The study on bending performance of aluminum alloy honeycomb panel-beam composite grid structure

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Abstract
Long-span space structures are particularly sensitive to their self-weight. In this paper, a honeycomb plate with a high strength and light weight is reliably connected to a single-layer aluminium alloy lattice shell to form a new type of combined lattice shell structure, which substantially improves the overall stiffness and stability of the lattice shell without a plate. The bending performance of the aluminium alloy honeycomb panel-beam combined grid structure (AAH combined grid structure) plays a key role in the stability of the combined lattice shell structure. Therefore, the bending performance of the AAH combined grid structure was studied through six groups of tests and refined finite element models. Then, the calculation formula for the equivalent bending stiffness of the AAH combined grid structure was obtained through a theoretical analysis. The results show that the contribution of the honeycomb structure to the stiffness of the structure is very obvious, and the proposed formula provides the theoretical basis and a practical method for the engineering design of new aluminium alloy combined lattice shell structures in the future.

1. Introduction

Compared with steel structures, aluminium alloy structures have good corrosion resistance and are lightweight and rationally used for extruded shapes [1]. Therefore, aluminium alloys have been widely used in structural engineering applications since the 1950s, especially for single-layer lattice shell structures [2]. Research on stability and joint semi-rigidity issues has been a key topic in single-layer reticulated shell structures, and some research on aluminium alloy single-layer lattice shells has been completed in recent years. Liu et al [3] studied the stability of single-layer aluminium alloy reticulated shells with Temcor joints through numerical analysis, and a formula for calculating the stability bearing capacity was summarized. Guo et al [4–6] conducted a detailed analysis of the semi-rigidity of aluminium alloy gusset joints, and then a semi-rigid model for these joint plates was proposed. Immediately after, Xiong et al [7–9] conducted a detailed analysis of the stability of single-layer reticulated shells with aluminium alloy gusset joints through experiments and numerical simulations. Ma et al [10] proposed an improved Temcor joint and analysed its mechanical performance in detail.

A honeycomb sandwich structure consists of composite skins and a honeycomb core, and as a typical lightweight and high-strength panel, it is often used in aviation applications [11–14]. Many studies on the mechanical performance of honeycomb panels have been completed thus far. Giglio et al [15] conducted a three-point bending test on a honeycomb sandwich panel composed of a Nomex honeycomb core and aluminium panels and then accurately simulated the test with a numerical simulation. Crupi et al [16] analysed the static and low-velocity impact responses of two typologies of aluminium honeycomb sandwich structures with different cell sizes through tests. It is also very valuable to study the stability of honeycomb panel structures. In the study on the stability of a honeycomb structure, Attard and Hunt [17] considered the shear deformation of the panel...
and the core honeycomb layer. Boudjemai et al. [18] studied the plastic instability of a honeycomb structure with uniform wall thicknesses under unidirectional in-plane compression by numerical analyses and testing. Many studies have been carried out to investigate the dynamic response and crushing behaviour of honeycomb panels [19]. Hou B studied quasi-static and impact loadings for a series of aluminium honeycombs through testing, and the results illustrated that the lateral inertia effect in the successive folding of honeycombs was the main factor responsible for the enhancement of the crushing pressure under impact loading [20]. Khan M K studied the in-plane and out-of-plane crushing properties of a honeycomb core with digital image correlation, and the results worked well for the determination of the global and local deformation mechanism of the honeycomb core [21]. Xu S studied the out-of-plane crushing behaviour of four types of aluminium hexagonal honeycombs and analysed the effects of the specimen dimensions, relative density, strain rate and honeycomb cell size on the mechanical properties of honeycombs [22]. Ivanez I investigated the response of composite sandwich beams with honeycomb cores subjected to low-velocity impact by using a finite-element model and found that the core controlled the energy absorption of the sandwich beams at the lowest impact velocities studied [23].

As a lightweight and high-strength material, aluminium alloys and honeycomb panels are very suitable for long-span structures. Caiqi Zhao [24–28] first proposed combining honeycomb panels with aluminium alloy beams and applied them to single-layer reticulated shell structures. Compared with the traditional aluminium alloy single-layer reticulated shell structure, the aluminium alloy honeycomb panel would enhance the rigidity and strength of the aluminium alloy honeycomb panel–beam (AAH) combined grid structure with a small increase in the mass. Therefore, the AAH combined grid structure can be widely used in large-span single-layer lattice shells, as shown in figure 1.

Against this background, this paper primarily focused on the bending stiffness of an AAH combined grid structure. According to Chinese code [29], there are some arrangement forms of grids that have already been used for some large-span single-layer lattice shells, as shown in figure 2. Type A and type C were adopted in the test. Six specimens were used to study the bending performance influenced by the distance of the connection and thickness of the honeycomb panel. Then, many numerical analysis models of the AAH combined grid structure were established based on the ‘sandwich panel theory’. Finally, the calculation formula of the equivalent bending
stiffness of the AAH combined grid structure was obtained through a theoretical analysis and numerical simulation. According to Shizao Shen [30], the stability bearing capacity of the single-layer reticulated shell was closely related to the bending stiffness of the reticulated shell. Therefore, the calculation formula of the bending stiffness could be used to estimate the stability bearing capacity of the AAH composite grid structure in the early stage of structural design.

2. Experimental program

2.1. The design of the experiment

To study the bending performance of the aluminium alloy honeycomb panel-beam (AAH) combined grid structure, this paper first conducted experimental research on this combined structure. In this test, the distribution form of aluminium alloy beams was selected as types A and C, and each specimen was composed of honeycomb panels and aluminium alloy beams, as shown in figure 3(a). Aluminium alloy beams were made of 6060-T5 aluminium alloy tubes with dimensions of 50 mm × 40 mm × 4 mm × 4 mm, and the honeycomb panels were composed of aluminium alloy skin and a honeycomb core with a plane size of 790 mm × 790 mm. Steel connectors were used to connect the aluminium alloy beams to ensure rigid connections, as shown in figure 3(b). The honeycomb panel was connected to aluminium alloy beams by hand tightened stainless steel M4 bolts in 4.5 mm drilled holes, as shown in figure 3(c). The load was provided by the lifting jack, and the corresponding load could be measured by a pressure transducer. Then, the concentrated load was transmitted to the four nodes by steel beams, and four corners were connected to the reaction frame by four steel rods that created a hinge, as shown in figure 3(d).

The test was mainly used to research the effects of the connection distance and honeycomb panel thickness on the bending performance of AAH combined grid structures. According to the connection distance, the type A specimens were divided into three cases: 80 mm, 120 mm, and 160 mm. Three different plate thicknesses were adopted for the type C specimens: 0 mm (without the honeycomb panel), 10 mm (the thickness of the upper and
lower skin was 1 mm and the height of the honeycomb core was 8 mm), and 16 mm (the thickness of the upper and lower skin was 1 mm and the height of the honeycomb core was 14 mm). Detailed information on all the specimens is presented in table 1.

Table 1. Detailed specimen information.

| Specimen identifier | Type | Bolts distance (mm) | Panel thickness (mm) | $D_{AAH}$ ($\text{N} \cdot \text{mm}^2$) | Yield load | Yield displacement |
|---------------------|------|---------------------|---------------------|---------------------------------------|------------|-------------------|
| A-1                 | A    | 80                  | 10                  | $2.65 \times 10^{10}$                  | 3%         | 19%               |
| A-2                 | A    | 120                 | 10                  | $2.60 \times 10^{10}$                  | 5%         | 15%               |
| A-3                 | A    | 160                 | 0                   | $2.45 \times 10^{10}$                  | 8%         | 17%               |
| C-1                 | C    | 80                  | 0                   | $3.0 \times 10^{10}$                  | 4%         | 5%                |
| C-2                 | C    | 10                  | 3.7 $\times 10^{10}$ | 12%                                   | 6%         |                   |
| C-3                 | C    | 16                  | 4.6 $\times 10^{10}$ | 10%                                   | 11%        |                   |

Table 2. Mechanical properties of the material.

| Components        | Yield strength (MPa) | Ultimate strength (MPa) | Elastic modulus (GPa) |
|-------------------|----------------------|-------------------------|-----------------------|
| Honeycomb panels  | 117                  | 164                     | 70.6                  |
| Beams             | 132                  | 185                     | 70.3                  |
| Bolts             | 470                  | 725                     | 206                   |

2.2. Materials
The honeycomb panel was made of aluminium alloy H3003, and the beam was made of aluminium alloy 6060-T5 [31]. Austenitic stainless steel was selected as the material for the bolts (material grade of A2-70) [32]. Tensile tests were performed to investigate the actual mechanical properties of the AAH combined structure specimens [33]. Six tensile coupons were cut from the same batch of aluminium material that was used in the test, as shown in figure 4. Then, the three bolts that were selected for the test were used for the tensile test. In the tensile tests, the yield strength, ultimate strength and elastic modulus of the materials were given. The test results of the three materials are listed in table 2.

2.3. Arrangement of the measuring positions
In this test, a TST3826F-L data acquisition instrument was used to record the test results, large-scale electrical displacement meters (400 mm) were used for measuring the displacement, and strain gauges were used to monitor the strain of the components. Large-scale electrical displacement meters were placed on the aluminium alloy beams, as shown in figure 5(a). The strain-gauge rosettes placed on the specimens are plotted in figure 5(b).

2.4. Experimental results
The load-displacement curves of the specimens are plotted in figure 4, which shows the maximum displacement (mid-span) of the specimens under loading. The load-displacement curves can be divided into two stages for all

![Figure 4. Tensile coupons of the aluminium alloy.](image)
the specimens with different primary parameters. Figure 6(a) shows that at the initial stage, all the specimens exhibit a similar rigidity and yield displacement, but their yield loads are different. With the decrease in the bolt distance, the yield load and yield displacement increase gradually. At the second stage, the rigidity of the specimens became sensitive to the distance of the bolt connections. Obviously, the honeycomb panel and aluminium alloy beam work well together in the initial stage, and then the coordinated working performance is weakened in the second stage; therefore, the rigidity of the AAH combined structure becomes sensitive to the distance of the bolt connections.

Several characteristics can be observed from figure 6(b): (1) At both stages of loading, the strength and rigidity of the specimens increase gradually with increasing panel thickness. (2) With the increase in the panel thickness, the plastic deformation apparently declines. (3) Compared with the bolt distance, the AAH combined structure is more sensitive to the thickness of the honeycomb panels.

Then, the bending stiffness (D\textsubscript{AAH}) of the AAH combined grid specimens can be calculated (figure 7) from the load-displacement curve, as shown in table 1. It can be seen from table 1 that (1) the bending stiffness of the AAH combined grid structure gradually decreases with increasing connection distance, and the decreasing trend is increasingly obvious; (2) the bending stiffness of specimen C-3 is approximately 1.5 times that of specimen
In summary, due to the existence of the honeycomb panel, the bending stiffness of the AAH combined grid structure is effectively improved, so the AAH combined grid structure can be widely used in long-span space structures.

When the specimens yield, the maximum strain of the beam and panel are shown in figure 8. When the AAH combined structure yields, the maximum tensile strain of the aluminium alloy beam exceeds the yield tensile strain, and the maximum compressive strain just reaches the yield strain, as shown in figure 8(a). When the AAH combined structure yields, the tensile strain and compressive strain of the honeycomb panel are less than the yield strain, as shown in figure 8(b). Therefore, the specimens begin to yield as the beam yields. This finding is critical for studying the yield state of AAH combined structures in the future.

3. Finite element analysis

3.1. FEA model of the honeycomb panel

The nonlinear FE code ABAQUS is adequate for investigating the mechanical behaviour of honeycomb panels. If the actual model is used to analyse the honeycomb structure panel, which consists of a large number of honeycomb cores, it will not only lead to a large computational workload but will also inevitably cause numerical analysis errors. The 'sandwich panel theory' [34] is adopted to effectively simulate the mechanical behaviour of honeycomb panels. In this theory, honeycomb cores are equivalent to a homogeneous orthotropic sandwich with the same thickness, and the upper and lower skins obey the Kirchhoff hypothesis, as shown in figure 9. According to Zhao [35], the equivalent elastic parameters of the hexagonal aluminium honeycomb core layer are:

\[
E_{xc} = \frac{4}{\sqrt{3}} E_i \left(1 - \frac{3 t^2}{l^2}\right) \\
E_{yp} = \frac{4}{\sqrt{3}} E_i \left(1 - \frac{3 t^2}{l^2}\right) \\
E_{yz} = \frac{2}{\sqrt{3}} E_i \frac{t}{l}
\]

(1)

\[
\rho_c = \frac{8 t}{3 \sqrt{3}} \frac{1}{l^3} \rho_i, \mu_1 = 1 - \frac{4 t^2}{l^2}, \mu_2 = 1 - \frac{4 t^2}{l^2}
\]

(2)
where $E_i$, $G_{ci}$ is the elastic modulus of the honeycomb core in all directions, $G_{ci}$ is the shear modulus of the honeycomb core in all directions, $\rho$ is the density of the honeycomb core, $\mu_i$ is the Poisson’s ratio in all directions of the honeycomb core, $t$ is the wall thickness of the regular hexagonal aluminium honeycomb core, and $l$ is the edge length of the honeycomb core.

In this paper, the accuracy of the equivalent theory is analysed by FEA and previous tests \[36\]. Three rectangular aluminium alloy honeycomb plates with dimensions of 500 × 500 mm were used in the previous experiments. The total thickness of the honeycomb panel is 10 mm, and the thickness of the upper and lower skin is 1 mm. The wall thickness of the regular hexagonal aluminium honeycomb core is 0.05 mm, and the edge length of the honeycomb core is 6 mm. The panel is simply supported on four sides under uniform loading. The failure pattern of the test and stress distribution of the FEA are shown in figure 10. The stress distribution of the numerical simulation is in good agreement with the failure mode of the test. The load-strain curves of the centre point are shown in figure 11. It can also be seen from the figure that the results of the numerical simulation and experiment are very close in the elastic stage, but the difference between them increases gradually in the plastic stage. The total load of the honeycomb panel under yielding is shown in table 3. The table shows that the yield load of the numerical simulation is approximately 1.13 times that of the experimental yield load. According to figure 8, the strain of the honeycomb plate is less than that of the aluminium alloy beam when the AAH composite structure yields, and most strains of the honeycomb plate remain in the elastic stage. Therefore, the ‘sandwich panel theory’ could be used to simulate honeycomb structure panels in the elastic stage.
3.2. FEA model of the aluminium alloy beams

In ABAQUS, the solid element could simulate the box-shaped beams. In the FEA model, tie constraints were applied to simulate the connection between the beams. To verify the accuracy of the numerical simulation, specimen B1 (no honeycomb panel) was simulated, as shown in figure 12. The material properties of the aluminium alloy beams are listed in table 2. The Ramberg-Osgood model \([37]\) was adopted to simulate the material properties of the aluminium, and the bilinear model was employed to model the constitutive relationship of the bolt, as shown in figure 13. The FEA results are shown in figure 14. In the elastic phase, the stiffness of the numerical simulation was slightly larger than the stiffness of the test. This was because the structure and materials in the numerical model were not defective compared to those of the test. Overall, the results of the numerical simulation were in good agreement with the experimental results, so it could be stated that the steel connectors used in the test were close to rigid connections. Therefore, the FEA model of the aluminium alloy beams could be used for the FEA model the AAH composite structure.

| Specimen identifier | Yield load of the tests (kN) | Yield load of the FEA model (kN) | Error |
|----------------------|-----------------------------|---------------------------------|-------|
| 1                    | 6.19                        | 7.06                            | 14.1% |
| 2                    | 6.42                        | 7.06                            | 9.97% |
| 3                    | 6.13                        | 7.06                            | 15.2% |
| average value        | 6.25                        | 7.06                            | 13.0% |

Figure 12. FEA model.

Figure 13. Material constitutive relation.

Table 3. The comparison of the numerical simulation and test.
3.3. FEA model of the AAH composite structure

According to previous analyses, the ‘sandwich panel theory’ was used to simulate the honeycomb panel, tie connections were used to simulate the steel connectors, and embedded connections were used to simulate the bolt connections. There were three kinds of contact pairs in the FEA models of the AAH combined grid structure: bolts-to-panel contact, bolts-to-beam contact and beam-to-panel contact, as shown in Figure 15. The surface-to-surface contacts were used to simulate beam-to-panel contact. The essence of the bolt-to-panel contact and bolt-to-beam contact was mechanical occlusion between the bolts and the aluminium alloy members, so the embedded connections could be used to simulate the bolt-to-panel contact and bolt-to-beam contact in the AAH combined grid structure.

To accurately simulate the AAH combined structure, the elasto-plastic mechanical model was adopted for the members. The material properties of the AAH combined structure were measured by tensile tests, as listed in Table 2. The Ramberg-Osgood model \[37\] was adopted to simulate the material properties of the aluminium, and the bilinear model was employed to model the constitutive relationship of the bolts, as shown in Figure 13. The FEA model of the AAH combined structure is shown in Figure 16. In the FEA models of the AAH combined structure, the geometric dimensions of all the AAH combined structure components were the same as those of the AAH combined structure specimens.

3.4. Comparison of the FEA results with the test results

To prove the accuracy of the numerical simulation, the deformation shape of the specimen in the test and the deformation of the specimen in the numerical simulation are listed in Figure 17. It is obvious from Figure 17 that the deformation shape of the specimen in the test was very consistent with the results of the numerical simulation. A comparison of the load-displacement curves between the FEA model and experimental results is carried out, as shown in Figure 18. The comparison shows that the load-displacement curve of FEA agrees well with the experimental curve, also indicating that the FEA model effectively estimates the mechanical behaviour of the AAH combined grid structure. To further illustrate the accuracy of the numerical model, the relative errors of all specimens are recorded in Table 1. The average relative errors of the yield load and the yield displacement are 7% and 12%, respectively. In summary, the results of the FEA model can be used to quickly and...
accurately analyse the influence of the connection distance and honeycomb panel thickness on the bending stiffness of the AAH combined grid structure.

3.5. Optimization analysis of the bolt connection distance
The honeycomb panels and the aluminium alloy beams are often connected by bolts in the AAH combined grid structure. The determination of the connection distance ($L$) not only needs to consider the requirements for the honeycomb panels and the aluminium alloy beams to work together but a convenient distance for construction should also be taken into account. To analyse the deceleration rate of the bending stiffness of the AAH combined grid structure with the increase in the connection distance, the ratio of the bending stiffness ($D_{AAH-L,T}$) with different connection distances to the bending stiffness ($D_{AAH-80,T}$) for the connection distance of 80 mm is shown in figure 19. As a whole, the bending stiffness of the AAH combined grid structure gradually decreases as the connection distance increases, and the trend of the bending stiffness with different honeycomb panel
thicknesses is basically consistent. Compared with the connection distance of 80 mm, the bending stiffness of the AAH combined grid structure is reduced by approximately 10% when the connection distance is 240 mm. When the connection distance is greater than 400 mm, the bending stiffness of the AAH combined grid structure decreases substantially with increasing connection distance. The reason for this phenomenon is that the joint effect of the honeycomb panel and the aluminium alloy beams is weak and cannot be fully exerted when the connection distance is too large. In practical engineering applications, it is necessary to give full play to the strengthening effect of the honeycomb panel on the bending stiffness and to simultaneously ensure construction convenience. Therefore, the value range of the connection distance recommended in this paper is 80–240 mm.

3.6. FEA study on the stress state of the AAH composite grid structure

The honeycomb panel is composed of upper and lower skins and a honeycomb core, and its bending stiffness is mainly provided by the upper and lower skins. Therefore, when the AAH combined grid structure yields, the stress state of the upper and lower skins of the honeycomb panel is very substantial. It can be seen from the test results that the AAH combined grid structure starts to yield when the aluminium alloy beams reach the yield state. Based on this, numerical simulations can be used to obtain the stress distribution of the upper and lower skins along the tensile direction when the beams yield, as shown in figure 20. It can be seen from figure 20(a), that when the AAH combined grid structure yields, the compressive stress at the bolt connection is 95 MPa, which is already close to the yield stress (115 MPa), but the upper skin compressive stress in the span is only 30 MPa. In general, the stress on both sides of the upper skin is large, but the middle stress is small. The reason for this phenomenon is that the upper skin is tightly connected to the aluminium alloy beams near the bolt connection; however, the connection gradually weakens away from the bolt connection. From 20b, it can be concluded that

![bending stiffness with different connection distances](image1)

**Figure 19.** Bending stiffness with different connection distances.

![stress state of the skins of the honeycomb panel](image2)

**Figure 20.** Stress state of the skins of the honeycomb panel.

a) Stress on the upper skin during yielding  b) Stress on the lower skin during yielding
the maximum stress of the lower skin at the mid-span section is approximately 34 MPa, which is very small compared to that of the upper skin. As a result, the lower skin of the honeycomb panel is close to the neutral axis of the overall cross-section of the AAH combined grid structure.

4. Theoretical analysis of the equivalent bending stiffness

4.1. Study on equivalent thickness of the aluminium alloy grid

In a single-layer cylindrical reticulated shell, there are four common grid distribution forms, as shown in figure 2. Shen [25] proposed the following equivalent bending stiffness calculation formula for a grid structure:

\[
D_{bi} = \frac{Eh}{\Delta_1} + n \frac{Eh_c}{\Delta_c} \sin^4 \alpha \quad D_{b2} = \frac{Eh_2}{\Delta_2} + n \frac{Eh_c}{\Delta_c} \cos^4 \alpha \quad (4)
\]

I₁, I₂, and I₃ are the corresponding cross-sectional moments of inertia, and n is the number of inclined beams. The spaces between components \(\Delta_1, \Delta_2, \Delta_3\) and angle \(\alpha\) are shown in figure 2.

To verify the accuracy of the equivalent bending stiffness calculation formula of the grid structure, the bending stiffness \(D_{b1} = 3.0 \times 10^{10} \text{ N \cdot mm}^2\) of specimen B1 obtained from the test is compared with the equivalent bending stiffness \(D_b = 2.93 \times 10^{10} \text{ N \cdot mm}^2\). The equivalent stiffness is 97.7% of the test result, and the two are very close. Therefore, formula 4 is very applicable for the aluminium alloy grid structure. Then, according to the principle of equivalent bending stiffness, the aluminium alloy grid structure is equivalent to an aluminium alloy thin shell with the same material. The calculation formula of the thin shell thickness is:

\[
t_b = \sqrt[3]{\frac{12D_b}{E}} \quad (5)
\]

4.2. Study on the equivalent thickness of the honeycomb panel

The actual stress distribution of the honeycomb panel skin is very complex, and the process of calculating the bending stiffness of the honeycomb panel is very complicated. Therefore, based on the results in Chapter 3.5, the following assumptions are proposed for the honeycomb panel in the AAH composite grid structure: when the AAH combined grid structure yields, the stress of the upper skin reaches the yield stress at the shear connection, which is 0 in the middle, and the stress of the lower skin is 0, as shown in figure 21.

To facilitate the calculation, it is necessary to replace the honeycomb panel with a new honeycomb panel. According to the principle that the bending moment generated by the stress of the upper skin at the lower skin is unchanged, the honeycomb panel can be equivalent to a new honeycomb panel in which the stress of the upper skin reaches the yield stress at the shear connection, which is 0 in the middle, and the stress of the lower skin is 0, as shown in figure 21. In summary, the thickness of the equivalent honeycomb panel is:

\[
t_{ep} = \frac{t_p}{2} \quad (6)
\]

4.3. Calculation of the equivalent bending stiffness of the AAH combined grid structure

Because the stress of the lower skin of the honeycomb panel is very small, the effect of the lower skin on the bending stiffness of the AAH combined grid structure can be negligible. According to the above analysis, the cross-section of the AAH combined grid structure can be equivalent to the cross-section shown in figure 22. The neutral axis of the equivalent section gradually moves with increasing load, so the geometric centreline of the equivalent faces is approximately taken as the neutral axis. Therefore, the bending stiffness of the equivalent section of the AAH combined mesh can be obtained as:
Since the equivalent bending stiffness is obtained on the basis of some assumptions, the equivalent bending stiffness adjustment coefficient $\beta$ is introduced in formula 7. Therefore, the equivalent bending stiffness of the AAH combined grid structure is:

$$D_{eq} = E \left[ \frac{(t_b + 0.5t_p)^3}{12} - \frac{(0.5t_p - m)^3}{12} - \frac{(0.5t_p - m)(t_b - m)^2}{4} \right]$$

(7)

4.4. Parametric analysis

To accurately analyse the parameters, 160 numerical models are established in this paper. The detailed information of the model is as follows: (1) three lengths of aluminium alloy tubes with 2 m and 3 m are selected (the dimensions are 100 mm $\times$ 200 mm $\times$ 6 mm $\times$ 6 mm); (2) A, B, C, and D are used for the distribution of the aluminium alloy beams; (3) the distances of the shear connection are 80 mm, 120 mm, 160 mm, 200 mm and 240 mm; and (4) the thickness of the honeycomb panel is 10 mm, 15 mm, 20 mm, and 25 mm. The main results are shown in figure 23.

Figure 23 shows that $\beta$ gradually increases with increasing connection distance in accordance with formula 4. When the connection distance is between 80 mm and 240 mm, it can be calculated by the following formula:

$$\beta = 0.16 + 0.0007L$$

(10)

4.5. Comparison of the theoretical results with the test results

Based on the previous theoretical analysis and parameter analysis, the calculation formula of the bending stiffness is obtained in this paper. Finally, the accuracy of the calculation formula is verified by a comparison with the test results, as shown in table 4. Compared with the experimental results, the error of the theoretical calculation results is within 5%. Obviously, the theoretical calculation formula is very applicable, and it can be used in subsequent research on the stability calculation of AAH combined grid structures.
Table 4. The comparison of the theoretical calculation results and test results.

| Specimen identifier | Test results | Theoretical results | Error |
|---------------------|--------------|---------------------|-------|
| A-2                 | 2.65 × 10¹² | 2.68 × 10¹²          | 1%    |
| A-3                 | 2.60 × 10¹² | 2.62 × 10¹²          | 1%    |
| A-4                 | 2.45 × 10¹² | 2.56 × 10¹²          | 4%    |
| C-2                 | 3.69 × 10¹⁰ | 3.52 × 10¹⁰          | 5%    |
| C-3                 | 4.60 × 10¹⁰ | 4.31 × 10¹⁰          | 2%    |

5. Conclusions

In this paper, the bending stiffness of the AAH combined grid structure was analysed through theoretical analysis and experimental research, and the mechanical characteristics and failure mechanism of this kind of composite structure was verified. The main conclusions are summarized as follows:

1. The results of six groups of bending capacity comparative tests show that the contribution of the honeycomb plate on the stiffness of the structure is very substantial. With the decrease in the bolt distance and the increase in the honeycomb thickness, the bending stiffness of the AAH combined grid structure increases gradually.

2. The ‘sandwich panel theory’ can simulate the behaviour honeycomb structure panels, and embedded connections can be used to simulate bolt connections in AAH combined structures. It can be determined from the finite element simulation that the recommended distance of the bolt connection is 80 mm to 240 mm. The FEA models of the AAH combined structure in this paper can be used for subsequent research work and engineering design.

3. A calculation formula for the equivalent bending stiffness of the AAH combined grid structure is obtained through the theoretical analysis, and an adjustment parameter is introduced into the formula. Then, 160 numerical models are established to fit the calculation formulas of the adjustment parameter. Finally, the theoretical formulas are compared with the experimental results, and the results show that the calculation of the equivalent bending stiffness can be used to forecast the bending stiffness of the AAH combined grid structure. This study provides the theoretical basis and a practical method for the engineering design of new aluminum alloy composite lattice shell structures in the future.

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