Research on post-buckling performance of grid composite members

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Abstract. In this paper, the combination of simulation and experiment is used to study the performance of composite members after buckling. Considering the influence of initial defects on the buckling performance of the members, using the basic theory of contact and friction and the method of nonlinear analysis, the model of the composite members was established by ABAQUS finite element software and analyzed. At the same time, the compression test of the composite member was carried out to verify the correctness of the simulation. Finally, the calculated length coefficient of the composite member are obtained, which lays a foundation for the overall analysis of the long-span space grid structure.

1. Introduction
With the development of economy and the progress of the society, the application of the long-span space grid structure is becoming more common in the engineering. This structure has the advantages of good integrity, high stiffness and good seismic performance. It is widely used in airport, gymnasium, convention center and other buildings [1]. Under the long-term action of equipment excitation and external load, the buckling of the truss members may occur, which may lead to the collapse of the whole structure.

In the design of large span truss structure, the single member is used to replace the actual combined member for stress analysis. Due to the contact and friction between different components, the calculated length coefficient of the composite member is different from that of the euler member with hinge support at both ends, and its post-buckling performance and hysteresis performance are also different from that of the single member. At the same time, the influence of the initial defects on the bearing capacity of the composite members cannot be ignored.

Therefore, it is of great significance to consider the influence of the initial defects and the combination effects between components to study the post-buckling performance of the composite member as well as to calculate the length coefficient and hysteresis model of the composite member.

2. Application of nonlinear theory in ABAQUS

2.1. Material nonlinearity
Material nonlinearity means that the stress-strain relationship of the material is not linear. When using ABAQUS to analyze nonlinear problems of materials, the real stress and real strain of materials must be used for material properties.
Since plastic deformation is incompressible, the relationship between real stress $\sigma$ and nominal stress $\sigma_{\text{nom}}$ is:

$$\sigma = \frac{F}{A} = \frac{F}{A_0 \frac{l}{l_0}} = \sigma_{\text{nom}} \left(\frac{l}{l_0}\right)$$  \(1\)

Where, $F$ denotes the tension or pressure of the test; $A_0$ and $l_0$ are the cross sectional area and the length of the member before stretching; $A$ and $l$ are the cross sectional area and length of the member after stretching.

The relationship between real strain $\varepsilon$ and nominal strain $\varepsilon_{\text{nom}}$ is:

$$\varepsilon = \ln(1 + \varepsilon_{\text{nom}})$$ \(2\)

2.2. Geometric nonlinearity

Geometric nonlinear problems [2] are mainly classified as follows:

(1) Small strain and large displacement, such as collapse of grid structure;
(2) Large strain and large displacement, such as metal forming process;
(3) Changes in load or boundary conditions.

2.3. Nonlinearity of boundary conditions

Contact problem [3] is a typical nonlinear boundary condition problem. The following points should be noted when dealing with contact issues using ABAQUS:

(1) If one of the two contact surfaces is rigid and the other is flexible, the main contact surface must be rigid and the secondary contact surface must be flexible;
(2) Contact with the main surface must be continuous. If finite slip is selected, the contact surface should have no sharp angle;
(3) The normal direction of a pair of contact surfaces must be opposite.

3. Study on calculated length coefficient of composite member based on ABAQUS

3.1. The establishment of composite member model

In this paper, the assembly of basic components is used to build a three-dimensional model of bolt ball, sealing plate, bolt sleeve and single member. The rods with length of 439mm, 507mm and 831mm were respectively established, and the defects of the rods were all $L/1000$[4].

Assemble components and set interactions. Binding constraints are set between the bolt-ball and the steel tube-sealing plate. Friction contact is between the sleeve-sealing plate and the sleeve-bolt ball, the friction coefficient is 0.15, and the normal direction is hard contact. In order to facilitate the loading of bolt ball, two reference points RP-1 and RP-2 were established to make them coupled with the bolt ball hemisphere.

Four analysis steps are set for compression analysis of the composite member [5]:

Analysis step 1: apply an initial load to the bolt, which is much smaller than the prestress of the bolt. The purpose is to make the calculation process easier to convergence. Therefore, set the initial load to 10N;
Analysis step 2: increase the load on the bolt to 100000N;
Analysis step 3: fix the bolt to its current length;
Analysis step 4: apply compression displacement of the composite member.

Finally, the combined member is meshed, and the element type is selected as eight-node linear hexahedral element with non-coordinated mode. The model of the composite member is shown in figure 1.

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3.2. Numerical simulation results of buckling composite member under compression

Due to the influence of initial bending, during the continuous loading process, the combined member under axial compression is constantly bent. When the applied load exceeds its ultimate bearing capacity, instability will occur and the bearing capacity will decrease rapidly.

Displacement is applied to the end of different lengths of composite rods to make them bear pressure. The Load-Displacement curve of rod end is shown in figure 2. When the displacement of the rod end is 1.27833mm, the load of the rod end reaches the maximum value, which is 58735.80078N. When the length of steel tube is 507mm and the displacement of the pole end is 1.16825mm, the load reaches the maximum value, which is 65811.89844N. When the length of steel tube is 439mm and the displacement of the pole end is 0.99425mm, the load reaches the maximum value, which is 65811.89844N.

By comparing the Load-Displacement curve of the rod end of three composite members of different lengths, we can know that the overall stability ultimate bearing capacity of the members decreases with the increase of slenderness ratio, and the smaller the overall stability ultimate bearing capacity of the members, the more likely the overall instability failure will occur.

3.3. Study on length coefficient of composite member based on simulation

The expression of the overall stable ultimate bearing capacity of the axial pressed round steel tube under the elastic limit state is as follows.

\[
N_u = \frac{f_e + \frac{\pi^2 E}{\lambda^2} + A \frac{\pi^2 E}{\lambda^2} \delta_0 - \left( f_e + \frac{\pi^2 E}{\lambda^2} + A \frac{\pi^2 E}{\lambda^2} \delta_0 \right)^{\frac{1}{2}} - 4 \frac{\pi^2 E}{\lambda^2} f_e}{2} \times A
\]  

(3)
Where: $\lambda$ is the length-to-thinness ratio of components; $W$ is the elastic resistance moment of section; $f_y$ is the yield strength of the material; $E$ is the elastic modulus of the material; $\delta_0$ is the initial bending deflection value; $A$ is the gross cross section area of members under axial compression.

According to the expression of the overall stable ultimate bearing capacity under the elastic limit state of the axial pressed round steel tube, the calculated length coefficient of the composite member can be derived [6].

$$\lambda = \frac{\mu l}{i} = \sqrt{\frac{I}{A}}$$

(4)

Where: $\mu$ is the calculated length coefficient of the combined member; $l$ is the calculated length of the combined member, which represents the distance from the center of the ball to the center, and the lengths are respectively 999mm, 675mm, 607mm; $i$ is the radius of gyration; $I$ is the moment of inertia.

The length of steel tube is 831mm, and the calculated length coefficient is $\mu=1.067744056$; The length of steel tube is 507mm, and the calculated length coefficient is $\mu=1.061357634$; The length of steel tube is 439mm, and the calculated length coefficient is $\mu=1.058141827$.

4. Experimental study on the stability of composite member

4.1. Test materials and equipment

Composite members (two composite members with steel tube length of 439mm, 507mm and 831mm respectively); Press (model: yE-200A, maximum load: 200 tons); Strain gauge; Terminal; Wire; Data acquisition instrument; Multimeter; Displacement meter; Steel plate; Hemispherical groove; Ten tons of pressure sensors.

4.2. Test scheme and phenomenon

After polishing and decontamination, the rods are assembled. The total length of the assembled rods is 707mm, 775mm and 1099mm respectively.

Six strain gauges are arranged for each hexagonal socket, and one transverse and one longitudinal strain gauge is arranged for every 90 in the middle of the steel tube [7]. A total of eight strain gauges are arranged for each steel tube. Two displacement meters are arranged in the middle of the member and the lower steel plate, and the included Angle is 90. The arrangement of the displacement meter and strain gauge in the middle of the member is shown in figure 3.

Connect the data acquisition instrument to load and collect data. The loading device is shown in figure 4.

![Figure3. The arrangement of the displacement meter and strain gauge](image3)

![Figure4. The loading device](image4)

It can be found that the buckling shape of the composite bar presents the shape of half sine wave, which conforms to the simulation results of ABAQUS. The shape of the combined bar after buckling under pressure is shown in figure 5.
4.3. Test result

After processing the experimental data, the Load-Displacement curve of the rod end of three combined rods with different lengths was drawn, as shown in figure 6.

![Load-Displacement curve of the rod end of the composite member](image)

By observing the Load-Displacement curve of the composite member, it can be found that the load of the composite member with the length of steel tube 831mm reaches the maximum value of 61892N when the displacement of the member end reaches 2.24mm; When the displacement of the steel tube end reaches 2.15mm, the load reaches the maximum value of 71248N; When the length of steel tube is 439mm and the displacement of the rod end reaches 1.71mm, the load reaches the maximum value of 74600N.

4.4. The comparison between the experimental results and the simulation results

The test value and simulation value of the displacements and loads curve at the end of three kinds of composite members are compared and analyzed, as shown in figure 7.

Combined with image, the maximum load of the simulation results were greater than the test result, but the shape of the two curves and the trend is basically the same. It shows that the parameters and calculation methods set in the simulation process are basically correct, and the contact and friction between components are also basically reasonable. The experimental results are in good agreement with the simulation results.
4.5. Study on length coefficient of composite member based on test
The determination method for the calculated length coefficient is shown in section 2.3 of this paper. According to the test data, the calculated length coefficient of the combined member with the length of steel tube 831mm is $\mu = 1.064258417$; The calculated length coefficient of the combined member with the length of steel tube 507mm is $\mu = 1.059415268$; The calculated length coefficient of the combined member with the length of steel tube 439mm is $\mu = 1.055436274$.

It can be seen that the calculated length coefficient of the composite member is about 1.06 in both simulation and test.

5. Conclusion
In this paper, the basic theory of contact and friction and the method of nonlinear analysis are applied, and the influence of initial defects on the performance of the composite member after buckling is fully considered. ABAQUS software is used to establish the model of the composite member and simulate the combination effect between components. At the same time, the compression test is carried out on the basis of numerical simulation, and the correctness of the simulation is verified. The calculated length coefficient of the composite member is obtained. Due to the influence of sleeve and friction, the ultimate bearing capacity of composite member is reduced. The results show that the calculated length coefficient of the composite member is about 1.06.

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