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On the Pull-out Mechanical Properties of the Diabolical Ironclad Beetle Bionic Jigsaw Connection

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In engineering, connections between components are often weak areas. Unreasonable connection methods can easily reduce the strength of components, resulting in unpredictable failure modes. In nature, numerous connection methods for biological structures with excellent mechanical properties have evolved. Studying the connection methods of organisms in nature can inspire new ideas for bionic connection methods. When the diabolical ironclad beetle is under pressure, the elytra are not easy to separate, which ensures the stability of the beetle's external structure, thus making the beetle extremely resistant to pressure. The reason for this is the interlocking and toughening effect of the unique jigsaw connection between the elytra. Therefore, in this paper a theoretical analysis model is established and used to analyze the mechanical behavior of the diabolical ironclad beetle's jigsaw connection during the drawing process and determine the influence of factors such as quantity, angle, and geometric characteristics on the mechanical properties of the jigsaw connection. The results of the theoretical analysis are then compared with the results of experiments and ABAQUS finite element simulation.

keyword: Theoretical analysis; bionics; jigsaw connection; 3D Printing; finite element

INTRODUCTION

In engineering, various components must be connected [1]. Common connection methods include welding, bonding, and bolt connection, but these connection methods have shortcomings, which may lead to the damage of the connection of the components and lessen the overall safety of the structure [2]. Animals also have a variety of structural connections, which can serve as a source of inspiration for bionic structural connections. Connection methods in nature vary in geometric shape and function [3−5], such as the skull is a straight line [5], the woodpecker beak is a triangular wave [6]. In addition, biological structure junctions [7], such as the diatom junction belt [8], woodpecker beak [6], and turtle shell [9], are beneficial because they can undergo large deformation and provide energy absorption [10]. The strength and toughness of a joint depends largely on its geometry. In the case of the same bonding material, the strength of a sinusoidal connection is three times higher than that of a straight connection, and a periodic triangular connection can make the stress at the connection interface more uniform. It is beneficial to improve the overall structural stability [13]. In addition, adding elements with triangular connection can enhance its mechanical properties [14−15]. Connections with specific geometric shapes and interlocking features can improve the toughness of brittle materials such as ceramics and glass [16−17].

In the long process of natural evolution, in order to adapt to changes in their living environment and resist predators, the diabolical ironclad beetle has evolved hardened forewings, called elytra, with a unique jigsaw connection [18−21]. The jigsaw connection of the elytra allows the elytra to be tightly combined to avoid the influence of lateral force and give the beetle better compressive ability. Rivera et al. conducted a stress test on the iron ingot beetle. Although the beetle is only about 2 cm in length, it can withstand forces up to 149 N, meaning it can support about 39,000 times its own body weight. Studying the connection of the diabolical ironclad beetle's elytra could provide inspiration for new bionic connection methods.

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This paper focuses on analyzing the mechanical behavior of the jigsaw connection of the diabolical ironclad beetle's elytra during the drawing process by establishing a theoretical analysis model and using it to determine the influences of factors such as quantity, angle, and geometric characteristics on the mechanical properties of the jigsaw connection. The analysis results of the model are then compared with the results of experiments and ABAQUS finite element simulations [23−24].

JIGSAW CONNECTION OF THE DIABOLICAL IRONCLAD BEETLE'S ELYTRA

Different from the triangular connection of other beetles' elytra, the elytra of the diabolical ironclad beetle (Fig. 1a) have a jigsaw-shaped connection of interlocking joints (Fig. 1b) to prevent the elytra from separating. As shown in Fig. 1c, three ellipses are connected to each other at a specific angle ($\theta_0 = 25°$) to form the basic unit of the jigsaw connection, which is referred to as the jigsaw unit. Multiple jigsaw units are repeatedly arranged to form a connection. The ratio of the semi-major axis (a) to the semi-minor axis (b) of each ellipse is 1.8 : 1 [22].

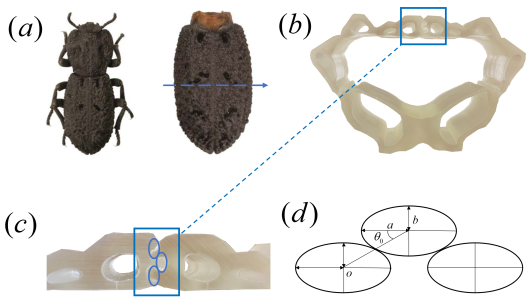

FIG. 1: (a) The diabolical ironclad beetle. (b) 3D printing model of the cross-section of the diabolical ironclad beetle. (c) 3D printing model of the junction of the elytra of the diabolical ironclad beetle. (d) Geometric features of the jigsaw unit of the junction of the elytra.

Based on the geometric features of the jigsaw unit of the diabolical ironclad beetle, a single jigsaw unit model is established (Fig. 2a). Analyzing the geometric parameters of a single jigsaw unit (Fig. 2b), the geometric parameters of the jigsaw unit can be represented by the semi-minor axis b and the connecting angle θ_0. The tangent point of two ellipses is Q. When the distance of OQ is M, the length L and width w can be obtained:

$$L = 2b(1 + \sin\theta_0\sqrt{1 + 2.24\cos^2\theta_0}) \tag{1}$$

$$w = 4M\cos\theta_0 = 4b\cos\theta_0\sqrt{1 + 2.24\cos^2\theta_0} \tag{2}$$

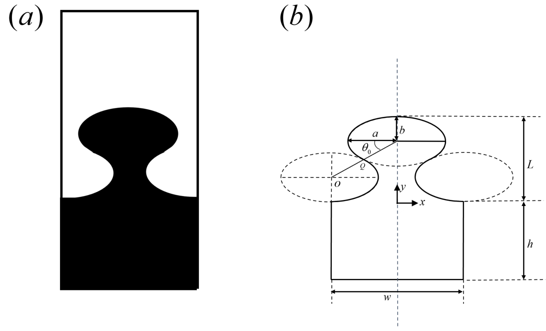

FIG. 2: (a) Single jigsaw unit model. (b) Geometric features of a single jigsaw unit model.

This study focuses on the mechanical behavior of a single jigsaw element model during the drawing process, wherein the lower boundary of the model is fixed, and the upper boundary of the model is subjected to a certain displacement u. It is assumed that the upper and lower parts of the model are bounded by the jigsaw connection, are all isotropic entities, within the linear elastic range (the elastic modulus is E, and the Poisson's ratio is ν). For the forces generated by the model during the drawing process, it is simplified to the interlocking effect and friction of the geometry, and there is no bond at the joint. For the analysis of a single jigsaw unit, its main geometric parameters are model thickness t, semi-minor axis length b, connection angle θ_0, length L, width w, and upper and lower height h. For analytical models, it can be simplified to a plane stress problem with the following boundary conditions:

$$\begin{cases} u_y(x, -h) = 0 \\ u_y(x, L+h) = u \end{cases} \tag{3}$$

The left and right boundaries satisfy the following conditions:

$$\begin{cases} u_x(w/2, y) - u_x(-w/2, y) = w\bar{\varepsilon}_x \\ u_y(w/2, y) = u_y(-w/2, y) \end{cases} \tag{4}$$

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The average strain in the x direction is represented by $\bar{\varepsilon}_x$. Since the model's geometry and boundary conditions are symmetrical about the y axis (Fig. 3a), the displacement in the x direction satisfies the following equation:

$$u_x(x, y) = -u_x(-x, y) \tag{5}$$

Based on equations (4) and (5), the symmetrical boundary conditions are obtained:

$$\begin{aligned} u_x(0, y) &= 0 \\ u_x(w/2, y) &= \frac{w}{2}\bar{\varepsilon}_x \end{aligned} \tag{6}$$

When h is large enough, the strain along the x direction can be ignored, so $\bar{\varepsilon}_x = 0$, and then the boundary conditions can be simplified as:

$$\begin{aligned} u_x(0, y) &= 0 \\ u_x(w/2, y) &= 0 \end{aligned} \tag{7}$$

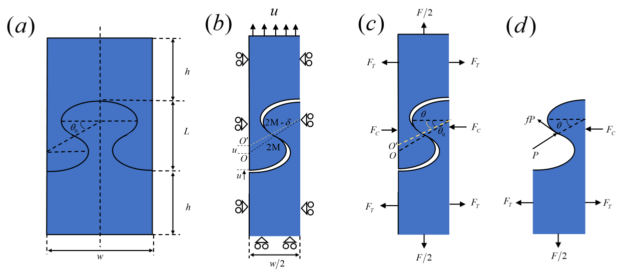

FIG. 3: (a) Initial geometry of a single jigsaw unit model. (b) Model with symmetrical geometry and boundary conditions. (c) Stressed state of the model. (d) Stressed state of the lower model.

Fig. 3b shows the simplified symmetric model, corresponding to the boundary conditions of equations (3) and (7). During the drawing process, the elastic deformation of the model is assumed to be negligible. By comparing the initial geometry of the model and the geometry after applying displacement, the following geometric relationship is obtained:

$$2M\cos\theta_0 = (2M - \delta)\cos\theta \tag{8}$$

$$u = 2M\sin\theta_0 - (2M - \delta)\sin\theta \tag{9}$$

As shown in Fig. 3, the spacing changes from $2M$ in the initial state to $2M - \delta$ after applying the displacement u, where $2M$ is the distance between the centers of the two ellipses, and δ is the shortening of the distance between the centers of the two ellipses. Additionally, θ is the angle between the line connecting the centers of the ellipses and the horizontal line after applying the displacement u. For the stress state analysis of the model, the horizontal pressure F_T is balanced by the tension F_C ($F_C = 2F_T$), and the sum of the left and right forces of the model is zero. In the process of model drawing, the force is generated at the contact boundary, as shown in Fig. 3d, and the vertical tension F can be balanced by the normal force P and the friction force fP. Then:

$$F = 2P(\sin\theta + f\cos\theta) \tag{10}$$

The shortening of the distance between the centers of the two ellipses can be obtained from the non-Hertzian contact in contact mechanics [25]:

$$\delta = \frac{a^2}{2M}\left[2\ln\left(\frac{4M}{a}\right) - 1\right] \tag{11}$$

where M is the distance from the center of the ellipse to the contact point, and a is the half width of the contact surface, which can be expressed as:

$$a^2 = \frac{4PM}{\pi t E} \tag{12}$$

where t is the thickness of the model and E is the elastic modulus of the material.

Corresponding to different M, E, and θ_0, the functional relationship between the pulling force F and the distance M can be solved. Combined with equation (8), the shortening δ is normalized to get:

$$\frac{\delta}{M} = 2\left(1 - \frac{\cos\theta_0}{\cos\theta}\right) \tag{13}$$

Combined with equation (9), the drawing distance u can be obtained:

$$\frac{u}{L} = \frac{\sqrt{1 + 2.24\cos^2\theta_0}(\sin\theta_0 - \tan\theta\cos\theta_0)}{1 + \sin\theta_0\sqrt{1 + 2.24\cos^2\theta_0}} \tag{14}$$

Then u is normalized by L to get the tensile strain of the model in the y direction. Combining equations (11) and (12), we can get:

$$\frac{\delta}{M} = \frac{2}{\pi}\frac{P}{MtE}\left[\ln\left(4\pi\frac{MtE}{P}\right) - 1\right] \tag{15}$$

Solving equation (15), we can get the expression for P/MtE. Combining this expression with equation (10), we can get

$$\frac{F}{MtE} = \frac{2P}{MtE}(\sin\theta + f\cos\theta) \tag{16}$$

If we use F/wtE instead of F/MtE, we get:

$$\frac{F}{wtE} = \frac{P}{MtE}(\frac{\sin\theta + f\cos\theta}{2\cos\theta_0}) \tag{17}$$

So far, the general law of the mechanical behavior of the single jigsaw unit connection model of the diabolical ironclad beetle during the drawing process has been obtained. In order to verify the correctness of the theory, we now compare the theoretical results with the experimental and finite element anlaysis results.

EFFECTS OF THE NUMBER OF JIGSAW UNITS ON THE MECHANICAL PROPERTIES

As shown in Fig. 4, models with different numbers of jigsaw units are designed, and the models are fabricated for tensile testing by 3D printing with a ZRapid-SLA800 light-curing printer and light-curing resin ASTM D638. The material parameters are $E = 400\pm20$ MPa, $\nu = 0.35$, and $\sigma_y = 38 \pm 1.9$ MPa. Pull-out tests of the model are carried out using the MTS testing machine. The geometric parameters of the model are set as $W = 40$ mm, $L+2h = 55$ mm, and $t = 5$ mm. This paper discusses the influence of the number of jigsaw units on the mechanical properties under the conditions of same contact area and same size of the jigsaw units.

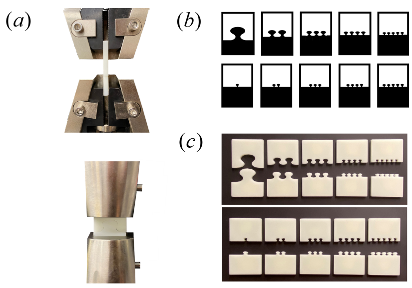

FIG. 4: (a) MTS test device. (b) Models with same contact area and same size. (c) Models fabricated via 3D printing.

In addition, the models are simulated by the finite element software ABAQUS. The material parameters in the simulation are set to $E = 400$ MPa, $\nu = 0.35$, and $\sigma_y = 38$ MPa. Displacement is applied to the upper end of the model, the lower end is fixed, the force–displacement data are extracted from the top reference point, and the simulation results are compared with the experimental results.

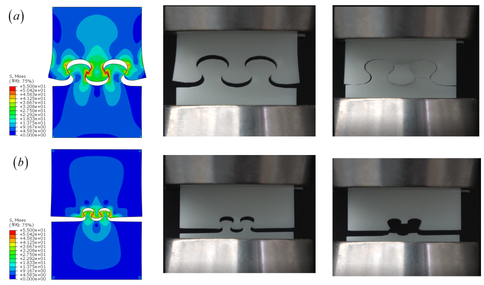

FIG. 5: (a) Simulation and test deformation diagrams of two jigsaw units with the same contact area. (b) Simulation and test deformation diagrams of two jigsaw units with the same size.

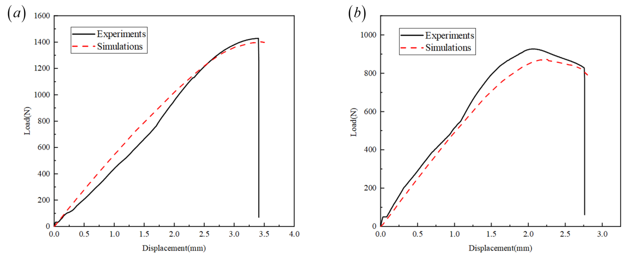

FIG. 6: (a) Comparison of simulation and test results of two jigsaw units with the same contact area. (b) Comparison of simulation and test results of two jigsaw units with the same size.

From the comparison results in Fig. 6, it can be seen that the experimental results are consistent with the simulation results, and the reliability of the finite element simulation is also verified. In order to verify the correctness of the theory, the peak tension for the two sets of models F_{max}/wtE is normalized for analysis and comparison with experimental data and finite element simulations. Then equation (17) becomes:

$$\frac{F_{\max}}{wtE} = \frac{P_{\max}}{MtE}(\frac{\sin\theta + f\cos\theta}{2\cos\theta_0}) \tag{18}$$

If the number of jigsaw units is represented by n, the effects of plastic deformation, size effect, and unit interlocking are considered, and a correction coefficient λ is introduced to modify the formula, we get:

$$\frac{F_{\max}}{wtE}_{(n)} = n\lambda \frac{P_{\max}}{MtE}\left(\frac{\sin\theta + f\cos\theta}{2\cos\theta_0}\right) \quad (19)$$

The normalized peak pull force of different numbers of jigsaw units F_{max}/wtEcan be predicted by equation (19). In order to verify the correctness of the theory, the theory, experiments, and finite element results are verified. The comparison results are shown in Fig. 7.

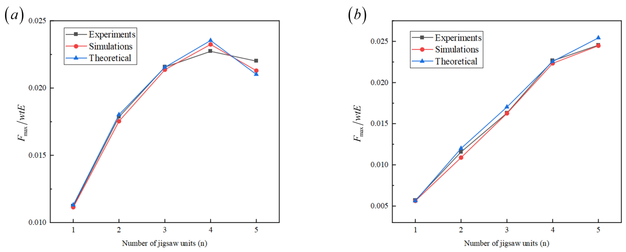

FIG. 7: (a) Normalized comparison of peak loads for different numbers of jigsaw units under the condition of same contact area. (b) Normalized comparison of peak loads for different numbers of jigsaw units under the condition of same size.

For the same contact area and different numbers of jigsaw units, the value of the correction coefficient λ is 0.8696; for the same size and different numbers of jigsaw units, the value of the correction coefficient λ is 0.9448. It can be seen from Fig. 7 that the revised theoretical results are consistent with the experimental data and finite element simulation, which verifies the correctness of the theory.

It can be seen from Fig. 7 that in two different cases, with the increase of the number of jigsaw units, the peak load basically shows a linearly increasing trend. This is due to the increase in the number of puzzle units. During the drawing process, the number of stressed parts increases, so the total positive pressure P increases, resulting in a significant increase in the pulling force along the y-axis. For the conditions of same contact area and same size, the peak loads occur at 4 and 5 jigsaw units, respectively. The reason for the difference between these two peak loads is that in the case of the same contact area, the increase of the number of jigsaw units leads to the reduction of the size of each jigsaw unit, the deepening of the drawing degree, and the increase of the plastic deformation, so the tensile force F peaks at 4 units and then decreases.

In order to better understand the effect of the number of jigsaw units on the mechanical properties, the stiffness and toughness of the model in two cases are discussed.

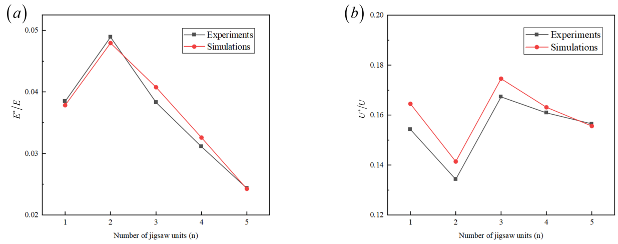

FIG. 8: Comparison of 3D printing tensile test and simulated stiffness and toughness with different numbers of jigsaw units under the condition of same contact area. E: elastic modulus of material; E^*: initial stiffness of force and displacement curves; U^*: toughness (area of stress–strain curve); U: material toughness.

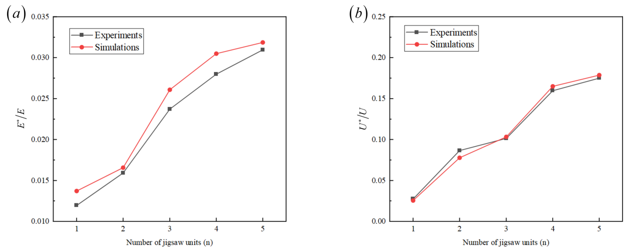

FIG. 9: Comparison of 3D printing pull-out test and simulated stiffness and toughness with different numbers of jigsaw units under the condition of same size.

For the condition of same size, with the increase of the number of jigsaw units, the stiffness and toughness show a linearly increasing trend, which is because with the increase of the number of jigsaw units, the number of stressed parts increases. For the condition of same contact area, the stiffness of the model decreases after reaching an extreme value at two units, and the toughness reaches a maximum value at three units. This is because when there is constant contact area, with the increase of the number of units past two, the unit size decreases, and the neck tension phenomenon becomes obvious. This causes plastic deformation of the neck to be-

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come the main mode of dissipating energy, which greatly reduces the stiffness compared to the case of two units. In the case of three units, the interlocking degree between the jigsaw units is deepened, the adjacent units are mutually restrained, and the degree of plastic deformation of the neck is not high, so the model with three jigsaw units has the highest toughness.

EFFECT OF JIGSAW UNIT ANGLE ON MECHANICAL PROPERTIES

This section analyzes the change of the angle θ in the drawing process and the geometric connection angle θ_0 of a single jigsaw unit, and discuss the influence of the angle on the mechanical properties. In the second section, the theoretical analysis model of the model in the drawing process will be obtained. When the jigsaw units are connected at a fixed angle θ_0, we can get the force–displacement curves for a single jigsaw unit without considering friction ($f = 0$).

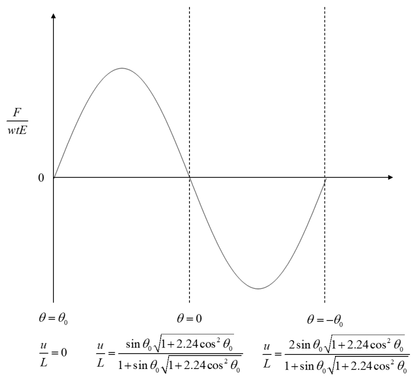

FIG. 10: The function curve of a single jigsaw unit during the drawing process without friction.

As shown in Fig. 10, the force–displacement curves of a single jigsaw unit during the drawing process are sine functions, and the pulling force F increases and then decreases with the change of the angle θ. After reducing to zero, the pulling force becomes a pushing force. At $\theta = 0$, the contact force P acts in the vertical direction of the pulling force F, so there is no pulling force F along the axis of symmetry. After exceeding $\theta = 0$, the contact force P becomes the pull-out direction along the upper part, the upper and lower parts "push" each other, and F gradually decreases to maintain the force balance. When the upper and lower parts are no longer in contact, F eventually changes to 0.

To investigate the effect of different jigsaw connection angles θ_0 on the mechanical properties, a pull-out test must be carried out. Therefore, jigsaw unit models with different connection angles are fabricated with the 3D printer. To ensure that the elements do not intersect, the connection angle $\theta_0 < 45°$.

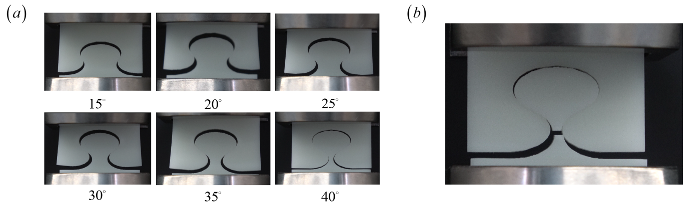

FIG. 11: (a) Model test with different connection angles. (b) Connection angle and model tensile failure mode.

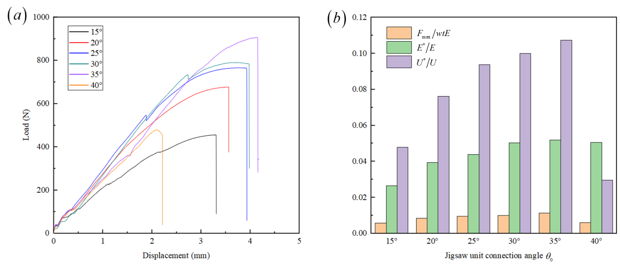

FIG. 12: (a) Model test force–displacement curves of different connection angles θ_0. (b) Normalized comparison of peak load, stiffness, and toughness for different connection angles θ_0.

From the test results (Fig. 12), it is noted that as the connection angle θ_0 increases, the peak load, stiffness, and toughness also increase. When $\theta_0 > 25°$, the growth trends of peak load, stiffness, and toughness slow down and then switch to decreasing trends after $\theta_0 = 35°$. This is because with the increase of the connection angle, the degree of interlocking of the units deepens. During the drawing process, the force from the contact edge is gradually transformed into the force on the neck of the unit. The plastic deformation increases, and the plastic deformation of the neck becomes the main form of energy dissipation. The failure mode is transformed from the failure of the upper part of the model to neck tension failure (Fig. 11b). When $\theta_0 = 40°$, the neck tension phenomenon is the most obvious, which eventually leads to the brittle fracture of the neck.

EFFECTS OF THE GEOMETRICAL DIMENSIONS OF THE JIGSAW UNITS ON THE MECHANICAL PROPERTIES

Through the geometric analysis of the junction of the elytra of the diabolical ironclad beetle, the semi-major and semi-minor axes of the jigsaw units are spliced together according to a certain proportion and a certain angle. To better understand the effect of geometry on mechanical properties, we adjust the a:b ratio of the jigsaw unit to 1:1, so the elliptical jigsaw unit degenerates into a circular jigsaw unit. Then we fabricate models with different numbers of circular jigsaw units to compare with elliptical (a:b = 1.8:1) jigsaw units with the same displacement applied.

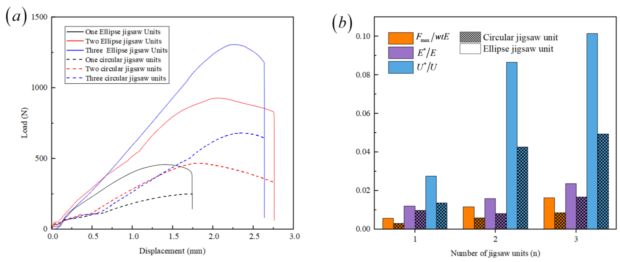

FIG. 13: (a) Test curves of circular and elliptical jigsaw units under the same displacement. (b) Peak load, stiffness, and toughness normalization of circular and elliptical jigsaw unit tests under the same displacement.

From the test results in Fig. 13, it can be seen that the mechanical properties of the elliptical jigsaw are greatly improved compared to the mechanical properties of the circular jigsaw. This is because the circular jigsaw does not have the interlocking phenomenon of the elliptical jigsaw. During the drawing process, the force is basically dependent on the contact edge, and the force on the neck is not obvious. The interlocking jigsaw connection can cause tension deformation of the neck during the drawing process, which improves the tensile mechanical properties.

To better understand the influence of geometry on the mechanical properties of the jigsaw connection, models with different a:b ratios are imported into the finite element analysis software for calculation.

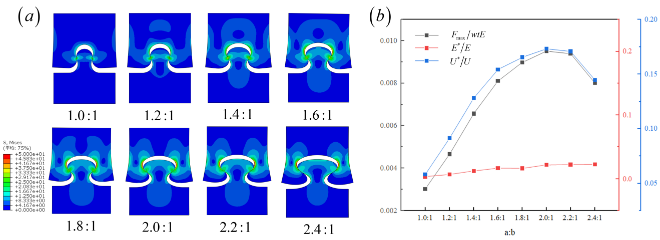

FIG. 14: (a) Finite element stress nephograms for different ratios of semi-major axis to semi-minor axis (a:b). (b) Normalized peak load, stiffness, and toughness of finite element simulations with different a:b ratios.

From the simulation results in Fig. 14, it can be seen that with the increase of the a:b ratio, the peak load and toughness increase, reach their maximum values, and then decrease when the ratio is 2.0:1, whereas the stiffness shows a continuous growth trend with the increase of the ratio. When the ratio is 1:1, the ellipse degenerates into a circle, and the edge contact bears the main tensile force during the drawing process. As the ratio increases, the shape becomes flatter, the degree of interlocking deepens, and the neck bears part of the tension, which improves the tensile performance.

As the ratio continues to increase, the area of the contact parts decreases, and the contact parts are mainly squeezed against each other. At the same time, the interlocking makes it difficult to separate the upper and lower parts, so the neck is pulled and the upper ends of the model are deformed to resist the tension; this deformation becomes a major source of energy dissipation. The reduction in size at the neck and upper ends of the model cause the peak load and toughness to decrease after reaching extreme values.

CONCLUSION

In this study, according to the unique geometric characteristics of the jigsaw connection of the elytra of the diabolical ironclad beetle, an analysis model was established to predict the pulling force of the jigsaw connection model during the drawing process. The results of experiments and finite element simulations were compared with the theoretical analysis results to verify the correctness of the analysis model. The effects of the angle, number, and geometrical dimensions of the jigsaw units on the mechanical properties of the drawing process were analyzed.

1. For the same contact area, as the number of jigsaw units increases, the size decreases, and the tensile force also increases, reaching a peak at four units. Stiffness and toughness reach their maximum values with two and three units, respectively.

2. For the same size, with the increase of the number of jigsaw units, the tensile force, stiffness, and toughness of the model drawing process show a linearly increasing trend.

3. Within a certain angle range, with the increase of the connection angle of the jigsaw units, the drawing mechanical properties of the model improve. When the connection angle $\theta_0 > 35°$, the mechanical properties worsen.

4. For different ratios of semi-major axis to semi-minor axis (a:b) of the jigsaw unit, the peak load and toughness reach the maximum value at 2.0:1, and the stiffness reaches the maximum value at 2.4:1.

Based on our findings, to improve the mechanical properties of the jigsaw connection based on the diabolical ironclad beetle during the drawing process, we should increase the number of jigsaw units, connection angle, and ratio of semi-major axis to semi-minor axis within certain ranges and improve the degree of interlocking.

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