Assessment of the global stability of three-limbed steel tube latticed column using finite element modelling

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Abstract. In order to study the stability performance of the three-limbed steel tube latticed column, the finite element numerical analysis method based on the structural stability theory is adopted. Firstly, the linear analysis of the three-limbed steel tube latticed column without diagonal lacing bar is carried out, and the calculation method of elastic buckling load considering the influence of shear deformation is obtained. Then, the elastic buckling analysis and elastoplastic buckling analysis three-limbed steel tube latticed column with diagonal lacing bar are carried out. The elastic buckling load and elastoplastic buckling load of three-limbed steel tube latticed column with diagonal lacing bar are studied when only the global initial geometric defects, only the member initial geometric defects, and both kinds of defects are considered at the same time. The results show that the direct finite element analysis method can be used to calculate the elastic buckling load of three-limbed steel tube latticed column with diagonal lacing bar, and the error is 6.67%. In the elastic analysis of three-limbed steel tube latticed column with diagonal lacing bar, the column global stability mainly depends on the global initial geometric defects, and the member initial geometric defect is negligible. And when two kinds of defects are applied at the same time, the structural buckling load is reduced by less than 0.20% compared to the global initial geometric defects. In the elastoplastic analysis, the column global stability is determined by both the global initial geometric defect and the member initial geometric defect. When both defects are applied at the same time, the structural buckling load decreases by less than 0.65% compared to the global initial geometric defect only, and 7.60% compared to the member initial geometric defects only. It can be concluded that there is little difference in the overall stability bearing capacity between the two kinds of defects.

1. Introduction

In recent years, with the development of light steel structure, the latticed members with hollow steel pipes as basic components are found in the rigid frame structure system, which are suitable for larger span and higher column. Among them, the spatial latticed columns with circular steel tubes as chord and section as positive triangle have been applied in engineering practice [1]. This kind of spatial latticed structure system has the advantages of simple joint treatment, reasonable stress, large stiffness and steel saving. The stiffness of latticed columns around the real axis is larger, which is similar to that of solid web members; When the latticed column is forced around the imaginary axis, the stiffness around the imaginary axis is small, and the shear deformation caused by lacing and batten elements should be considered, which has a great impact on the stability of the member. At the same time, different from the solid web column, the latticed column needs to consider the global stability and limb stability, so it is particularly necessary to study the special instability problem of latticed columns.

Many scholars have done relevant research on the stability of latticed compression-bending members: Liu et al.[2, 3] found that the current calculation method of latticed members is not reasonable by comparing the previous versions of steel structure design codes, and proposed to unify the calculation formula of latticed members with that of solid web members through example checking; A.G.Razdolsky [4] equivalent the equal section latticed column to the solid web member and carried out the buckling analysis; Eisenberger [5] and Al-Gahtani [6] established the stiffness matrix of variable cross-section beam column element under tension.
compression, bending and torsion; Hong [7] provided a stability analysis method for checking the stability of variable cross-section latticed columns by deriving the equivalent bending and shear stiffness of the column, and applied it to the actual calculation; Deng [8] proved that different batten arrangement has different effects on the conversion slenderness ratio by using the virtual work principle; Tong [9] used the formula of conversion slenderness ratio to derive a new reduction factor, and studied the influence of shear deformation on the column; Wang [10] studied and compared the lace-barred latticed column and batten plate latticed column, and obtained the optimal steel consumption of two different columns by changing the parameters such as the space between the limbs, the geometric size of the batten, the calculated length of the column, etc. Because latticed columns rely on weak battens to resist shear, the global shear stiffness is reduced. And for latticed columns, the influence of shear deformation must be considered in stability checking, that is, the shear stiffness of columns needs to be obtained. However, no effective and feasible method has been put forward in current research, and the influence of initial defects on bearing capacity cannot be ignored.

In this paper, the finite element method is used to calculate the shear stiffness of the three-limbed steel tube latticed column without diagonal lacing bar; Then, the stability performance of three-limbed steel tube latticed column with diagonal lacing bar is compared, which only considers the global initial geometric defects, the member initial geometric defects and the two kinds of defects at the same time, so as to provide the basis for the mechanical performance analysis and structural design of three-limb steel tube latticed column.

2. Linear analysis of three-limbed steel tube latticed column without diagonal lacing bar

Firstly, APDL method is used to establish the finite element model of three-limbed steel tube latticed column without diagonal lacing bar, and the linear analysis is carried out. At the same time, a simple method for obtaining shear stiffness of three-limbed steel tube latticed column without diagonal lacing bar is proposed.

2.1. Computation model

The geometric parameters of three-limbed steel tube latticed column without diagonal lacing bar are shown in Table 1. According to Table 1, the ANSYS finite element models of eight three-limbed circular steel tube latticed columns are established. Beam188 is selected as the member element. The material constitutive relation is linear elasticity, the elastic modulus is 2.06 GPa, and the Poisson's ratio is 0.3. At the bottom, the rigid connection state of steel tube latticed column joints in practical engineering is simulated, and fixed supports are used to constrain all degrees of freedom. The unit shear load of 1 is applied along the X direction at the top of the column, and the structural shear diagram and bending moment diagram are obtained, as shown in Figure 1.

It can be seen from figure 1 that the ratio of shear force shared by the three limbs is about 1/2:1/2√3:1/2√3, the bending moment ratio is about √3:1:1, and the bending moment ratio of the limb bearing the minimum bending moment and the batten is about 1:2, which is consistent with the theoretical stress. Extracting the shear angle γa of latticed column under unit shear force in ANSYS is compared with the unit shear angle γf calculated by theory [11]. The results are shown in Table 1. It can be seen that when the ratio of the slenderness ratio of the limb and the lacing bar λf/λa is between 1.2 and 1.4, the unit shear angle error of them can be basically controlled within 6%, which indicates that the finite element model can better reflect the mechanical properties of the actual structure, and can be used to extract the shear stiffness of the latticed column. The shear stiffness K is the ratio of unit shear force to shear deformation, i.e. $K = 1/\gamma_a$ in this paper.
Figure 1. Model of three-limb ed steel tube latticed column without diagonal lacing bar and its internal force distribution.

Table 1. Comparison of unit shear deformation of three-limb ed steel tube latticed column without diagonal lacing bar.

| Limb (external diameter × internal diameter) (mm) | Lacing bar (external diameter × internal diameter) (mm) | \( l_d \) (m) | \( b \) (m) | \( \lambda d/\lambda b \) | \( \gamma_a \) | \( \gamma_l \) | Error |
|-----------------------------------------------|-----------------------------------------------|---------|---------|----------------|---------|---------|-------|
| 0.36×0.355                                    | 0.18×0.175                                    | 2.2     | 0.9     | 1.21           | 5.95E-08| 6.01E-08| -1.06%|
| 0.32×0.315                                    | 0.16×0.155                                    | 2       | 0.8     | 1.24           | 7.68E-08| 7.01E-08| 8.75% |
| 0.30×0.295                                    | 0.15×0.145                                    | 2       | 0.8     | 1.24           | 9.21E-08| 8.55E-08| 7.11% |
| 0.28×0.275                                    | 0.14×0.135                                    | 2       | 0.8     | 1.24           | 1.12E-07| 1.06E-07| 5.46% |
| 0.24×0.235                                    | 0.12×0.115                                    | 2       | 0.8     | 1.24           | 1.79E-07| 1.71E-07| 2.17% |
| 0.20×0.195                                    | 0.1×0.095                                     | 2       | 0.8     | 1.23           | 2.99E-07| 3.03E-07| 1.10% |
| 0.16×0.155                                    | 0.08×0.075                                    | 2       | 0.8     | 1.23           | 5.86E-07| 6.12E-07| 4.39% |
| 0.09×0.085                                    | 0.05×0.045                                    | 2.12    | 0.8     | 1.44           | 3.20E-06| 3.16E-06| 1.39% |

Note: (1) \( l_d \) is the length of single limb, \( b \) is the length of lacing bar; (2) The error calculation method is \((\gamma_a - \gamma_l)/\gamma_a\).
Firstly, the method in 1.1 is used to load and solve, and the shear stiffness $K$ of latticed column applied to equation (1) is extracted; Then the axial load is applied to obtain the eigenvalue buckling load $P_{cr3}$. By using the above three elastic buckling load calculation methods, the elastic buckling load of three-limbed steel tube latticed column without diagonal lacing bar is obtained as shown in Table 2, and $\Delta P_{cr} = (P_{cr3} - P_{cr1})/P_{cr3}$.

Table 2. Comparison of elastic buckling loads of three-limbed steel tube latticed column without diagonal lacing bar.

| limb(external diameter×internal diameter)/mm | lacing bar(external diameter×internal diameter)/mm | $l_d$ (m) | $b$ (m) | $P_{cr1}$ (kN) | $P_{cr2}$ (kN) | $P_{cr3}$ (kN) | $\Delta P_{cr}$ |
|--------------------------------------------|-----------------------------------------------|-----------|--------|--------------|--------------|--------------|---------------|
| 0.36×0.355 | 0.18×0.175 | 2.2 | 0.9 | 7.47E+03 | 1.34E+04 | 8.00E+03 | 6.67% |
| 0.32×0.315 | 0.16×0.155 | 2.2 | 0.9 | 6.00E+03 | 1.19E+04 | 6.25E+03 | 4.00% |
| 0.30×0.295 | 0.15×0.145 | 2.2 | 0.9 | 5.28E+03 | 1.12E+04 | 5.43E+03 | 2.68% |
| 0.28×0.275 | 0.14×0.135 | 2.2 | 0.9 | 4.60E+03 | 1.04E+04 | 4.66E+03 | 1.37% |
| 0.24×0.235 | 0.12×0.115 | 2.2 | 0.9 | 3.30E+03 | 8.89E+03 | 3.26E+03 | -1.20% |
| 0.20×0.195 | 0.10×0.095 | 2.2 | 0.9 | 2.16E+03 | 7.38E+03 | 2.08E+03 | -3.64% |
| 0.16×0.155 | 0.08×0.075 | 2.2 | 0.9 | 1.23E+03 | 5.87E+03 | 1.16E+03 | -5.83% |
| 0.09×0.085 | 0.05×0.045 | 2.2 | 0.9 | 2.68E+02 | 3.22E+03 | 2.73E+02 | 1.94% |

It can be seen from Table 2 that the elastic buckling load $P_{cr2}$ calculated by the Euler formula, i.e. the second method, is about twice that calculated by the other two methods, because the influence of shear deformation is not considered in the Euler formula. The difference between the elastic buckling load $P_{cr1}$ calculated by the first method and the elastic buckling load $P_{cr3}$ calculated by the finite element model is less than 6.67%, which shows that the method proposed in 1.1 is effective and reliable. Both methods (1) and (3) can effectively calculate the elastic buckling load of three-limbed steel tube latticed column. It should be noted that the method of extracting shear stiffness and substituting Equation (1) for calculation is suitable for modeling and calculation of three-limbed steel tube latticed column without diagonal lacing bar when the ratio slenderness ratio of limb and lacing bar $\lambda_d/\lambda_b$ is between 1.2 and 1.4.

3. Nonlinear analysis of three-limbed steel tube latticed column with diagonal lacing bar

In the nonlinear analysis of three-limbed steel tube latticed column, the research at home and abroad mainly focuses on the consideration of the global initial geometric defects and material nonlinearity of the members. Based on this, the influence of the member initial geometric defects on the column is considered, and a finite element method is proposed to consider the member initial defects.

3.1. Computation model

Using the direct finite element analysis method in 1.2, taking the three-limbed steel tube latticed column with diagonal lacing bar, which is commonly used in engineering and two limbs landing on the ground, as the model, and considering the geometric nonlinearity and elastic-plastic material nonlinearity caused by initial geometric defects, the finite element model of latticed column as shown in figure 2 is established. The lacing and batten elements are perpendicular to each limb and arranged in a positive triangle. The diagonal lacing bar is connected from the top of the triangle to the two ends of the bottom of the upper triangle. The material, element, geometric parameters and boundary conditions are the same as 1.2. The nonlinear buckling analysis of the model is carried out.
3.2. Second order elastic buckling analysis considering initial geometric defects

The initial geometric defects of columns can be divided into two parts: the global initial geometric defects and the member initial geometric defects. This paper discusses the influence of these two kinds of initial geometric defects on the stability bearing capacity of columns, respectively.

3.2.1. Only global initial geometric defects. The buckling mode in eigenvalue buckling analysis is selected as the global initial geometric defect. The array considering the global initial geometric defects is read into the new model and the coordinates are changed accordingly. Then, the second-order elastic buckling analysis is carried out by using the arc length method.

3.2.2. Only the member initial geometric defects. The above method fails to consider the global buckling form and the local buckling form at the same time. When the direct analysis method is used in the steel structure code [11], the global initial geometric defects of the column can be considered according to the above method, but the member initial geometric defects should also be considered. Generally speaking, for the member initial geometric defects, the method of applying assumed uniform load to each member can be adopted for simplification, and the value is determined according to the following formula [11]:

\[ q_0 = \frac{bN_k e_0}{l^2} \]  

3.2.3. Both the global initial geometric defects and the member initial geometric defects at the same time. The results [12] show that the directionality of member initial geometric defects has little effect on the ultimate bearing capacity of the whole column, so the two kinds of defects are combined directly. The initial geometric defects of the first two cases are written into the array, a new model is created, and the array data is read in by changing the node coordinates of the existing model. In this case, the global and member initial geometric defects are considered at the same time.

3.2.4. Comparison of three different defects. The ratio of the length of the limb to the length of the lacing bar \( l_d/b \) is changed for comparison, the results are shown in table 3, where \( P_{t1} \) represents the ultimate bearing capacity of the column considering only the global initial geometric defects, \( P_{t2} \) represents the ultimate bearing capacity of the column considering only the member initial geometric defects, and \( P_{t3} \) represents the ultimate bearing capacity of the column considering two kinds of defects at the same time, with a difference of \( \Delta t1 = (P_{t1} - P_{t2})/P_{t3}, \Delta t2 = (P_{t2} - P_{t3})/P_{t3}. \)
As it can be seen from Table 3:

(1) The maximum buckling load is obtained when only the member initial geometric defects are considered and \( \Delta_{t1}/\Delta_{t2} < 2\% \). This indicates that in the second-order elastic analysis, the global initial geometric defects play a major role in the global stability of the column, and the member initial geometric defects have little effect. Considering the two kinds of defects at the same time will make the column develop towards a more unfavorable trend. In this case, the global buckling load is the minimum. When \( l_d/b < 2 \), the reduction due to the two kinds of defects at the same time is not more than 0.2\% compared with that due to only applying the global initial geometric defects.

(2) With the increase of \( l_d/b \), \( \Delta_{t2} \) increases, and the buckling load with three kinds of defects all decreases. This shows that the latticed column is more slender, the influence of the member initial geometric defects on the column is smaller, and the latticed column is more slender, which will make the column more unsafe.

### Table 3. Analysis and comparison of elastic buckling of three-limbed steel tube latticed column with three different defects.

| \( l_d/b \) | \( P_{t1}(kN) \) | \( P_{t2}(kN) \) | \( P_{t3}(kN) \) | \( \Delta_{t1} \) | \( \Delta_{t2} \) |
|-------|-----------|-----------|-----------|--------|--------|
| 1     | 15644.97  | 16539.31  | 15627.72  | 0.11\% | 5.63\% |
| 1.2   | 12602.86  | 13991.54  | 12785.28  | 0.14\% | 9.43\% |
| 1.4   | 10726.10  | 12090.50  | 10706.23  | 0.19\% | 12.93\%|
| 1.6   | 9053.46   | 10305.29  | 9035.69   | 0.20\% | 14.05\%|
| 1.8   | 7776.61   | 8835.99   | 7765.860  | 0.14\% | 13.78\%|

As it can be seen from Table 3:

3.3. Elastoplastic buckling analysis considering initial geometric defects and material nonlinearity

The above discussion is about the bearing capacity of the column when the material is in the elastic stage, but the plastic development stage of the material should be considered in practical engineering. Based on the above model, the elastic-plastic properties of Q345 steel are considered in the nonlinear analysis stage. The constitutive relation is ideal elastic-plastic, and the elastic modulus, Poisson's ratio and yield strength are 2.06 GPa, 0.3 and 345 MPa, respectively.

Change the length ratio of the limb and lacing bar \( l_d/b \) for multi group comparison as shown in Table 4, where \( P_{t1} \) represents the ultimate bearing capacity of the column considering only the global defects, \( P_{t2} \) represents the ultimate bearing capacity of the column considering only the member defects, \( P_{t3} \) represents the ultimate bearing capacity of the column considering two kinds of defects at the same time, and the difference \( \Delta_{t1} = (P_{t1} - P_{t3})/P_{t3} \), \( \Delta_{t2} = (P_{t2} - P_{t3})/P_{t3} \).

It can be seen from Table 4 that with the increase of \( l_d/b \), \( \Delta_{t1} \) increases by about 0.47\% - 0.65\% and \( \Delta_{t2} \) increases by about 0.71\% - 7.60\%, which indicates that the member initial geometric defects have a greater impact on the slender column.

### Table 4. Analysis and comparison of elastoplastic buckling of three-limbed latticed column with three different defects.

| \( l_d/b \) | \( P_{t1}(kN) \) | \( P_{t2}(kN) \) | \( P_{t3}(kN) \) | \( \Delta_{t1} \) | \( \Delta_{t2} \) |
|-------|-----------|-----------|-----------|--------|--------|
| 1     | 3916.45   | 3925.71   | 3897.94   | 0.47\% | 0.71\% |
| 1.2   | 3861.79   | 3918.98   | 3842.84   | 0.49\% | 1.98\% |
| 1.4   | 3781.50   | 3901.12   | 3762.63   | 0.50\% | 3.68\% |
| 1.6   | 3679.77   | 3849.38   | 3661.06   | 0.51\% | 5.14\% |
| 1.8   | 3541.22   | 3785.51   | 3518.19   | 0.65\% | 7.60\% |

As it can be seen from Table 4:

(1) The maximum buckling load is obtained when only the member initial geometric defects are considered; \( 8.6\% < \Delta_{t1}/\Delta_{t2} < 66.2\% \), which indicates that in the elastoplastic analysis, the global stability of the column is affected by both the initial geometric defects and the member initial geometric defects, and the global initial geometric defects play a major role and the member initial geometric defects play a secondary role.

Considering the two kinds of defects at the same time will make the column develop more disadvantageous, in which case the global buckling load is the minimum. When \( l_d/b < 2 \), the reduction of the two kinds of defects is not more than 0.65\% compared with only the global initial geometric defects, and the reduction is not more than 7.60\% compared with only the member initial geometric defects.

(2) With the increase of \( l_d/b \), \( \Delta_{t1} \) and \( \Delta_{t2} \) increase, and the buckling load with three kinds of defects all...
decreases. This shows that the latticed column is more slender, and the influence of the global and member initial geometric defects on the structure is smaller. More slender latticed columns will make the structure more unsafe.

4. Conclusion and Prospect

4.1. Conclusion

From the above analysis, the following conclusions can be drawn:

1. The finite element method is used to extract the shear stiffness of three-limbed steel tube latticed columns without diagonal lacing bar. When the ratio of slenderness ratio of the limb and lacing bar $\lambda_d/\lambda_b$ is between 1.2 and 1.4, the formula results are in good agreement with the direct finite element method. This method can calculate the buckling load of the structure by extracting the stiffness of the latticed column without diagonal lacing bar, and effectively improve the calculation efficiency.

2. In the elastic buckling analysis, the global initial geometric defects play a major role in the global stability of the column, while the member initial geometric defects have little effect on the global stability, which can be ignored; In the elastoplastic buckling analysis, the global stability of the column is affected by both the global initial geometric defects and the member initial geometric defects of members, in which the global initial geometric defects play a major role, and the member initial geometric defects of members play a secondary role and it cannot be ignored; Under the same defect form, the elastoplastic bearing capacity is reduced by 54.7% - 75.1% compared with the elastic bearing capacity. When two kinds of initial geometric defects are applied at the same time, the column will develop in a more unfavorable direction.

3. With the increase of $\lambda_d/b$, that is, the column becomes more slender, and the influence of the global and member initial geometric defects on the stable bearing capacity of the three-limbed steel tube latticed column decreases. At this time, the column bearing capacity depends more on its own structural parameters than on the defect form.

4.2. Prospect

1. This paper mainly adopts the method of numerical simulation analysis based on ANSYS, and the stability analysis of lattice components is lack of experimental verification. In the follow-up research, we should add appropriate content of stability experiment of lattice components, and compare the experimental content with the results of numerical analysis.

2. The research object of this paper is tubular lattice members, and the application of H-steel, angle steel in latticed columns is also very wide. The stability analysis of other sections can be considered to investigate whether different section forms will draw the same conclusion.

3. In the whole process of structural stability analysis, the research on the specific stress mechanism of members after buckling is still relatively simple, and the development situation of internal force needs to be further studied.

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