Research on Anti-Penetration Performance of Topologically Interlocking Ceramic Composite Target Plates

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Abstract

Topological structures based on nature-inspired combinations often exhibit superior performance compared with single structures. To explore the impact resistance of ceramic-metal composite plates with topological structures, a ceramic-metal composite plate model was established in this study. Based on the structural forms of hexahedral and octahedral topological interlocking units, the thickness ratio of the topological interlocking blocks, the interlocking angle, and the side length of the unit blocks were taken as variables to simulate and investigate the effects of different topological interlocking structures on the overall impact resistance of the composite plates. From the deformation and damage contour maps after penetration of the composite plates with various structures, the damage characteristics of the ceramic-metal composite plates with topological structures in the interlocking regions were obtained, and the residual velocity of the projectile during the penetration process was further compared and analyzed. The simulation results show that hexahedral and octahedral units can exert the impact resistance of the composite target plate only when they reach a moderate thickness ratio (6mm); the interlocking angle plays a crucial role in the degree of engagement of the topological structure, with the optimal interlocking angles of the hexahedral and octahedral units being 15° and 10°, respectively; and the penetration resistance of composite plates constructed with octahedral interlocking units is generally superior to that of those with hexahedral units.

Full Text

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Abstract: Topological structures based on nature-inspired combinations often exhibit superior performance compared with single structures. To investigate the impact resistance of ceramic-metal composite plates with topological structures, this study establishes a ceramic-metal composite plate model. On the basis of topological interlocking unit configurations using hexahedral and octahedral forms, the thickness ratio of the topological interlocking block, the interlocking angle, and the unit-block side length are taken as variables to simulate and explore the effects of different topological interlocking structures on the overall impact resistance of the composite plate. By analyzing the deformation and damage contours after penetration of each structural composite plate, the damage characteristics of topologically structured ceramic-metal composite plates in the interlocking region are obtained, and the residual velocity of the projectile during penetration is further analyzed through comparative study. The simulation results show that hexahedral and octahedral units can fully develop the impact resistance of the composite target plate only when an appropriate thickness ratio is reached (6 mm). The interlocking angle plays a crucial role in the meshing degree of the topological structure; the optimal interlocking angles of the hexahedral and octahedral units are 15° and 10°, respectively. Overall, the anti-penetration performance of the composite plate constructed with octahedral interlocking units is superior to that with hexahedral units.

Keywords: ceramic–metal composite plate; topological interlocking structure; elastoplastic performance

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Abstract: Topological structures based on combinations inspired by nature often have better performance than single structures. In order to explore the impact resistance of topologically structured ceramic-metal composite panels, this study establishes a model based on the topological interlocking unit construction form of hexahedron and octahedron, and explores the influence of different topological interlocking structures on the overall impact resistance of composite panels by varying the thickness ratio, interlocking angle, and unit block side length. By analyzing the deformation damage cloud diagram after penetrating each structural composite plate, we can observe the damage characteristics in the interlocking part of the topological structure ceramic-metal composite plate and further analyze the residual velocity of projectiles during

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penetration through comparison. The simulation results indicate that only when the hexahedral and octahedral units reach a moderate thickness ratio (6 mm) can their impact resistance be fully utilized; furthermore, the size of the interlocking angle plays a crucial role in the meshing degree of the topological structure. The optimal interlocking angles of hexahedral and octahedral units are 15° and 10°, respectively; generally speaking, the penetration resistance of composite panels constructed of octahedral interlocking units is generally better than that of hexahedral units.

Key words: ceramic–metal composite plate; topological interlocking structure; bulletproof performance

In modern high-tech warfare, protective armor must possess high resistance to penetration and impact[1]. In design, factors such as material mass and cost must also be considered; therefore, protective armor should, as far as possible, satisfy requirements such as high hardness, high strength, high toughness, low cost, and low density[2]. Metals are very widely used as armor-protection structures in the military field[3]. As armor has developed from ordinary steel armor to high-hardness steel armor, its protective capability has continuously improved; however, because of its relatively high density, it affects the realization of tactical performance. Consequently, ceramics and composite materials[4] with lower mass and excellent performance have gradually attracted extensive attention and have replaced pure metallic armor in many fields. Ceramics themselves are refined from high-purity natural inorganic substances and artificial organic substances[5]; thus, their material properties are superior to those of metallic materials[6] and polymer materials[7]. After many advanced tanks around the world adopted high-performance ceramic materials[8], their protective capabilities were significantly enhanced, and their use in armor systems has now become a major trend. However, the main disadvantage of ceramics is brittleness[9]. Although a great deal of research has been carried out, this remains a major limitation. Fortunately, research has found that biological materials in nature can combine strength and toughness to a high degree, overcoming the brittleness of minerals in bone[10], nacre[11], or dental enamel[12]. These materials are mainly composed of hard minerals and are formed through weak interfacial bonding[13]. Such finely tuned structures can enable effective deformation and failure mechanisms, thereby producing a degree of high toughness that engineering materials have so far been unable to attain. These principles have inspired new topological structural designs, which ingeniously combine performance and function[14].

Geometric interlocking, as a strain-hardening mechanism, delays local spreading deformation in bulk materials. It is widely used in topologically structured materials; therefore, such materials are also referred to as topologically interlocked materials (TIMs)[15]. The concept of topologically interlocked assemblies attracted considerable scholarly attention in its early stages. GLICKMAN[16] proposed the concept of G-blocks through a pavement system that reduces substructures and maintenance costs, and DYSKIN et al.[17] expanded and formalized the terminology. TIMs can be regarded as a new type of mechanical unit material, because their unique performance does not originate from material composition but from structure; forces and energy can only be transmitted through contact surfaces, and therefore TIMs almost do not generate large tensile forces under loading. Because of these characteristics, TIMs also possess distinctive properties and can be used to create structures for adaptive and severe conditions, such as random and harmonic vibration, thermal loading, repeated impact, and acoustic attenuation. DYSKIN et al.[18] demonstrated that TIMs are damage-tolerant: cracks within one unit do not propagate through the contact interface into neighboring units. KHANDELWAL et al.[19] conducted experimental research on the quasi-static response of TIMs assembled from regular tetrahedra, and proposed an analytical model for predicting the quasi-static behavior of TIMs using thrust-line theory. MATHER et al.[20] studied the remanufacturability of TIMs and showed that, after TIMs fail, only a small fraction of the units cannot be reused. Regarding the application of TIMs, ESTRIN et al.[21] proposed their potential use as protective ceramic tiles for spacecraft. TESSMANN et al.[22] explored TIMs with more complex geometric shapes for potential applications in system structures. Through the ordered assembly of unit blocks, TIMs establish topologically interlocked structures in a bottom-up manner, and materials formed by combining with such structures have already addressed corresponding mechanical issues, such as topological toughening and size effects. The ceramic materials therein can be well integrated with this topological structure, which has unique mechanical properties such as fracture resistance[23], fracture toughness[24], yield strength[25], and thermal stability[26]. In addition, some scholars have studied the thermal-impact performance, damage tolerance, and flexural stiffness of topologically structured ceramics. An extension of this is a multilayer topological brickwork layer, each layer consisting of separate ceramic tiles. These additional degrees of freedom provide possibilities for the design of laminates, and topological ceramic structures can be adjusted to eliminate stress concentrations[27]. On this basis, designing multilayer system-structured ceramics as topologically interlocked blocks endows them with the ability to solve problems of large-deformation bending flexibility and bending stiffness, while also effectively improving the overall toughness of the target plate. However, this improvement comes at the cost of tensile strength and stiffness. The study by YIN et al.[28], through the combination of an integral ceramic plate with a metal backing plate, compensated for this deficiency and brought new inspiration to the structure of topologically ceramic-metal composite armor. Therefore, on the basis of establishing a highly tough integral topological ceramic, this study combines an integral ceramic plate with a ductile backing plate as a method to overcome limitations in strength and stiffness, and investigates the influence of interlocking structures on the overall penetration resistance of composite target plates. Based on the work of GLICKMAN et al.[16-17], the topologically structured ceramics employ the hexahedral and octahedral interlocking structures in TIMs[15] to identify the topologically interlocked structural parameters with optimal penetration resistance under different interlocking-structure combination schemes.

This study takes monolithic ceramics, topologically interlocked ceramics[29], and metal back⋯

Using the combined forms of the plates, numerical simulations were carried out for the high-speed impact problem of the composite target plate. The interlocking ceramic unit blocks adopted the basic interlocking structures of hexahedra and octahedra, respectively. On the basis of variables such as the plate thickness ratio, interlocking angle, and interlocking-unit size, multiple sets of topological interlocking structures were combined. The calculation results for each set were analyzed and studied in terms of block deformation and damage, residual projectile velocity, and energy dissipation of the plate, thereby obtaining the influence laws of different structural parameters on the overall penetration-resistance performance of the target plate.

1 Design of Composite Ceramic Target Plates with Topological Interlocking Structures

On the basis of topological interlocking structures, the hexahedral and octahedral structures shown in Fig. 1 and Fig. 2, respectively, are used as topological base units to assemble ceramic plates.[29] Such interlocking units have multiple degrees-of-freedom parameters for adjusting the structure and performance of the interlocking plate. Taking the hexahedron as an example, this structure is symmetric. Its basic parameters include unit height h, short side a, long side b, and the interlocking angle θ shown in Fig. 3 and Fig. 4. For this interlocking unit, the cross-section obtained by cutting laterally through the middle thickness is referred to as the mid-surface. The mid-surface of the hexahedron is a square, and that of the octahedron is a regular hexagon; the side length of the mid-surface is called the central side length L, with all lengths equal to $L = (a + b)/2$.

Fig. 1 Schematic diagram of the hexahedral interlocking unit structure
(a) Front view; (b) top view; (c) three-dimensional view.
Visible annotations: interlocking surface; h; a; b.

Fig. 2 Schematic diagram of the octahedral interlocking unit structure
(a) Front view; (b) top view; (c) three-dimensional view.
Visible annotations: interlocking surface; h; a; b.

If it is assumed that the interlocking unit moves downward after impact, then in Fig. 1–Fig. 4 the side surface is the contact surface where the central unit first acts directly on the adjacent unit, namely the interlocking surface. Fig. 3 and Fig. 4 show schematic diagrams of the interaction between two units in side view. When the central unit moves, its interaction with adjacent units produces an interlocking normal pressure F_{N} and an interlocking friction force F_{f}, respectively. This form of action can fully buffer the impactor, and the degree of action can be changed by adjusting the unit parameters.

Fig. 3 Schematic diagram of hexahedral interlocking principle
(a) Front view; (b) side view.
Visible annotations: interlocking surface; hexahedral interlocking-unit side view; adjacent interlocking-unit side view; F_{N}; F_{f}; F'_{N}; F'_{f}; θ; h.

Fig. 4 Schematic diagram of octahedral interlocking principle
(a) Front view; (b) side view.
Visible annotations: interlocking surface; octahedral interlocking-unit side view; adjacent interlocking-unit side view; F_{N}; F_{f}; F'_{N}; F'_{f}; θ; h.

The top views of ceramic target plates obtained by assembling interlocking units are shown in Fig. 5. Based on the displacement generated by impact on the central block , the figure illustrates the interlocking sequence and interlocking direction. Because of symmetry, the hexahedral and octahedral structures are described using a 1/4 portion and a 1/3 portion, respectively. The interlocking direction between the central block and adjacent units can start from central block and, through transmission by adjacent units, proceeds as $\rightarrow\rightarrow\rightarrow\rightarrow$ for the hexahedron, and as $\rightarrow\rightarrow\rightarrow$ and $\rightarrow\rightarrow\rightarrow$ for the octahedron, finally returning to unit to form a complete closed loop and thus achieving interlocking of the entire target plate. Owing to the regular-hexagonal characteristics of its mid-surface, under impact the octahedral central unit has a total of 6 interlocking loops, such as the two loops $\rightarrow\rightarrow\rightarrow$ and $\rightarrow\rightarrow\rightarrow$ shown in Fig. 5. This is more than the 4 interlocking loops of the hexahedral unit, giving it higher interlocking engagement.

Fig. 5 Interlock unit sequence
(a) Hexahedron; (b) octahedron.

From the perspective of impact-resistant target-plate design, the interlocking ceramic structure can substantially

increase the overall toughness and impact resistance of the target plate to a certain extent, but at the same time it will sacrifice a large portion of strength and stiffness performance. Especially under high-speed projectile impact, its independent action cannot fully bring out the advantages of the interlocking structure. Therefore, a composite-structure target plate is ultimately adopted to overcome this problem. The target-plate combination is shown in Fig. 6. The top still adopts a high-strength single-block ceramic-plate structure to resist the projectile impact in the high-speed stage; the second layer is a mortise-and-tenon interlocking ceramic structure, where the projectile is in the intermediate-speed stage. Together with the buffering effect of the bottom metal backing plate, the composite target plate can effectively resist the further impact of the projectile.

On this basis, the impact resistance of this composite target plate will be investigated by adjusting the structural parameters of the interlocking blocks and the thickness ratios of different target-plate layers.

Single-block ceramic plate

Mortise-and-tenon interlocking ceramic plate

Metal backing plate

(a) Hexahedral interlocking structure

Single-block ceramic plate

Mortise-and-tenon interlocking ceramic plate

Metal backing plate

(b) Octahedral interlocking structure

图 6 复合陶瓷金属组合靶板结构

Fig. 6 Composite ceramic metal combined target plate structure

In the design scheme, the interlocking-block height h and interlocking angle θ are respectively taken as variables to study this combined structure.

2 Finite Element Simulation and Calculation

In this simulation, a ceramic plate of 15 cm × 15 cm × 1 cm and a metal backing plate of 15 cm × 15 cm × 0.5 cm are used. The ceramic is divided into 2 layers, with a total ceramic-layer thickness of 1 cm. Three schemes are designed for the ceramic layers: first layer 6 mm and second layer 4 mm; first layer 5 mm and second layer 5 mm; first layer 4 mm and second layer 6 mm. The ceramic material is boron carbide–titanium boride[30], and its material properties adopt the JH-2 brittle-material constitutive model. The metal material is alloy steel[31]. The impacting projectile is a 12.7 mm steel-core armor-piercing projectile[32], whose material properties adopt the JC constitutive model. The initial impact velocity of the projectile is 800 m/s, and the total areal density of the composite target plate remains unchanged at 7.125 g/cm^2; the areal density of the single metal target plate is kept consistent with that of the composite ceramic plate.

The finite element model of the projectile impacting the interlocking-structure target plate is shown in Fig. 7. Based on the symmetry of the interlocking structure, a 1/4 model is used for the hexahedral unit, a 1/2 model is used for the octahedral unit, and the projectile model is the actual size of the 12.7 mm steel-core armor-piercing projectile. When building the model in LS-DYNA, the mesh size of the projectile part is 0.12 cm, the mesh size of the target-plate part is 0.06 cm, and the friction coefficient between interlocking blocks is 0.23.

(a) Single metal structure

(b) Hexahedral interlocking structure

(c) Octahedral interlocking structure

图 7 弹体冲击模型

Fig. 7 Projectile impact model

In the simulation scheme, an interlocking-structure plate with too small a thickness will amplify the brittle characteristics of the single plate, which is not conducive to the overall impact-resistance performance; too large a thickness will weaken the strength and stiffness of the whole composite-structure plate. Therefore, the thickness of the interlocking structure is taken as a moderate 4, 5, and 6 mm, and comparison and analysis are also carried out for the case in which the entire ceramic plate is 10 mm; for the case in which the hexahedron is increased in thickness to 10 mm, the above situation is briefly explained. In addition, the unit interlocking angle also has a relatively large influence on the overall structure. When other conditions remain unchanged, a wide range of angle variation is first used to qualitatively analyze this variable: the hexahedral interlocking angles are taken as 15°, 30°, and 45°, and the octahedral interlocking angles are taken as 15°, 22.5°, and 30°. The range is then further narrowed to study the optimal interlocking angle, and the middle-edge length of the interlocking unit is analyzed. In the simulation, the impact-resistance performance of the mortise-and-tenon structure is compared with that of the traditional structure.

3 Impact Response Results and Analysis

In the impact model of the single metal plate and the mortise-and-tenon interlocking composite ceramic plate,

In the simulation, the minimum residual velocity for the single metal plate is 574 m/s, whereas the minimum residual velocity for the hexahedral-unit interlocking structure is 376 m/s. The residual velocity of the hexahedral-unit interlocking structure is 34.49% lower than that of the single metal plate. The simulation results show that the protective effect of the hexahedral-unit interlocking structure is superior to that of a conventional single metal plate. Therefore, the following study investigates the protective performance of composite ceramic plates with hexahedral- and octahedral-unit topological structures.

Fig. 8 Effect of a single metal plate and a topological-structure composite ceramic plate on residual velocity
In-figure labels: residual velocity $/(m \cdot s^{-1})$*; time* $/\mu s$*; single metal plate; hexahedral composite ceramic plate.*

For the hexahedral interlocking structure, the residual projectile velocities of each group are shown in Fig. 9. In terms of the thickness of the interlocking structure, an interlocking structure with a higher thickness ratio is more favorable for improving the impact resistance of the composite plate. When the interlocking angle remains unchanged, as the interlocking thickness increases from 4 mm to 6 mm, the corresponding thickness of the individual block decreases from 6 mm to 4 mm, and the residual velocity of the projectile generally decreases by a relatively large margin. Therefore, under the premise that the interlocking angle is unchanged, the thinner the individual ceramic plate, the better the penetration-resistance performance of the composite ceramic target plate, and the lower the projectile residual velocity. When the interlocking angle varies within the above range while the thickness remains unchanged, a large interlocking angle (45°) causes a greater degradation in the overall impact resistance, whereas a small interlocking angle (15°) is more conducive to exploiting the advantages of the interlocking structure.

Fig. 9 Residual velocity of the projectile under different thicknesses and interlocking angles of hexahedral elements
In-figure labels: residual velocity /$(m \cdot s^{-1})$; interlocking angle /(°); hexahedral topological-layer thickness 4 mm; hexahedral topological-layer thickness 5 mm; hexahedral topological-layer thickness 6 mm.

Table 1 shows the deformation cross-sectional views of the composite target plate under different structural conditions. From these views, the penetration-resistant damage and deformation of each part of the composite plate can be observed. As the thickness ratio of the interlocking structure increases, the damaged range of adjacent interlocking units decreases to varying degrees. This is closely related to the interlocking form of the structure. A smaller interlocking angle can also achieve similar results, while the degree of damage is further reduced.

Table 1 Penetration deformation of the cross section of a hexahedral interlocking unit

Thickness / mm	Angle 30°	Angle / (°)	Thickness 5 mm
4	[cross-sectional penetration deformation image]	15	[cross-sectional penetration deformation image]
5	[cross-sectional penetration deformation image]	30	[cross-sectional penetration deformation image]
6	[cross-sectional penetration deformation image]	45	[cross-sectional penetration deformation image]

From the deformation of the ceramic blocks in Table 1, the highly damaged regions of the central block and adjacent interlocking blocks can be preliminarily identified. As shown by the red circles in Fig. 10, the "acute-angle part" is such a region; severe damage at this location can cause interlocking failure of the entire interlocking-unit block structure. From the internal damage cloud map shown in Fig. 11, the damage range of the interlocking structure can be observed. The severe damage regions on the periphery all occur along the side regions of the unit blocks and are distributed in strip-like patterns.

Fig. 10 The vulnerable area of the "acute-angle part" in the interlocking unit

Fig. 11 Internal damage cloud map

From the sectional damage cloud map (Fig. 12), it can be seen that the interlocking unit, with the sub-

···the sliding of the blocks caused by projectile penetration.

Fig. 12 Damage of cross-sections in different directions

- **(a)** Crack damage occurring in the interlocking part near the center of the adjacent unit
- **(b)** Crack damage occurring in the interlocking part at the contact surface

In Fig. 12, when the central block is pushed by the projectile, the sliding blocks adjacent to the central block all undergo sliding to a lesser extent than the central block; this damage mode provides a certain buffering effect. Under varying unit thicknesses, the central unit is directly penetrated by the projectile and undergoes large deformation, accompanied by damage caused by bending stress, whereas the failure modes of the adjacent interlocking units differ to some extent. When the unit thickness is relatively small, the adjacent unit bends to a certain degree because of the downward movement of the central block, and the region of large-deformation fracture lies close to the center of the unit (Fig. 12a). For thicker units, however, the bending stress generated by the central unit is insufficient to induce bending and deformation at the middle of the adjacent unit, so the large-deformation region has already occurred at the contact surface between the two units (Fig. 12b).

For the octahedral interlocking structure, the residual projectile velocity results are shown in Fig. 13. When the thickness of the interlocking ceramic layer is relatively small, at 4 mm and 5 mm, the residual velocity fluctuates only within a small range; changes in the interlocking angle have little influence, and a large interlocking angle at the 5 mm thickness slightly reduces the overall interlocking performance. When the thickness is 6 mm, however, good penetration resistance is exhibited. Over a wide range of interlocking angles, the overall performance improves as the angle decreases. At 6 mm and 15°, the projectile residual velocity reaches 253.4 m/s, which is the best result among the entire set of simulations.

Fig. 13 Residual velocity of the projectile under different thicknesses and interlocking angles of octahedral units

Figure labels: y-axis, residual velocity / $(m \cdot s^{-1})$; x-axis, interlocking angle / (°). Legend: octahedral topology-layer thickness 4 mm; octahedral topology-layer thickness 5 mm; octahedral topology-layer thickness 6 mm.

Compared with the hexahedral case, in the octahedral case the sliding distance of adjacent interlocking sliders is greatly reduced, making it difficult to directly observe obvious differences. As shown in Table 2, the deformation and failure modes are similar, both occurring at the contact surfaces between unit blocks. Figures 14–15 show the damage conditions of interlocking units at different positions, including crack propagation in the interlocking part and the non-directly interlocked part, cracks propagating at the contact surface, and cracks propagating near the central slider of adjacent units.

Table 2 Penetration deformation diagrams of octahedral interlocking-unit sections

Thickness / mm	Angle 22.5°	Angle / (°)	Thickness 5 mm
4	[deformation diagram]	15	[deformation diagram]
5	[deformation diagram]	30	[deformation diagram]
6	[deformation diagram]	45	[deformation diagram]

Fig. 14 Schematic cross-sections at different angles

Visible angle labels: 0°, 60°, 120°.

Fig. 15 Damage of cross-sectional interlocking units in three directions

- **(a)** 0°
- **(b)** 60°
- **(c)** 120°

Through the supplementary simulations of thickness using the hexahedral structure as an example in Table 3, the variation law of the proportional relationship between the interlocking-structure thickness and the thickness of the single plate can be preliminarily obtained. As stated above, this value should be neither too high nor too low. If the interlocking-structure thickness is too small, such as less than 5 mm, the high-toughness and energy-absorption characteristics of the interlocking structure cannot be fully utilized, and the penetration resistance decreases. If the thickness is too large, such as greater than 7 mm, the strength and stiffness of the overall target plate are insufficient, causing a substantial decline in penetration resistance. For example, when the thickness is 10 mm, the projectile residual velocity is nearly 100 m/s higher than that for 7 mm.

Tab. 3 Projectile residual velocity for hexahedral elements with interlocking-structure thicknesses of 7, 8, and 10 mm

Interlocking-structure thickness h/mm	Projectile residual velocity $/(\mathrm{m \cdot s^{-1}})$
7	295.7
8	330.3
10	393.6

Because this is a high-speed impact, if the thickness of the interlocking unit block plays an entirely dominant role—as in the case of $h = 10$ mm—the projectile begins by directly penetrating the central unit block. As shown in Fig. 16, when only a small portion of the unit block has been pushed out, its top has already suffered severe erosion, and the frictional contact surface decreases rapidly. This results in only very small displacements of the adjacent sliding blocks, so that they do not effectively provide a cushioning effect.

Fig. 16 The projectile penetrates the 10 mm interlocking unit block

For the hexahedral case, the projectile residual-velocity results are shown in Fig. 17. Keeping the interlocking thickness $h = 5$ mm and the interlocking angle $\theta = 15°$ unchanged, and taking the central side length L of the interlocking unit as the variable, the limited number of numerical simulations indicates that, as the central side length increases from its minimum to its maximum value, the overall behavior can be roughly divided into three stages. In the small-size range, the projectile does not penetrate mainly into the central interlocking block; instead, it exerts a comparatively large impact on the adjacent ceramic blocks. Failure of this form of interlocking unit increases the stiffness of the interlocking structure, thereby reducing its energy-absorption capacity, which is unfavorable for the impact resistance of the target plate. From the first three sets of simulation data, the smaller the central side length of the unit block, the poorer the overall anti-penetration performance of the target plate. When the central side length increases to 15 mm, the anti-penetration performance is the best; as the side length continues to increase, the anti-penetration performance decreases again and then stabilizes within a certain range. This is because, when an excessively large unit block is penetrated by the projectile, the proportion of failure associated with bending damage becomes increasingly large. For ceramic blocks, this is also an unfavorable failure mode, which reduces the overall anti-penetration performance. Therefore, the simulation results for 17.5 mm and 20 mm are not ideal.

Keeping the hexahedral interlocking thickness $h = 6$ mm and the interlocking angle $\theta = 15^{\circ}$ unchanged, Fig. 17 shows that the octahedral elements likewise exhibit a marked decrease in anti-penetration performance at the smallest central side length of 7.5 mm, because an excessively small size reduces the energy-absorption capacity of the unit blocks. In the range of 10 $\sim$ 17.5 mm, however, the interlocking structure shows good anti-penetration performance, with the residual velocity fluctuating only within a small range (32 m/s); the effect at 15 mm is relatively better.

Fig. 17 The influence of the central side length of hexahedral and octahedral elements on residual velocity

Keeping the hexahedral interlocking thickness $h = 5$ mm and the central side length $L = 15$ mm unchanged, and taking the interlocking angle as the variable, the projectile residual-velocity results are shown in Fig. 18. In the previous simulations with a large range of angle variation, an excessively large interlocking angle caused failure during sliding along the contact surface, thereby reducing the engagement degree of the interlocking structure and ultimately decreasing the anti-penetration performance of the target plate. However, within the smaller interlocking-angle range ($10^{\circ} \sim 20^{\circ}$) considered in this group, the previous trend is not observed. When the interlocking angle is too small, the interlocking effect is also insufficient because the degree of interlocking is inadequate. In this group of simulations, the anti-penetration performance reaches its optimum when the interlocking angle is 15°.

Fig. 18 The influence of the interlocking angle between hexahedral and octahedral elements on the residual velocity

Keeping the octahedral interlocking thickness $h = 6$ mm and the central side length $L = 15$ mm unchanged, in the numerical simulations with a smaller range of interlocking angles, as shown in Fig. 18, projectile deflection occurs in several groups with better anti-penetration performance. For example, when the interlocking angles are 5°, 7°, and 10°, the corresponding projectile deflection angles are 4.49°, 3.18°, and 5.58°, respectively. Because the engagement degree of the octahedral interlocking structure is higher than that of the hexahedral structure, at smaller interlocking angles it already···

can reach a tight interlocking state; in this set of simulations, 10° is the optimal interlocking angle.

Through simulation, when the center side length of the hexahedron is 15 mm, the thickness of the topological ceramic layer is 5 mm, and the interlocking angle is 15°, the minimum residual velocity of the projectile after impact is 302.1 m/s. When the center side length of the octahedron is 15 mm, the thickness of the topological ceramic layer is 6 mm, and the interlocking angle is 15°, the minimum residual velocity of the projectile after impact is 253.4 m/s. Because the stability of the three-directional uniform interlocking of the octahedron is higher than that of the two-sided opposing interlocking of the hexahedron, under impact loading it is less prone to interlocking failure during unidirectional damage. This prolongs the effective interlocking time of the structure, dissipates more energy, and thereby improves the overall penetration resistance.

4 Conclusions

This study mainly used the structural parameters of a two-layer interlocking ceramic plate as variables to conduct preliminary numerical simulation and comprehensive analysis of their influence on the impact resistance of the overall target plate. The interlocking-unit types were hexahedral units and octahedral units. The following conclusions were obtained.

1) In the comparative analysis between a traditional metal plate and a ceramic plate with a topological structure, the ballistic performance of the topological-structure ceramic plate is superior to that of the traditional structure under the same areal-density conditions.

2) From the deformation maps and damage cloud maps, the damage characteristics of the interlocking region were obtained. They mainly consist of two different damage forms: "strip-shaped" damage zones occurring at the side edges of adjacent units, and damage caused by displacement of the central block.

3) For the unit thickness h of the interlocking-unit block and the interlocking angle θ, a larger interlocking-unit thickness weakens the impact resistance of the individual ceramic block and reduces the overall strength of the target plate, whereas a smaller thickness produces the crack-propagation phenomenon seen in the impact failure of traditional ceramic plates. Only an appropriate thickness ratio for the double-layer interlocking ceramic plate can fully bring out the performance of the ceramic material. In the simulations, under the condition that the total thickness of the ceramic plate is 1 cm, the overall impact resistance of the target plate is optimal when the interlocking thickness of both the hexahedron and the octahedron is 6 mm. The interlocking angle also has a key influence on the overall behavior: with a large interlocking angle, damage occurs when the contact surface slips, thereby reducing the meshing degree of the interlocking structure; with a small interlocking angle, insufficient interlocking prevents a fully interlocked effect. In the numerical simulations, the optimal interlocking angle for the hexahedral unit is 15°, and the optimal interlocking angle for the octahedral unit is 10°.

4) For the center side length L of the interlocking unit, its influence on the overall interlocking-structure system was found to be divided into three stages. In the small-range stage, in addition to the central block, the projectile also has a relatively large impact interaction with adjacent ceramic blocks. Failure of this type of interlocking unit increases the stiffness of the interlocking structure, thereby reducing its ability to absorb energy. When the side length is 15 mm, the penetration resistance reaches its optimum.

If the side length continues to increase, the proportion of bending-damage failure increases, thereby reducing the overall penetration resistance.

5) In the comparative analysis of different interlocking-unit types, both the overall meshing degree and the penetration resistance of the octahedral interlocking unit are superior to those of the hexahedral unit under the same conditions.

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Note: Figure translations are in progress. See original paper for figures.