.3. The baseline models.

The baseline model comprises of 200mm × 200mm × 20mm amour Aluminum (AA7075-T651) tablets, the
thickness of each tablets is 0.5mm and consists of 100 Voronoi polygons tablets. As shown in Figure 2, the split shape of each layer of aluminum tablets is different from its adjacent aluminum tablets. In order to realize the analysis and research of the impact resistance mechanism of the composites at the microscopic angle, as many layers as possible are set in the thickness direction. In the baseline model, 40 layers tablets are set up along the thickness direction.

In order to study the mechanical mechanism of the hard layer and the soft layer for the nacre-like composite, this paper inserts cohesive elements between all adjacent aluminum tablets, as shown in Figure 3(a). It is worth noting that, in order to reduce the warping problem of the cohesive elements during the deformation process, and make the cohesive elements to be dominated by tensile failure and shear failure during the impact process, cohesive elements with no thickness in space is set up [27, 28], and the calculated thickness is one tenth of the adjacent aluminum tablets.

As shown in Figure 3(b), the cohesive elements at different positions are connected in different ways. For the cohesive element between the upper and lower tablets, due to the Voronoi diagram is different between the adjacent tablet layers, so that is very difficult to make the nodes of the upper and lower surfaces correspond. Therefore, the cohesive elements between the adjacent layers are inserted by adopting the connection method of common nodes and tie constraints. For the cohesive elements between the same layer of aluminum tablets, a self-defined subprogram is used to insert the cohesive elements inside the aluminum tablets, and all the nodes of the inserted cohesive elements have the same number as the adjacent aluminum tablets elements.

During the impact process, the two boundaries of the model parallel to the impact plane are free, and the other four boundaries are fixed. The impact position of the bullet is the target center, and the initial position is 0.5mm away from the tablets. The size of blunt bullet is shown in Figure 2, and its has a mass of 197g. It is worth mentioning that the friction coefficient of 0.2 is set globally. In order to express more clearly on the diagram, 4-
layer tablets are added into a curve in this paper, so the damage energy of 40 layers tablets is divided into 10 groups, as shown in Figure 3(a).

3. Material properties

3.1 Damage model of cohesive elements

The delamination failure mode and debonding behavior of composites can be simulated by the cohesive zone model [29]. Maximum nominal stress criterion is the damage initiation criterion, and a typical bilinear traction separation response model is employed to research the damage evolution of cohesive elements. The toughened epoxy adhesive Betamate 1044 is used as the adhesive layers between aluminum tablets, its material properties are shown in Table 1.

Cohesive elements' damage initiation refers to the beginning of degradation of the response of a material point, and the process of degradation begins when the stresses and strains satisfy certain damage initiation criteria. Damage is assumed to initiate when the maximum nominal stress ratio reaches a value of one [30]. This research selects the Maximum nominal stress criterion as the damage initiation criterion, which can be represented as:

\[
\max\left\{\frac{t_n}{t_0^n}, \frac{t_s}{t_0^s}, \frac{t_t}{t_0^t}\right\} = 1
\]

(2)

where \(t_n\) represent the normal components of normal stress vector \(t\); where \(t_s\) and \(t_t\) represent the shear traction; where \(t_0^n\), \(t_0^s\) and \(t_0^t\) represent the peak values of the normal stress when the deformation is either purely normal to the interface or purely in the first or the second shear direction, respectively.

A typical bilinear traction separation response model is employed to research the damage evolution of cohesive elements, and the scalar damage variable represents the overall damage in the material and captures the combined effects of all the active mechanisms. It initially has a value of 0, and the scalar damage monotonically evolves from 0 to 1 upon further loading after the initially of damage [30]. The stress components of the traction-separation model are affected by the damage:
\( t_n = \begin{cases} (1 - D) \bar{t}_n & \bar{t}_n > 0 \\ \bar{t}_n = 0 & \text{otherwise} \end{cases} \quad (3) \)

\( t_s = (1 - D)\bar{t}_s \quad (4) \)

\( t_t = (1 - D)\bar{t}_t \quad (5) \)

where \( \bar{t}_n, \bar{t}_s \) and \( \bar{t}_t \) are the stress components predicted by the elastic traction-separation behavior for the current strains without damage.

When the bullet impacts the composite surface vertically, the cohesive element between the upper and lower layers is equivalent in two tangential directions, and the Benzeggagh-Kenane (B-K) fracture criterion is particular useful when the critical fracture energies during deformation purely along the first and the second shear directions are the same [30]. Therefore, B-K damage criterion is used in the process of energy dissipation, that is:

\[ G_C^s = G_C^t \quad (6) \]

The form (6) is given by:

\[ G_C = G_C^t + (G_C^s - G_C^t) \left( \frac{G_C^s}{G_C^t} \right)^\eta \quad (7) \]

where \( G_C, G_C^s \) and \( G_C^t \) are the total, shear and normal critical fracture energy respectively; \( G_s \) is the dissipated energy in the out-of-plane direction; \( G_t \) is the total dissipated energy in all three directions; \( \eta \) is the relevant material coefficient in the B-K formula.

### 3.2 Material models of aluminum tablets

In order to simulate the elastic-plastic deformation and fracture behavior of nacre-like composites under the bullets impact, the Johnson-Cook material model [32] and Johnson-Cook fracture criterion [44] are used together to simulate the mechanical behavior. The aluminum alloy of AA 7075-T651 is used as the hard material of nacre-like composites, and its material properties are shown in Table 2.

Johnson–Cook constitutive law [32] is an empirical model, which is widely used in impact problems. Its formula is as follows:
\[ \sigma = [A + B(\dot{\varepsilon}^p)^n][1 + C \ln(\dot{\varepsilon}^p/\dot{\varepsilon}_0)](1 - \hat{\theta}^m) \]  

where \( \sigma \) is the yield stress at nonzero strain rate; \( \dot{\varepsilon}^p \) is the equivalent plastic strain rate; \( \dot{\varepsilon}_0 \) and C are material parameters measured at or below the transition temperature. B and n account for the effects of strain hardening; the temperature \( \hat{\theta}^m \) is ignored, assuming isothermal conditions.

Johnson-Cook fracture criterion [33] based on a liner damage accumulation rule, and failure is assumed to occur when the damage parameter exceeds 1. The damage parameter \( \omega \) is defined as:

\[ \omega = \sum \left( \frac{\Delta \dot{\varepsilon}^p}{\dot{\varepsilon}^f} \right) \]  

where \( \Delta \dot{\varepsilon}^p \) is an increment of the equivalent plastic strain, \( \dot{\varepsilon}^f \) is the strain at failure, and the summation is performed over all increment in the analysis. The strain at failure is assumed to be dependent on a nondimensional plastic strain rate, \( \frac{\dot{\varepsilon}^p}{\dot{\varepsilon}_0} \), \( \hat{\theta} \), defined earlier in the Johnson-Cook hardening model. The dependencies are assumed to be separable in the following form.

\[ \dot{\varepsilon}^f = \left[ d_1 + d_2 \exp \left( d_3 \frac{\dot{\varepsilon}^p}{\dot{\varepsilon}_0} \right) \right] \left[ 1 + d_4 \ln \left( \frac{\dot{\varepsilon}^p}{\dot{\varepsilon}_0} \right)^{2/3} \right] (1 + d_5 \hat{\theta}) \]  

where \( d_1 - d_5 \) are material parameters determined from different mechanical test.

### 3.3 Validation of the Johnson-Cook material model

Referring to the impact experiment AA7075-T651 of Børvik et al. [34]. In the experiment, they selected a circular target with a diameter of 600 mm and a nominal thickness of 20 mm, and restrained it with a circular frame and bolts at a diameter of 500 mm. The circular target is impacted by two types of bullets.

The experimental and simulation results of two different bullets are compared in Figure 4(a) and 5(a), and Recht-Ipson model is used to fit the curve of impact velocity and residual velocity [35]. The formula is as follows:

\[ V_r = a(V_i^p - V_{bl})^{1/P} \]  

where \( a \) and \( P \) is constants of best fit data points, and \( V_{bl} \) is the projectile limit. The maximum difference
between experiment and simulation occurs near the projectile limit, an underestimate of 15.6% and an overestimate of 6.4% of the ballistic limits are observed for blunt and ogive bullets respectively. The coincidence degree of the two curves increases with the increase of impact velocity, it can be observed that the experiment and simulation verification have good consistency.

4. Numerical results and discussions

4.1. Failure mechanism analysis

Figure 6 shows the stress distribution and deformation mode of baseline models under the impact of blunt bullet. In the result analysis of Abaqus Dynamic/Explicit, the sectional pictures at different times are captured to show the damage mode. It can be observed that from the impact contact of the bullet to the penetration of composites, the damage forms of tablets can be generally divided into two types:

1. For some front laminates, they show a brittle shear failure mode when impacted, and the thickness of brittle shear failure under impact may be affected by the impact velocity of the bullet, the geometry of the bullet, and the material properties of tablets;

2. For some middle and back laminates, crack deflection occurs with the failure of the cohesive layers. Because of the random and irregular arrangement of the tablets, this failure mode will spread to a wider range, and the damage range of the back side of the impact is much larger than front side.

The process of nacre-like composites resisting bullet impact can be divided into four stages:

1. Overall deformation ($t < 0.01\text{ms}$). At this stage, a stress zone with the impact point as the center is formed, in which all tablets and cohesive layers jointly resist the impact load of bullets. In addition, the cohesive layers stress gradually spreads outward from the impact contact edge of the bullet, and a larger stress zone is formed on the back of composites.

2. Local deformation ($0.01\text{ms} < t < 0.04\text{ms}$). This stage is dominated by the failure of tablets and cohesive
layers at the bullet impact position, and the back of composites is gradually arched. In addition, the impact resistant stress zone of composite gradually shrinks, and a larger stress zone is formed at the bullet impact position.

(3) Interlock failure (0.04ms < t < 0.12ms). This stage is characterized by the failure of cohesive layers between tablets, which causes the tablets to debonding and be pulled out. In addition, due to load transfer, friction and other factors, a large range of stress zone is generated during the process of tablets are pulled out.

(4) Bullet penetration (0.12ms < t). At this stage, the tablets are complete debonding at the impact position, and the composites have formed a conical failure zone.

From Figure 7, we can see that the damage range of the cohesive layers is basically the same as tablets, and the failure of the cohesive layer usually occurs before the failure of tablets. Some cohesive layers at the front end of the bullet are well protected, because several layers of tablets in front of the blunt bullet are pulled out together due to the debonding mechanism, and no large relative displacement is generated. The reason for this effect may be related to the warhead form and the random arrangement form of tablets.

In order to further evaluate the energy absorption capacity of different components of composite, and the resistance characteristics at different stages are analyzed through their main energy dissipation forms. Therefore, the plastic dissipation energy of the tablets, damage dissipation energy of cohesive layers and friction dissipation energy are selected as the research objects. Because friction contact exists not only between tablets, but also between bullets and tablets, so the friction dissipation energy is analyzed as a whole.

It can be seen from Figure 8(a) that the plastic dissipation energy of the tablets is the main energy absorption mode of the composites, and its growth rate is the fastest at the initial stage. The plastic dissipation energy, damage dissipation energy and friction dissipation energy of the baseline model are 1129J, 178.1J and 509.9J respectively at 0.02ms. Combined with Figure 6 and 8, we can find that the bullet directly penetrates several front laminates at 0.04ms, and the tablets are penetrated to generate more plastic dissipation energy than large deformation. From
Figure 7, we can see that all cohesive layers near the impact position have been damaged to a certain extent within 0.04ms, indicating that friction contact and cohesive layers play an important role in the process of tablets' resistance. For the stages after 0.04ms, because the drop of bullet velocity, the damage increase of cohesive layers and the reduction of residual thickness of the composites, the failure mode is changed to that the tablets are pulled out, and the composite forms a conical failure zone.

The special hierarchical structure plays two important roles in the process of impact resistance: (1) because of its layered structure and intrinsic and extrinsic toughing mechanics, it prevents the continuous propagation of cracks [36]; (2) It promotes the global energy absorption by interlayered interlocking mechanism [37].

5.2. Influence of tablets thickness

In this section, the impact resistance of composites with different numbers of tablet layers under the same thickness is studied, and the hierarchical structure in the thickness direction are shown in Figure 9. It is worth noting that when the thickness of the tablet layers change, the calculated thickness of adjacent cohesive layers changes proportionally.

It can be seen from Figure 10 that for the model of 40-layer tablets, the tablets bending in the edge damage zone are greater than other models. This is because the stiffness of the tablets decreases with the decrease of thickness, and it is easier to deform and transfer the impact load to the next layer of tablets. In addition, the increase in the number of layers is conducive to improving the global energy absorption of composite. For the 40-layer tablets, the stress of the tablets in the deformation zone is higher than other models in the process of resisting bullet impact. It can be seen from Figure 11(a) that the damage dissipation energy and friction dissipation energy increase with the increase of the number of layers, this shows that the friction contact and the cohesive layers play a more powerful interlayered interlocking mechanism, so that the overall resistance to deformation of the tablets can be further developed.
We can see from Figure 11(a) that increasing the number of the tablets can increase the friction dissipation energy by 85.4% and damage dissipation energy by 48.8%, but it has little effect on the plastic dissipation damage energy of the tablets. The reason is that when the number of layers decreases, the failure mechanism of tablets with different thicknesses changes. For the number of layers is larger, the failure form of the middle and rear laminates is mainly that the tablets are pulled out, and the stress diffusion zone gradually forms in the middle and rear laminates, which promotes the global energy absorption of composites.

However, for the plastic dissipation energy of tablets is little change, this needs to be analyzed from the perspective of tablets failure and deformation. As mentioned above, the stiffness of the tablets increases with the increase of the thickness, and the increase of the tablets thickness will produce two factors, these factors will lead to the easier penetration of the tablets by bullets: (1) the tablets are not easy to transmit the load through bending; (2) The ability of composites to inhibit crack growth is weakened. Therefore, when the number of tablets layers decreases, more tablets are penetrated by bullets.

From the Figure 12, we found that the plastic dissipation energy of the middle laminates increases significantly when the number of layers decreases. Based on the above discussion, we know that the laminates are directly penetrated by bullets instead of forming effective load transfer. Especially for tablets-groups 5, 6 and 7, when the number of tablets layers increases, they are more likely to be penetrated by bullets and generate more plastic dissipation energy. However, this does not mean that reducing the number of layers can effectively improve the total plastic dissipation energy. When the number of layers increase, the plastic dissipation energy of the front laminates and the back laminates increases slightly. Because the increase of the number of tablets layers can increase the global energy absorption capacity, so that the tablets in a wider range can jointly resist the impact of bullets and generate more plastic dissipation energy. This also explains the reason for the damage dissipation energy of cohesive layers and friction dissipation energy decrease when the number of layers decreases in Figure
As shown in Figure 11(b), the residual velocity of the bullet after penetrating 40-layers of tablets is the minimum, which is consistent with our prediction that increasing the number of layers can improve the global absorption energy. However, the residual velocity of bullet penetrating 20-layers tablets is slightly higher than 10-layers tablets, which may be caused by the random arrangement of tablets. Combining Figures 10 and 11(b), we can find that before 0.08ms, the bullet velocity drops faster when impacting 20-layer tablets. After 0.08ms, the bullet velocity drops faster when impacting 10-layer tablets suddenly, and the final penetration velocity is slightly less than bullet that impact 20-layers tablets. Because the shape and size of tablets are completely random, when the number of composite layers is small, the impact resistance of the structure is more likely to be affected by the arrangement of tablets, which also explains why the velocity curve of bullets is not smooth. To sum up, increasing the number of layers can improve the impact resistance of composites to a certain extent. By comparing the drop of bullet velocity, the drop velocity of 40-layers tablets is 20.5% higher than that of 10-layers tablets.

5.3 Influence of polygons number

A parametric study is conducted to investigate the influence of the polygon numbers for the impact resistance of the nacre-like composite under bullet impact. Since the polygons are random distributed in a plane, a quadratic transformation is considered to control the number of polygons, so that 10 × 10 indicates 100 polygons within the same layer. The arrangement of models with different number of polygons is shown in Figure 13.

From Figure 15(a), we can find that reducing the number of polygons can increase the plastic dissipation energy by 34.9% and the damage dissipation energy by 53.7% respectively. This trend is mainly due to the enhancement of interlaminar interlocking mentioned above, which enables the tablets to transmit in a wider range when subjected to impact load. It can be seen from Figures 12(a) and 16 that the increase of the overlapping area of the tablets directly leads to a significant increase in the plastic dissipation energy of the rear laminates, thus the
total plastic dissipation energy increase. However, the friction dissipation energy of polygons of $6 \times 6$ is only 1.3% higher than $8 \times 8$, and $8 \times 8$ is 27.4% higher than that of $10 \times 10$ at 0.2ms. The reason for this phenomenon is that the tablets are subjected to the friction contact of adjacent tablets during debonding and pulling out, and the larger damage area also means more relative sliding. Therefore, the reduction of the number of polygons can increase the overlapping area between tablets and promote the increase of friction dissipation energy. But the friction dissipation energy difference between polygons of $6 \times 6$ and $8 \times 8$ is small. This may be because the polygons of $6 \times 6$ are not completely pulled out at 0.2ms, and there is still friction between the tablets. If we continue to analyze the friction dissipated energy after 0.2ms, the friction dissipated energy of polygons of $6 \times 6$ will be larger than polygons of $8 \times 8$. However, this does not mean that the relationship between the number of polygons and the impact resistance of composites is linear, the toughening mechanism caused by the change of polygon number still needs further analysis. In addition, it can be seen from Figure 14 that the stress between tablets may be inversely proportional to the contact area between tablets, which makes the friction dissipation energy no longer increase significantly when the number of polygons decreases to a certain extent. It can be seen from Figure 15(b) that the velocity curves of bullet that impacts different number of polygons before 0.04ms is close, which indicates that composites mainly suffer from local damage at this stage. After 0.04ms, the smaller the number of polygons, the more their velocity decreases, which is consistent with the results we discussed earlier.

6. Conclusion

Nacre-like composites models was established to study the impact resistance characteristics, and the mechanical mechanism and parametric analysis of the impact stage are carried out. The impact resistance of nacre-like composite can be divided into four stages, and they are overall deformation, local deformation, interlock failure and bullet penetration respectively. The deformation mechanism and failure characteristics at different stages are completely different due to the coupling and the interlaminar interlocking mechanism of the tablets, and
the deformation mechanism and failure characteristics also determine the energy absorption of nacre-like composites. Moreover, according to the dissipation energy and bullet velocity of multi-layer composite, the following parametric analysis is carried out: (a) Number of tablets layers; (b) Polygon counts. The influence of different parameters on the deformation mechanism and energy dissipation process of nacre-like composites is conducted. Based on the above research process, the following conclusions can be drawn.

(1) In the whole deformation and local deformation stage of nacre-like composites, the inhibition of crack growth is an important resistance mechanism. The global resistance by structural characteristic of nacre-like composite plays a significant role in the interlocking failure stage.

(2) The plastic dissipation energy of the tablets is mainly composed of two parts: (a) brittle fracture and failure of the front laminates; (b) large deformation of middle and back laminates. And the plastic dissipation energy is the main energy absorption mode for nacre-like composites.

(3) Increasing the number layers of composite and reducing the number of polygons can improve the interlayered interlocking mechanism of nacre-like composites, and improve the global energy absorption by expanding the damage range affected by impact.

(4) The layered and randomly arranged of tablets can effectively inhibit crack growth, so that a conical stress zone will be generated, and this stress mechanism can improve the global energy absorption effect. These research results show that nacre-like composite structure has great development potential, and how to make full use of the interlayered interlocking to make the composite structure generate more global energy absorption is the key to the nacre-like biomimetic composite research.

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
Data availability

Data will be made available on request.

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CRediT authorship contribution statement

Dongyang Gao: Writing—original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization, Validation. Pengcheng Chen: Software, Methodology, Visualization. Guoyun Lu: Formal analysis, Methodology, Data curation, Funding acquisition. Huiwei Yang: Investigation, Writing—review and editing, Supervision, Project administration, Methodology.


[17] Wu XD, Meng XS, Zhang HG. An experimental investigation of the dynamic fracture behavior of 3D printed...


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Figure 1: Schematic diagram of mollusk shell scanning electron microscope observation and Voronoi generation.

Figure 2: The baseline model of nacre-like composites.
Figure 3: (a) Grouping diagram for model. (b) Connection method of different cohesive elements.

Figure 4: (a) Comparison between experimental [34] and predicted residual velocities for AA7075-T651
by blunt bullet; (b) Simulated perforation by blunt bullet with $V_i=209\text{m/s}$.

Figure 5: (a) Comparison between experimental [34] and predicted residual velocities for AA7075-T651 by ogival bullet; (b) Simulated perforation by ogival bullet with $V_i=320.5\text{m/s}$.

Figure 6: Impact failure mode of nacre-like composite tablets. (a) Front view; (b) Section cross; (c) Back view.
Figure 7: Impact failure mode of cohesive layers. (a) Back view; (b) Section cross;

Figure 8: The dissipation energy of the baseline model
Figure 9: Schematics of different tablets thicknesses.

Figure 10: Impact failure mode of nacre-like composite tablets. (a) 40 layers; (b) 20 layers; (c) 10 layers.
Figure 11: (a) Dissipation energy in different forms of three kinds of layer numbers; (b) Bullet velocity of three kinds of layer numbers.
Figure 12: Plastic dissipation energy of different groups. (a) 40-layers; (b) 20-layers; (c) 10-layers.

Figure 13: Schematic diagram of different number of polygons.

Figure 14: Impact failure mode of nacre-like composite tablets. (a) 10×10 polygons; (b) 8×8 polygons; (c) 6×6 polygons.
Figure 15: (a) Dissipation energy in different forms of three kinds of polygons numbers; (b) Bullet velocity of three kinds of layer numbers.

Figure 16: Plastic dissipation energy of different groups. (a) 8x8 polygons; (b) 6x6 polygons.

Table 1
Material properties for toughened epoxy resin Betamate 1044 [7, 31]

<table>
<thead>
<tr>
<th>Material properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density $\rho$ (kg/m$^3$)</td>
<td>1350</td>
</tr>
<tr>
<td>Maximum normal traction $t_n$ (MPa)</td>
<td>85.5</td>
</tr>
<tr>
<td>Maximum shear traction $t_s$, $t_t$ (MPa)</td>
<td>70</td>
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<tr>
<td>Normal critical fracture energy $G^N_n$ (J/m$^2$)</td>
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<tr>
<td>Shear critical fracture energy $G^S_s$, $G^S_t$ (J/m$^2$)</td>
<td>3570</td>
</tr>
<tr>
<td>Elastic modulus in the normal direction $E$ (GPa)</td>
<td>3.1</td>
</tr>
<tr>
<td>Elastic modulus in the transverse directions $G_1$, $G_2$ (GPa)</td>
<td>1.55</td>
</tr>
</tbody>
</table>
Table 2
Johnson-Cook material parameters for aluminum AA7075-T651 [7, 34]

<table>
<thead>
<tr>
<th>Material properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density $\rho$ (kg/m$^3$)</td>
<td>2700</td>
</tr>
<tr>
<td>Young’s modulus of elasticity, $E$ (Gpa)</td>
<td>70</td>
</tr>
<tr>
<td>Poisson’s ratio, $\nu$</td>
<td>0.3</td>
</tr>
<tr>
<td>Proof/Yield stress, $A$ (Mpa)</td>
<td>520</td>
</tr>
<tr>
<td>Strain hardening coefficient, $B$ (Mpa)</td>
<td>477</td>
</tr>
<tr>
<td>Strain hardening coefficient, $n$</td>
<td>0.52</td>
</tr>
<tr>
<td>Strain hardening coefficient, $C$</td>
<td>0.001</td>
</tr>
<tr>
<td>Thermal softening constant, $m$</td>
<td>1</td>
</tr>
<tr>
<td>Reference strain rate, $\dot{\varepsilon}_0$ (s$^{-1}$)</td>
<td>$5 \times 10^{-4}$</td>
</tr>
<tr>
<td>Fracture strain constants:</td>
<td></td>
</tr>
<tr>
<td>$d_1$</td>
<td>0.096</td>
</tr>
<tr>
<td>$d_2$</td>
<td>0.049</td>
</tr>
<tr>
<td>$d_3$</td>
<td>-3.465</td>
</tr>
<tr>
<td>$d_4$</td>
<td>0.016</td>
</tr>
<tr>
<td>$d_5$</td>
<td>1.099</td>
</tr>
</tbody>
</table>