

Article

Experimental Study on the Mechanical Properties and Health Monitoring Methods of Joints in AAPF

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Abstract: Aluminum alloy frame is a novel structure system developed in recent years. In this article, the load-bearing performance of the beam-beam joint of the aluminum alloy frame is studied through numerical analysis and experiment and a safety monitoring method is developed. The impacts of the arch angle and bolt diameter on the beam-beam joint mechanical characteristics are explored through experiments under vertical load. When the diameter of the bolt was increased, the load-bearing performance of such joint displayed a pattern of first increasing and then decreasing. As the arch angle increased, the load-bearing performance on the joint gradually improved. Based on the experiments, numerical analysis models varying in arch angle were established, and the impacts of arch angles on the stiffness during the yield stage, ultimate load, and elastic stiffness of the aluminum alloy portal frame (AAPF) beam-beam joints were further explored through numerical simulation of the structure under vertical and horizontal loads. When the arching angle was increased, the elastic stiffness and yield stiffness of the beam-beam joint under vertical load showed a pattern of first increasing and then decreasing. When the arching angle was increased, the elastic stiffness and yield stiffness of the beam-beam joint under horizontal load significantly decreased. Based on the mechanical properties, a safety monitoring method for AAPF beam-beam joints based on displacement monitoring and frequency monitoring is proposed.



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Keywords: AAPF; beam-beam joints; experimental study; numerical analysis; safety monitoring

1. Introduction

Due to its excellent anti-corrosion performance, aesthetics, and non-magnetic properties, aluminum alloy demonstrates its distinctive appeal in the combination technique with spatial structures [1]. With its outstanding expressive power and good decorative effects, it is highly favored by architects and structural engineers [2]. At present, the most commonly used aluminum alloy structural form is the single-layer aluminum alloy shell structure [3], and rich research results have been formed in this field [4]. With the continuous innovation of the processing technology and joint system, as well as the gradual improvement of the design level, aluminum alloy spatial structures are widely used in semi-permanent or temporary constructions (e.g., medical, exhibitions, event activities, and logistics storage), as well as being applicable in permanent constructions (e.g., sports venues and exhibition centers), as shown in Figure 1.

The most widely used structural type for permanent aluminum structures is a single-layer lattice shell structure (Figure 1a). Xiong et al. [5,6] completed a K6 one-layer aluminum alloy mesh shell model (height 0.5 m; span 8 m) experiment, in which typical aluminum alloy plate joints were used as the joints. The experimental results indicated that the lattice shell exhibits a super rigid characteristic during the initial loading stage; that is, it has greater stiffness than the rigidly coupled joint lattice shell. The stiffness of the lattice shell

will be reduced by subsequent deformation of the joint bolt slip, and the deformation caused by the bolt slip is large and irreparable. Although the lattice shell instability belongs to an overall jumping type, the lattice shell can continue to bear load after buckling, and the load can further increase. Liu et al. [7] used numerical software to establish over 500 numerical structural models to clarify how the joint semi-rigidity and skin effects impact the static stability of one-layer aluminum alloy spherical latticed shells. Among them, the joint semi-rigidity model used a simplified bilinear model. Firstly, numerical simulation was conducted to determine how material nonlinearity and initial defects impacted the stability performance of the lattice shell, and on this basis, a comparative analysis was conducted considering the joint semi-rigidity and skin effect. As demonstrated by the analysis results, the skin effect enabled significant improvement in the static stability ultimate load for the aluminum lattice shells, along with the alteration in structural buckling mode. For the lattice shell, its ultimate bearing capacity could be significantly reduced by taking into account the joint semi-rigidity. When both the skin and joint stiffness were considered, the lattice shell stability performance remained basically unchanged. Finally, the computational formula was summarized for the stability ultimate load of the common-sized aluminum one-layer grid structure.



Figure 1. Aluminum alloy structures.

As displayed in Figure 1b, AAPF structures are often used as a structural system for temporary buildings. Since AAPFs generally have box-like cross-sections, substantial in-depth studies have been undertaken on the aluminum alloy components with box-like cross-sections. A series of explorations have been conducted into the bending performance and axial compression of such alloy components with box sections, and the calculation methods for local buckling and overall stability of these components have been obtained through research [8,9]. Due to the special sensitivity of aluminum alloy rods to high-temperature environments, particular emphasis should be placed on the load-bearing performance of aluminum rods in high-temperature environments. Meulen et al. [10,11] conducted a series of high-temperature experimental studies, taking into account three factors: different cross-sectional dimensions, temperature, and heating rate. Based on the outcomes of high-temperature mechanical tests on 28 aluminum alloy beam components, they verified the relevant European standard formulas, indicating that the standard calculation formulas were effective. Maljaars et al. [12,13] conducted extensive in-depth explorations into the high-temperature local stability of aluminum alloy components and proposed a simplified calculation model for local stability at high temperatures based on finite element simulation and experimental findings. Joint mechanical characteristics remarkably impacted the mechanical performance of the overall aluminum alloy structure [14–17]. However, the joints of AAPFs have rarely been investigated at present, especially the joint forms of I-shaped cross-section members.

The security of joints is crucial for the overall safety of the structure; therefore, joints have always been a key focus of structural health monitoring. Sentosa et al. [18] conducted local diagnostic tests on reinforced concrete (RC) frame joints, obtaining information on the occurrence of destruction, changes in natural frequency, and changes in stiffness through experiments, validating the degradation characteristics technique that takes into account

semi-rigid joint connection in the frame. Katkhuda et al. [19] proposed a new system identification and structural health assessment program for semi-rigid connected steel frame structures, which can detect the degree of damage to local components through the structural response. Bui et al. [20] conducted experimental research on local diagnosis of reinforced concrete structures composed of two columns and one beam, and the results showed that displacement sensors can be used to measure displacement, while accelerometers can be used for dynamic measurement. Antunes et al. [21] used fiber optic accelerometers and thirteen multi-channel displacement sensor networks to monitor adobe masonry structures, and the research results indicated that optical sensors can be applied to large-scale static and dynamic monitoring.

In this article, we conduct test research and numerical simulation on the beam-beam joints of AAPFs. We analyze the force mechanism and deformation characteristics on beam-beam joints under vertical loads through experimental research of the bolt diameter and arch angle [22]. Then, the numerical models are established to further study the effect of arch angle on the stress characteristics of the beam-beam joints of AAPFs under horizontal loads [22]. Finally, a health monitoring method for AAPF beam-beam joints based on displacement monitoring and frequency monitoring is invented.

2. Test Scheme

2.1. Specimen Design

An AAPF mainly consists of joints between beam and beam, joints between beam and column, and aluminum alloy members [22]. Detailed numerical and experimental explorations were undertaken on aluminum alloy beam column joints earlier. In preparation for further exploration of AAPFs, the beam-beam joint specimen shown in Figure 2a was designed. Similar to the beam-column joint, the beam-beam joint specimen comprises aluminum alloy H-shaped I-beams and tightly bolt-connected dual C-shaped connectors. The cross-sectional dimension was $H203 \times 106 \times 11 \times 11$ for the I-beam and $C181 \times 47.5 \times 5 \times 10$ for the C-type connector. On the lower and upper I-beam flanges, 4 and 6 bolt holes were set up, while on the web, 6 bolt holes were set up. Meanwhile, bolt holes were also set up at the matching locations of the C-shaped connector web and flange [22]. The bolt hole diameter was calculated by adding 0.20 mm to the bolt diameter. The lengths of the I-beam and the C-shaped connector were, respectively, 1149 mm and 443 mm, while the bolts were arranged on flanges and the web at 148 mm intervals. Figure 2a depicts the specimen's structural dimensions. The length unit in the figure is mm. The H-shaped beams were sectioned and drilled in the factory, while the dual C-shaped connectors were welded from steel plates [22]. Afterwards, as displayed in Figure 2b, the two were delivered to the laboratory for connection and assembly.

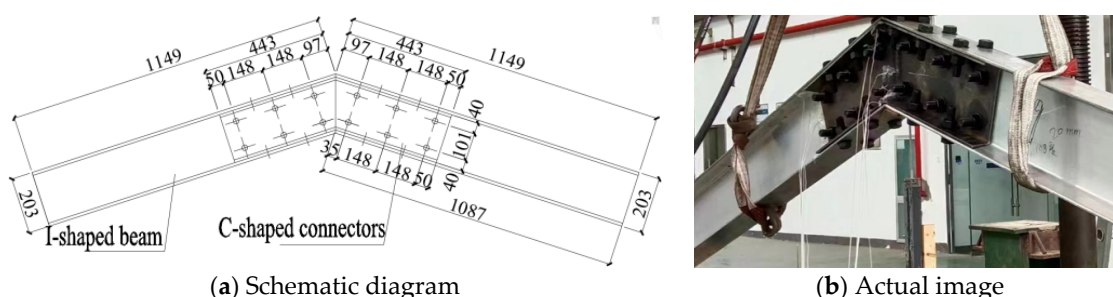


Figure 2. Test specimen.

From previous research [22], it can be concluded that for AAPFs, the influences of joint arch angle and bolt diameter on their mechanical performance should be fully considered. Hence, the number of beam-beam joint specimens envisaged in the present section totaled 5, and Table 1 lists the variables for every specimen. According to this table, it can be inferred that this experiment mainly envisaged specimens that vary in bolt diameter (8 mm,

14 mm, and 20 mm) and arch angle (90° , 108° , and 126°) to explore how the load-bearing performance of the AAPF beam joint is impacted by these two parameters [22]. The definition of arch angle is consistent with Section 3, which refers to the arch angle of AAPF roof, rather than the angle between beam joints. It should be pointed out that other structural parameters of the beam joint remained consistent when studying the effect of arch angle or bolt diameter.

Table 1. Statistics of joint parameters.

No.	Diameter of Bolt (mm)	Angle of Arch ($^\circ$)	Sectional Size of Beam (mm)	Sectional Size of Connector (mm)
SJ-A	8	108	H203 $\times$ 106 $\times$ 11 $\times$ 11	2C181 $\times$ 47.5 $\times$ 5 $\times$ 10
SJ-B	14	108	H203 $\times$ 106 $\times$ 11 $\times$ 11	2C181 $\times$ 47.5 $\times$ 5 $\times$ 10
SJ-C	20	108	H203 $\times$ 106 $\times$ 11 $\times$ 11	2C181 $\times$ 47.5 $\times$ 5 $\times$ 10
SJ-D	20	90	H203 $\times$ 106 $\times$ 11 $\times$ 11	2C181 $\times$ 47.5 $\times$ 5 $\times$ 10
SJ-E	20	126	H203 $\times$ 106 $\times$ 11 $\times$ 11	2C181 $\times$ 47.5 $\times$ 5 $\times$ 10

2.2. Testing Plan

The equipment for the test loading was basically consistent with the joint test [22], as shown in Figure 3a. The load structure mainly comprised a boundary frame, hinge support, lifting jack, as well as data acquisition and loading control instruments. In the experimental process, the two specimen ends were tightly connected to the hinged support first. Subsequently, as displayed in Figure 3b, the specimen center was imposed with a vertical concentrated force via a jack. With the utilization of the above-mentioned loading approaches and support forms, the boundary condition simulation under vertical load was possible for the AAPF beam joints, so that the effectiveness of test outcomes could be guaranteed. Over the course of the experiment, the loading speed was regulated by the loading control instrument. In this test, the speed of loading was 1 mm/min.

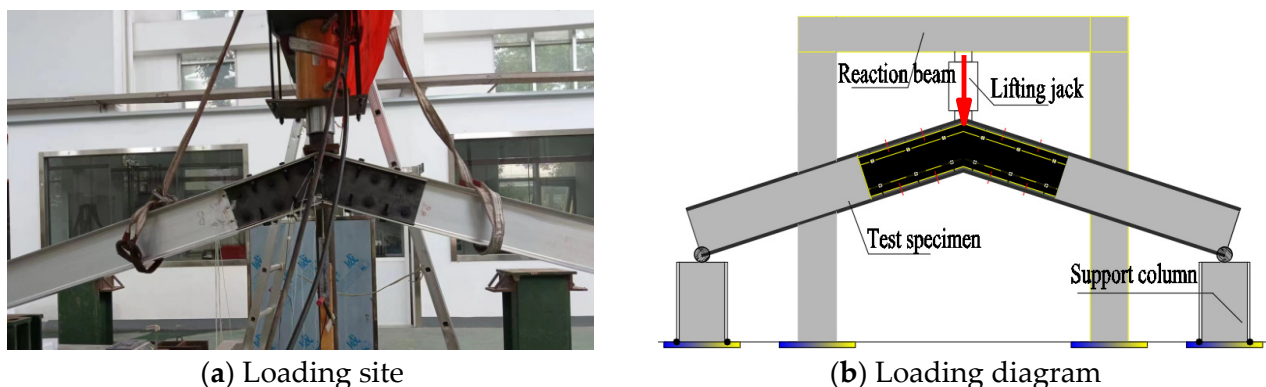


Figure 3. Schematic diagram of test loading.

Based on the force transmission mechanism of the researched beam joints in the vertical concentrated load setting, and combined with the type of component section, the experimental measurement scheme shown in Figure 4 was adopted. In the experimental process, a data acquisition instrument was utilized for documenting the specimen displacement and strain data at every moment.

To obtain the strain variation patterns of the I-beams and C-type steel connectors in the vertical load setting, 10 strain gauges were arranged on various cross-sectional parts, as displayed in Figure 4a. Five strain gauges (numbered 1–5) were arranged uniformly on the H-shaped I-beam along the cross-sectional height, which were adopted for measuring the strain development law for the entire beam cross-section during loading. Exploiting the same principle, we evenly arranged 5 strain gauges (numbered 6–10) along the section height of the C-shaped channel steel connector.

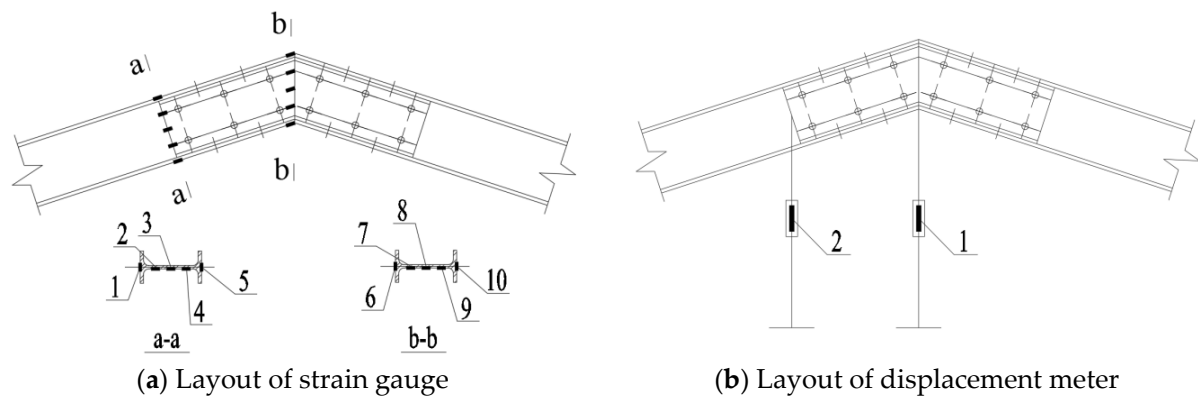


Figure 4. Schematic diagrams for measurement.

As shown in Figure 4b, two displacement meters were respectively arranged, with one being placed at the lower flange of the I-beam for recording the displacement changes at the loading point. The other meter was placed at the end of the C-type connector for documenting the displacement alterations at the joint domain edge.

2.3. Material Property Test

Similar to the beam-column joint, the beam-beam joint specimen comprised the H-shaped 6061-T6 [23] aluminum alloy I-beam and the Q235 steel double-groove connector. Samples from identical batches of metal utilized in the experimental members were taken [24]. The material properties test results from previous research results can be used, as shown in Table 2.

Table 2. Mechanical characteristics of materials.

Material	Yield Strength MPa	Tensile Strength MPa	Elastic Modulus GPa
Aluminum alloy	239	264	70.5
Steel	235	360	206
Bolt	887	992	204

3. Test Results

3.1. Analysis of Destructive Patterns

In the case of bolted joints, the size of the bolt diameter will have an impact on the joint stress state [22]. Figure 5 depicts the state of the wall of the bolt hole in the aluminum alloy I-beam after loading and failure of beam joints that varied in diameter. When the diameter of the bolt was 8 mm, there was an obvious crushing failure on the wall of the bolt hole [22]. With the bolt diameter being 14 mm, some walls of bolt holes exhibited obvious squeezing, whereas some walls exhibited no obvious compression. When the bolt diameter was 20 mm, the wall of the bolt hole was intact and undamaged. According to the analysis results, it can be concluded that when a larger bolt diameter is adopted, the bolt hole wall will not experience compression damage.

Figure 6 presents the damage forms of beam-beam joint specimens with varying arch angles [22]. When the arch angle of the AAPF was 90 degrees, the web plate of the groove connection of the beam-beam joint underwent tearing failure, and the beam top flange underwent warping. When the arch angle was 108 degrees, the beam-beam joint showed a groove-shaped connector tearing along the central flange and web plate. With an arch angle of 126 degrees, the beam joint underwent local buckling failure of the beam at the edge near the joint.

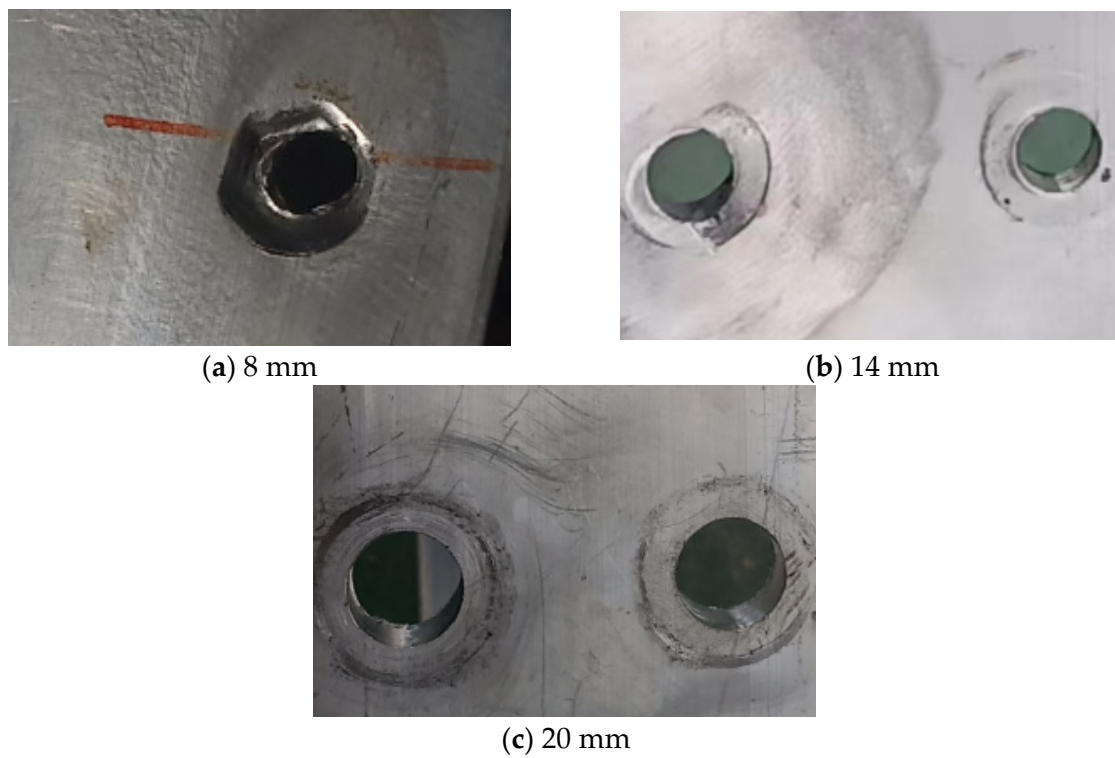


Figure 5. The influence of bolt diameter on failure mode.

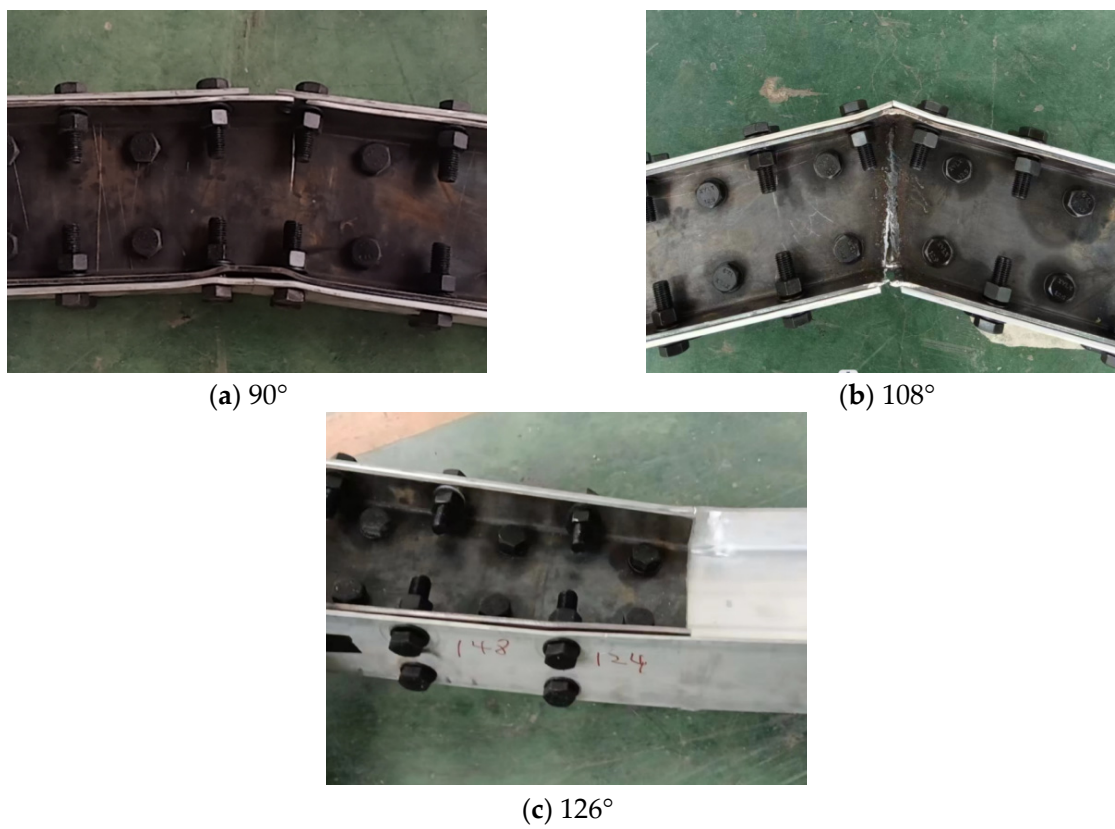


Figure 6. Failure modes of joints with different angles.

3.2. Distribution of Strain

From research on the strain distribution state of the entire cross-section of H-shaped beams and C-shaped connectors, the strain results obtained from experiments along the height distribution of the cross-section for each specimen are summarized in Figure 7. In Figure 7, F_u represents the ultimate load. Based on the strain graph curves under different loads, it can be concluded that (1) for every specimen, the cross-sectional strain distributions were fundamentally consistent between the channel steel connectors and the aluminum alloy beams. This is attributable to the fundamentally consistent mechanism for force transfer in every specimen. (2) Obviously, since the aluminum alloy beams were primarily subjected to bending moments under vertical loads, their overall strain tended to be greater on the beam flanges, while it was less on the beam web. (3) In the case of the channel connector, the strain was greatest at the intersection of the lower and upper flanges and the web, while it was comparatively smaller between the flanges and the web. This is because the channel type connector mainly bears shear force near the loading point. (4) Due to unpredictable errors in some strain gauges during the loading process of the specimens, some test structures underwent peculiar changes. However, these peculiar data will not affect the regularity of the experimental results in this section.

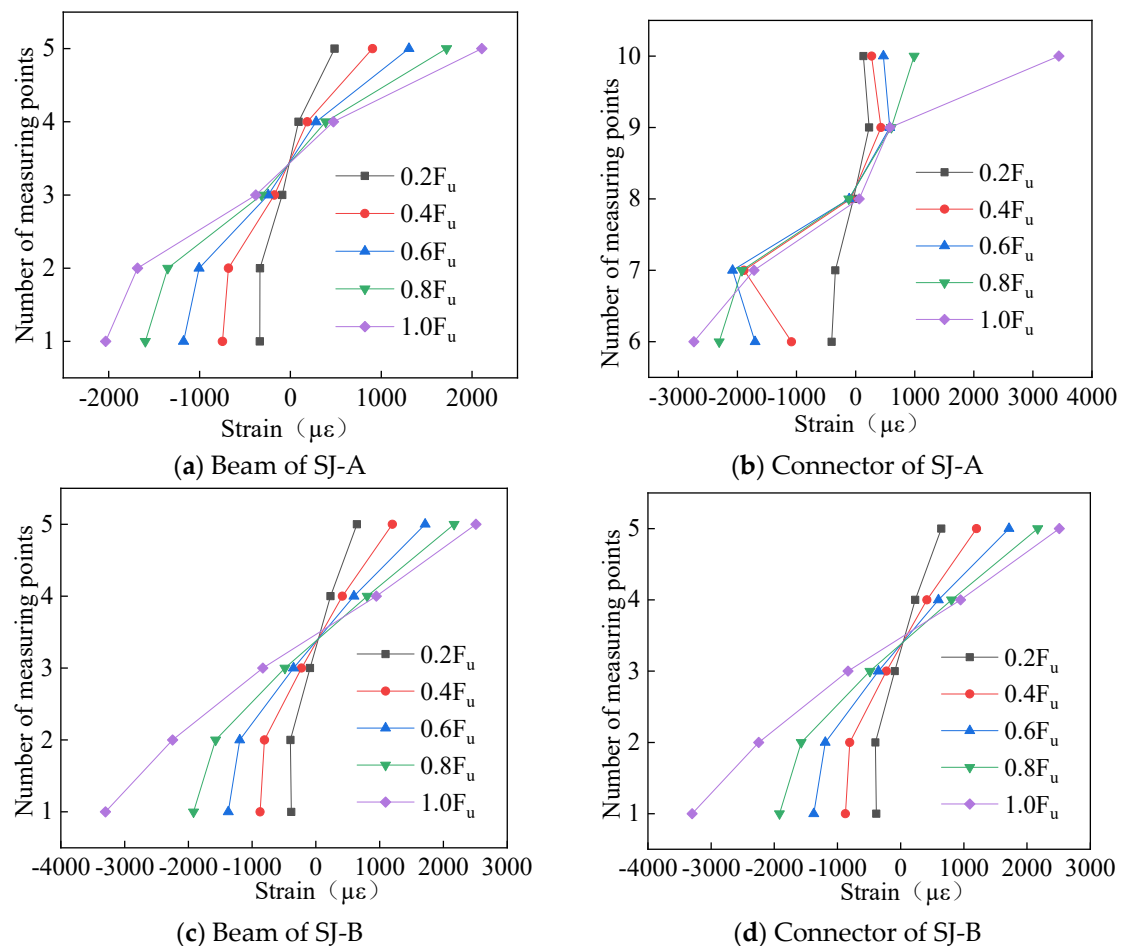


Figure 7. Cont.

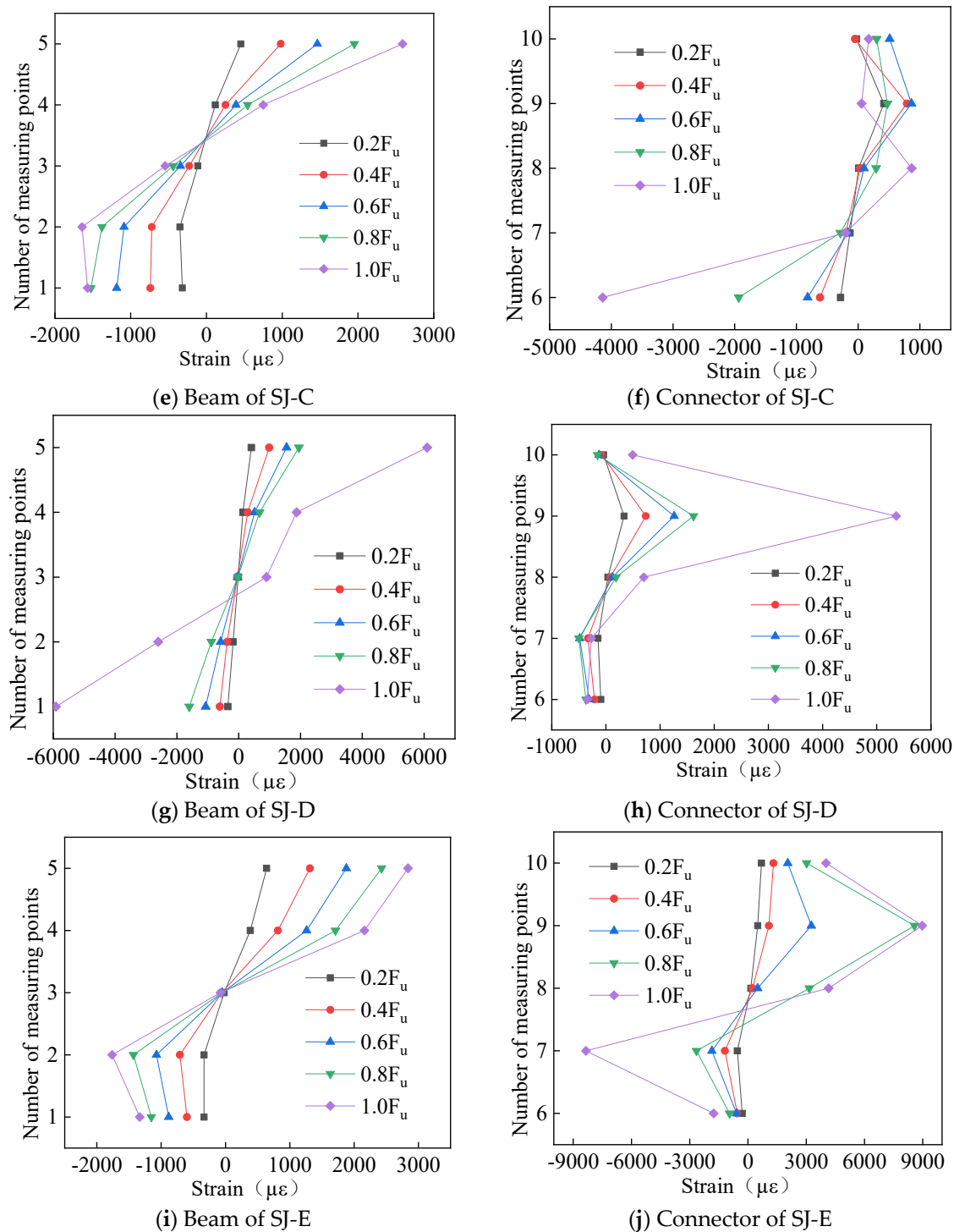


Figure 7. Schematic diagram of strain distribution.

Basically, the pattern of beam strain distribution indicated that when vertical load was applied, the specimen and groove connection were principally subjected to the bending moment and shear force, respectively. This is because the vertical load acted on the center of the groove connector, causing shear force to occur in the groove connector. Then, the shear force was gradually transferred to the H-shaped beam through the connection domain and converted into bending moment action.

3.3. Load-Deformation Curve

Figure 8 shows the load displacement plots for the investigated portal frame beam joints that varied in arch angle and bolt diameter when vertical load was imposed. These load displacement plots almost comprised three phases, namely, elastic, yield, and degradation. According to these three phases, the load displacement plots were examined in detail below under diverse arch angle and bolt diameter settings.

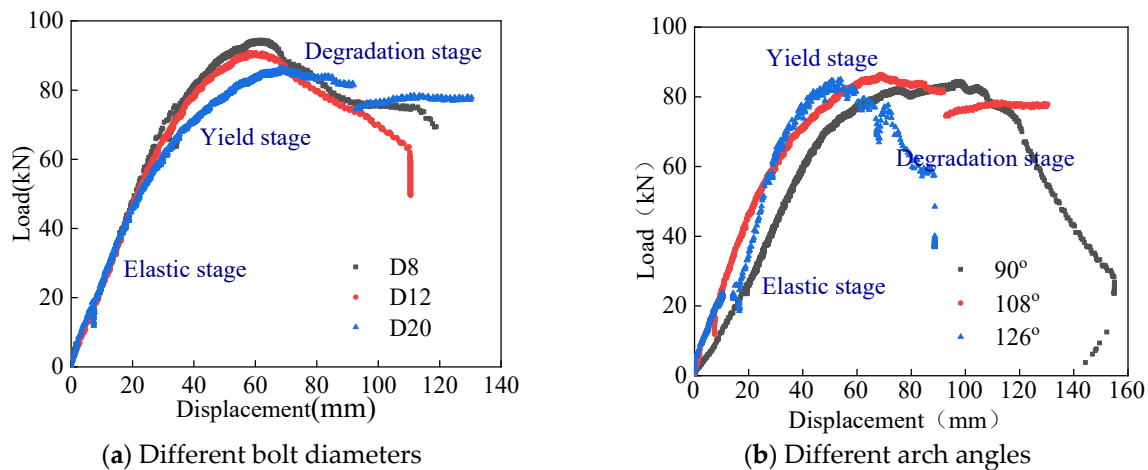


Figure 8. Load-displacement curve.

The load-deformation curves of varying diameters are shown in Figure 8a. During the elastic stage, bolt groups with different diameters of bolt could effectively transmit the load of the joint domain, so the load-deformation curves with different diameters of bolt basically overlapped during the elastic phase [22]. When the joint began to enter the yield state (with a yield load of 60 kN and a yield displacement of approximately 28 mm), the load-deformation curves of varying diameters of bolt gradually showed separation. With the diameter of the bolt increasing from 8 mm to 12 mm, the ultimate load decreased from 95 kN to 90 kN, and the ultimate displacement decreased from 59 mm to 56 mm, with relatively small changes. With the bolt diameter of 20 mm, the ultimate load and ultimate deformation were 82 kN and 80 mm, respectively. The reason for the above phenomenon is that when the bolt diameter is 8 mm, the shear capacity of bolts can meet the load transfer requirements of the joint [22]. Moreover, the increased bolt diameter did not increase the ultimate load of the joint, but instead weakened the beam section due to the large hole wall, thereby lowering the ultimate load of the joint.

Figure 8b portrays the load displacement against the arch angle. In the first stage (elastic stage), the load deformation graphs basically coincided, as the arch angle was enlarged from 90 to 108°. Besides, a slight decline was noted between the plastic and degradation phases. With the elevation in the arch angle to 126°, the load displacement graphs evidently differed between the three phases. To be specific, the specimen stiffness and ultimate bearing capacity presented a marked increased trend when vertical load was applied, with the ultimate bearing capacity increasing by 30% and the ultimate displacement decreasing by 35%. The cause of the above-mentioned phenomenon refers to the fact that under the condition that the angle of the arch elevates to a certain extent, the load on the beam from the vertical force alters from mostly bending to compression bending. To a great extent, pressure (axial load) can enhance the bending capability of the beam, which can thus lower the vertical displacement that resulted from the bending moment.

4. Establishing Numerical Models

4.1. Information of the Model

According to the shape of the AAPF beam joint, a numerical model of the joint was established (Figure 9a). The dimensions of the numerical model were strictly the same as the

test specimens, aiming to demonstrate the effectiveness of the model by comparing it with the experimental results [22]. The components of the joint used solid units (C3D8R units). In the model, the I-beam, double C-shaped connection pieces, and bolts were classified [22]. The contact relationship was assessed between the bolts, H-shaped aluminum alloy beams, and C-shaped connection piece, where “hard contact” was used in the normal direction and “friction contact” was used in the tangential direction (friction coefficient was 0.3). We simulated the bolt pre-tightening force by applying axial compression force to the bolt, with an applied compression force of 18 kN. Hinge constraints were set on the aluminum alloy beam end side of the beam joint specimen with the purpose of obtaining displacement and rotation on the aluminum alloy beam end side. Straightforward identification of the computational precision and velocity was possible using the finite element mesh division. For the proposed model, its mesh division is depicted in Figure 9b.

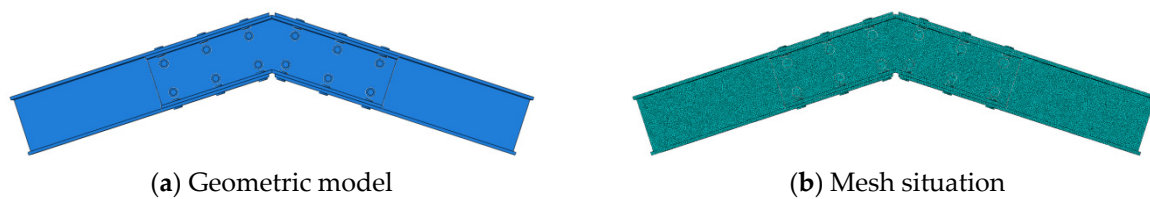


Figure 9. Numerical model of the joint.

According to previous research results, the constitutive relationship model shown in Figure 10 was directly adopted [4,25].

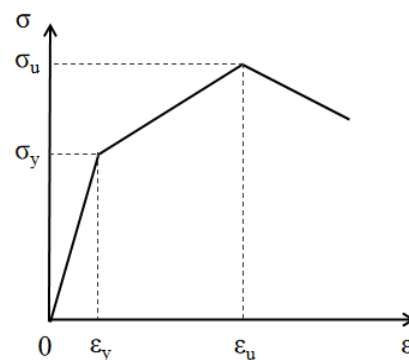


Figure 10. Material model.

Due to the fact that there was almost no bolt slip phenomenon during the experiment, the nut and screw were created as a whole, and a simplified bolt model was obtained by establishing a plane graph and rotating it 360 degrees. We simulated the torsional moment borne by the bolt by directly applying a preload force to the bolt element. Based on the loading protocol along with the test specimen constraints, the boundary conditions for the proposed model almost comprised the following three dimensions, namely, symmetric constraints, fixed-end constraints, as well as contact settings. Hinge constraints were set on the aluminum alloy beam end side with the purpose of obtaining displacement and rotation on the aluminum alloy beam end side. Symmetric constraints were imposed on the central web plate section according to the specimen’s geometric symmetry. Considering the presence of relative sliding between various specimen components, establishing a “limited slip” contact was necessary. Besides, establishment of a normal “hard contact” only was required for the bolt rod and hole wall, while consideration of friction was necessary in the case of other contacts. To be specific, here, a tangential “Coulomb friction” should be set up, with a coefficient value of 0.3.

4.2. Model Validation

With the use of the above methods, the numerical analysis models of SJ-A and SJ-C were established, and the results of the simulation were compared with the results of the test, which can be found in Figure 11 and Table 3. By comparing the experiment and numerical simulation results, it was found that the tangent slope of the load-deformation curve in the elastic stage of the numerical model was slightly higher than the test result. This was because there were no defects in the joints in the numerical model, but defects could not be avoided during the production and loading process of the test specimen. In the next stage (plastic stage), the load-deformation curve of the numerical simulation was relatively smooth, while the load-displacement curve of the experiment showed an obvious strength degradation phenomenon. This was because the ideal elastic-plastic model of material was used in the numerical model, without considering the degradation characteristics of the material. Overall, the load-deformation curves of the test and numerical model were in good agreement, and the error of the ultimate load and ultimate displacement was within 5%.

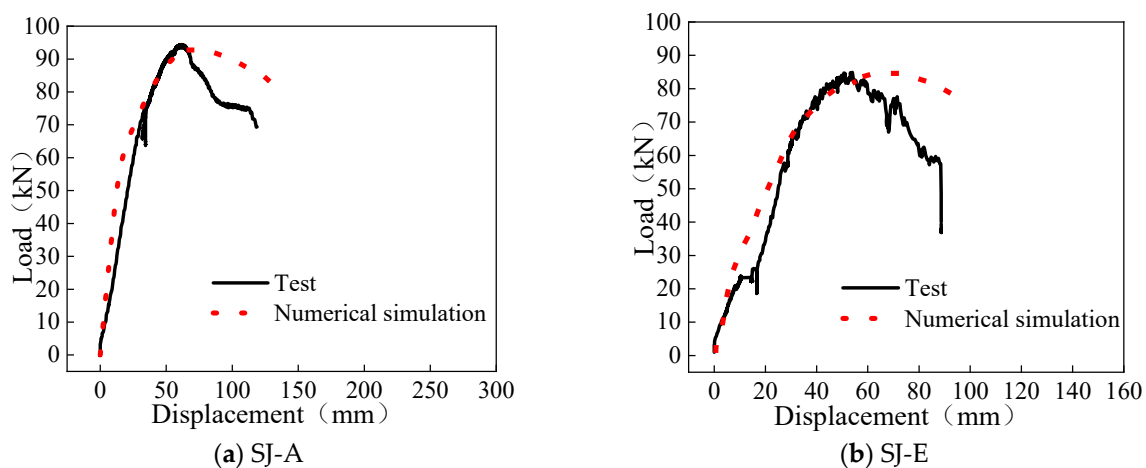


Figure 11. Comparison of load-displacement curves.

Table 3. Comparison of numerical model results with test results.

Specimen	Source	Deformation (mm)	Load (kN)
SJ-A	Test	64.4	94.1
	FEA	68.2	95.4
SJ-E	Test	53.9	84.9
	FEA	54.4	83.2

5. The Influence of the Arch Angle

5.1. Information of Basic Model

Numerical simulation with different parameter analysis is often used as a highly effective experimental supplementary analysis method [26]. To facilitate model classification, the definition of the basic model is introduced here. The subsequent changes in parameters were based on the basic model. The size of the cross-section was $H200 \times 100 \times 8 \times 10$ for the H-shaped rod in the basic model, whereas it was $2C180 \times 46 \times 5 \times 10$ for the steel connector. The arch angle setting was 106° , while the bolt diameter and grade were 20 mm and 10.9, respectively. Besides, the material for the H-shaped rod was 6061-T6 aluminum alloy, whereas Q235 steel was used for the groove-type connector. Based on the basic model, we established numerical analysis models with different arch angles and geometric parameters to analyze the changes in load-bearing performances of AAPF beam-beam

joints under different arch angles, and to obtain the recommended optimal arch angle for AAPF beam joints. The detailed parameters of the model are listed in Table 4. For structures, the degradation of load-bearing performance of joints is closely related to stiffness changes, so the main comparison will be made between the elastic stiffness and yield stiffness of joints [27,28].

Table 4. Parameters of numerical models.

Specimen	Bolt Diameter (mm)	Arch Angle (°)	Bolt Preload (N·m)	Bolt Clearance (mm)
SJ-1	20	106	20	0.4
SJ-2	20	112	20	0.4
SJ-3	20	118	20	0.4
SJ-4	20	124	20	0.4
SJ-5	20	130	20	0.4
SJ-6	20	136	20	0.4

5.2. Vertical Load

The mechanical performance of joint specimens under vertical load was preliminarily studied by performing the bearing capacity test at different arch angles. An analysis model with an arch angle of 106°–136° was established to analyze the effect of different arch angles on the beam-beam joints of AAPFs. The calculation results are summarized in Figure 12 and as follows:

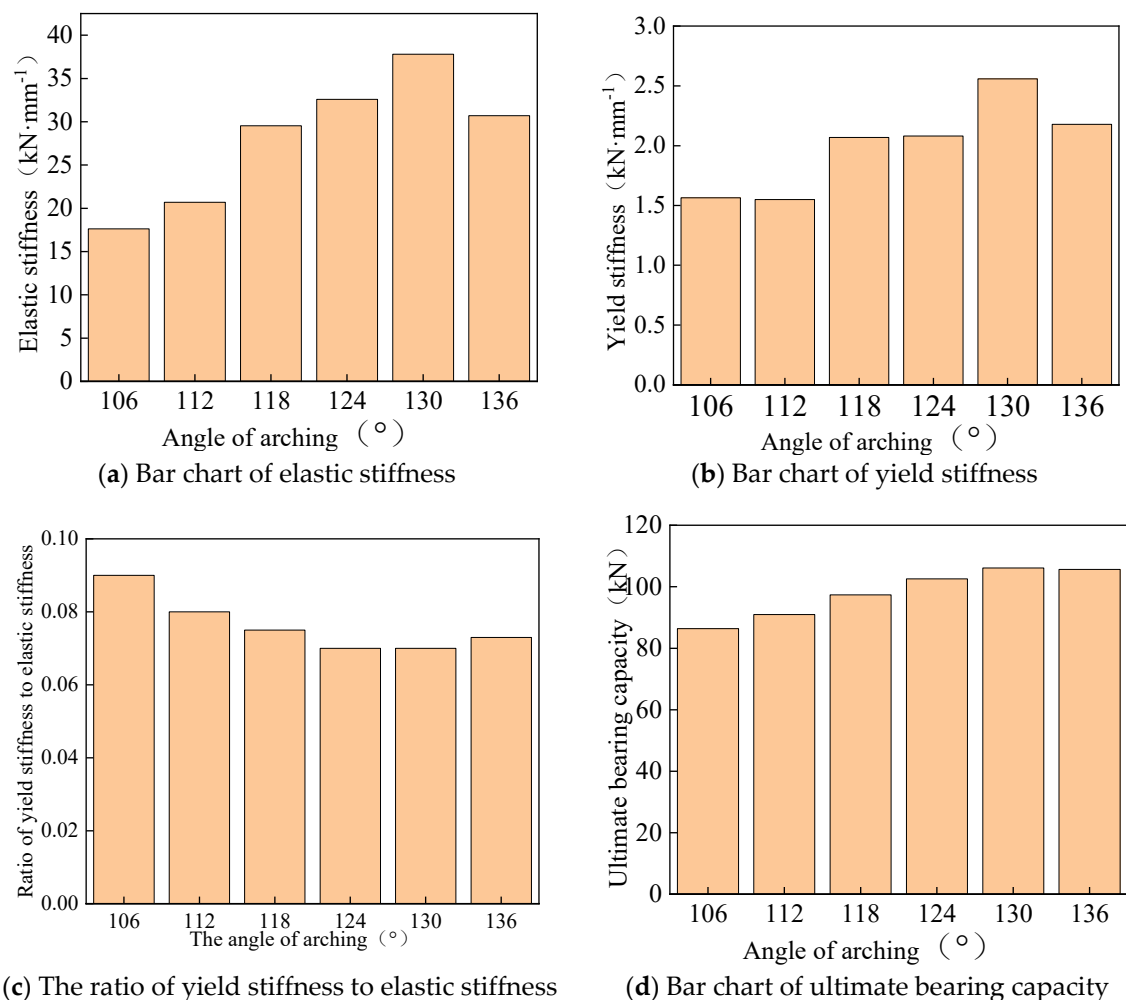


Figure 12. The effect of arch angle under vertical load.

(1) The elastic stiffness of specimens with different arch angles in the elastic stage under vertical load (Figure 12a) showed a variation pattern of first increasing and then decreasing. As the arch angle increased (106° to 130°), the vertical elastic stiffness increased by two times, and when the arch angle increased from 130° to 136° , the vertical elastic stiffness decreased by 23%.

(2) With the increasing arch angle, the stiffness of the beam joint during the yield stage under vertical load also exhibited a trend of first increasing and then decreasing, as shown in Figure 12b. When the arch angle increased (106° to 130°), the vertical elastic stiffness increased by 1.6 times, and when the arch angle increased from 130° to 136° , the vertical elastic stiffness decreased by 18%.

(3) When monitoring the damage situation of joints, the change in their stiffness was the focus of attention, as shown in Figure 12c. As shown in the figure, when the arch angle changed, the ratio of yield stiffness to elastic stiffness of specimens under vertical force change was relatively small, with a range of 0.08–0.09.

(4) With the increased arch angle, the ultimate load of the specimen under vertical load gradually increased. As the arch angle increased from 106° to 136° , the vertical ultimate bearing capacity increased by 1.2 times, as displayed in Figure 12d.

From the above analysis, it can be concluded that under vertical force, when the arch angle of AAPF increased, the ultimate bearing capacity of this joint showed a change pattern of first increasing and then decreasing; that is, the arch angle had an extreme point. The reason for this was because when the arch angle increased, the joint mainly bore the axial force under vertical load (the bending moment was minimized).

5.3. Horizontal Load

In AAPFs, in addition to vertical loads, beam joints also bear the action of horizontal loads. The impact of arch angle on the load-bearing capacity of beam-beam joints should not only consider the variation pattern of joints under vertical load, but also analyze the effect of arch angle on the load-bearing capacity of joints under horizontal load. The comparison results are shown in Figure 13 and as follows:

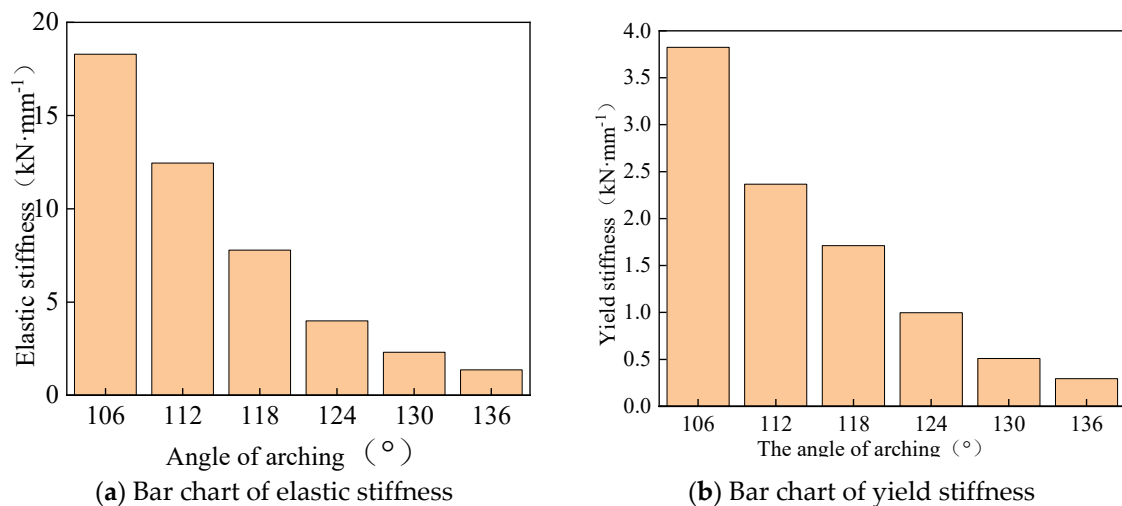


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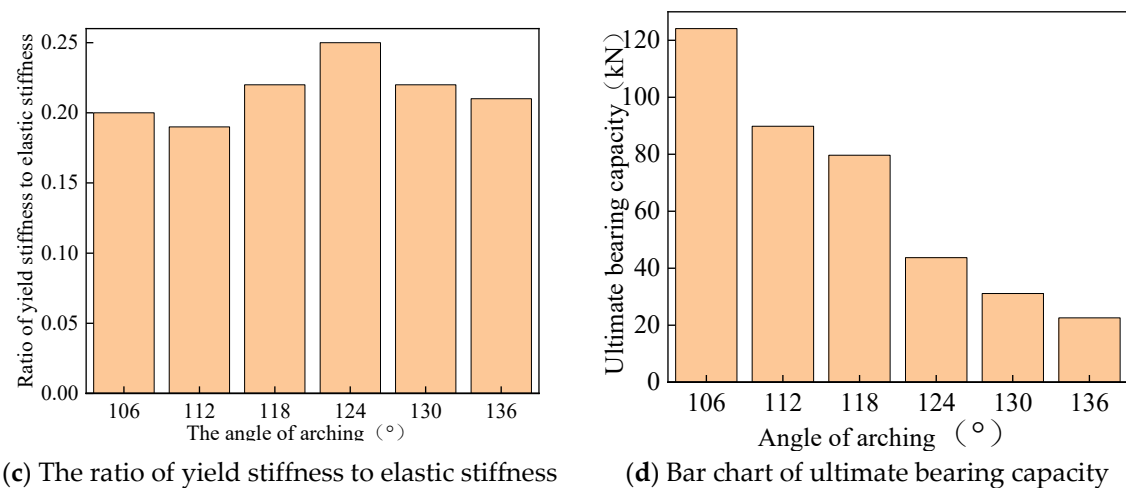


Figure 13. The influence of the arch angle under horizontal load.

(1) The elastic stiffness of the beam-beam joint under horizontal load (Figure 13a) gradually decreased due to the increase in the arch angle. With the increase of the arch angle from 106° to 136°, the horizontal elastic stiffness decreased by 92%.

(2) The stiffness of the yield stage of the beam-beam joint under horizontal load gradually decreased with the increase in the arch angle. When the arch angle increased (106° to 136°), the horizontal yield stiffness decreased by 87%, as shown in Figure 13b.

(3) The ratio of yield stiffness to elastic stiffness of joints under horizontal forces is shown in Figure 13c. With the change in arch angle, the ratio of yield stiffness to elastic stiffness was 0.20–0.25.

(4) The ultimate horizontal force of beam-beam joints gradually decreased with the increasing arch angle. Under the condition that the arch angle increased from 106° to 136°, the horizontal ultimate bearing capacity decreased by 82%, as shown in Figure 13d.

6. Safety Monitoring of Beam-Beam Joints

The safety monitoring of AAPF beam-beam joints consists of two steps, namely, displacement monitoring and frequency monitoring. Displacement monitoring is used to determine the safety of the structure, followed by frequency monitoring of the degree of damage to joints.

6.1. Displacement Monitoring

The displacement monitoring layout points of AAPF beam-beam joints are shown in Figure 14. L in Figure 14 represents the radius of the joint domain. We installed a displacement sensor at the center of the joint domain and placed one on both sides (left and right) $2L$ away from the center. The method for calculating the vertical and horizontal deformation of the beam-beam joint is:

$$f = f_M - \frac{f_L + f_R}{2} \quad (1)$$

$$v = v_M - \frac{v_L + v_R}{2} \quad (2)$$

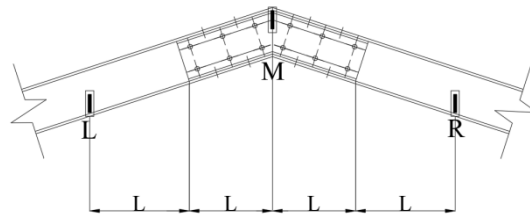


Figure 14. Measurement of joint displacement.

We established a sufficient numerical analysis model based on the commonly used geometric dimensions of AAPFs and summarized the vertical and horizontal displacement limits (Table 5) of the beam-beam joint of AAPFs based on the results.

Table 5. Limit values of displacement.

The Angle of Arching	106°	112°	118°	124°	130°	136°
Limit value of vertical displacement	1/47	1/50	1/54	1/36	1/30	1/26
Limit value of horizontal displacement	1/43	1/43	1/45	1/52	1/59	1/62

6.2. Frequency Monitoring

Frequency monitoring [29,30] is currently a highly accurate method in the area of building structures. From the previous study, it is known that the yield stiffness of the beam-beam joint is much lower than that at the elastic stage. Thus, to research the effect of natural frequency on stiffness, numerical analysis models with different stiffnesses were established, and the frequency variation pattern is shown in Figure 15. As the joint stiffness decreased, the first four natural frequencies of the joint gradually decreased. When the stiffness of the joint decreased from elastic stiffness to 0.1, the first natural frequency reduced by 70 Hz, the second frequency reduced by 66 Hz, the third frequency reduced by 443 Hz, and the fourth frequency reduced by 196 Hz. Due to the fact that the maximum amplitude of natural frequency variation was in the third order, the deformation of the third-order vibration mode should be mainly monitored during health monitoring.

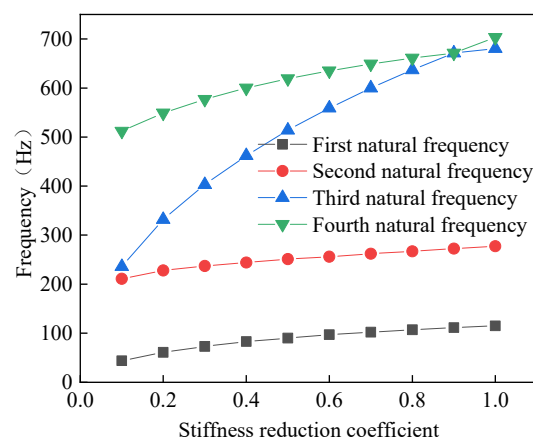


Figure 15. The effect of stiffness reduction on frequency.

From the previous analysis, it can be seen that under vertical loads, joint yielding occurred when the stiffness decreased to 10%, and under horizontal loads, joint yielding occurred when the stiffness decreased to 20%. The final decision was to reduce the stiffness to 20% at the third natural frequency, as the critical frequency value of the joint. According to the commonly used cross-sectional dimensions of AAPFs, numerical analysis models of beam-beam joints with different cross-sections were established. Then, we extracted the natural frequencies of each model at the yield stiffness, as shown in Table 6.

Table 6. Limit value frequencies.

The size of the cross-section	200 × 100 × 10 × 10	220 × 110 × 11 × 11	240 × 120 × 12 × 12
Limit value of frequency (Hz)	221	243	265
The size of the cross-section	260 × 130 × 14 × 14	280 × 140 × 16 × 16	300 × 150 × 18 × 18
Limit value of frequency (Hz)	287	309	332

7. Conclusions and Prospects

This article mainly described research on the beam-beam joints of AAPFs, exploring the bearing performance and health monitoring methods of this joint. The following conclusions were drawn:

(1) The test results showed that the load-displacement curve of the beam-beam joint was mainly divided into three phases: elastic phase, plastic phase, and degradation phase. As the diameter of the bolt increased, the vertical ultimate load showed a pattern of first increasing and then decreasing.

(2) With the increased arch angle, the stiffness at the elastic and yield phases of the joint under vertical load showed a pattern of first increasing and then decreasing, while the elastic stiffness and yield stiffness of the joint under horizontal load significantly decreased. The joints exhibited opposite changing trends under vertical and horizontal loads. When involving joints, full consideration should be given to the combined effects of vertical and horizontal loads on the joints, in order to achieve the optimal design of the joints.

(3) A health monitoring method for detecting beam-beam joints through displacement and frequency was proposed. Displacement monitoring was used to determine the safety of the structure, followed by frequency monitoring of the degree of damage to the joints. Due to the fact that the maximum amplitude of natural frequency variation was in the third order, the deformation of the third-order vibration mode should be mainly monitored during health monitoring.

(4) Subsequent research should focus on the load-bearing performance and monitoring methods of the overall structure of AAPFs.

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