Comparative analysis of bearing characteristics between triangular columns and variable-section columns

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Abstract. Fengnan 500KV substation fully united framework was taken as the engineering background for analyzing the effect of load on the bearing characteristics of triangular frame columns and variable-section steel columns under different working conditions. Through ANSYS simulation, the bearing characteristics of the two structures under the same working conditions were obtained. The possibility of replacing the original triangular frame column with a variable-section frame column in a 500kV fully united substation frame was analyzed.

1. Introduction
With the continuous expansion of the power grid construction, the size and load of the substation framework have also increased accordingly. Therefore, in recent years, some researchers have tried to replace the complicated framework pillars with new ones. Feng Renxiang [1] took Jinhua Wuning 500kV substation fully united framework project as an example, improved the A-type outgoing column to a single column form, and performed a force analysis using finite element software. Gao Zhan [2] replaced the original frame column with a single steel pipe column and performed structural finite element simulation and load calculation with Yichang Jiangnan 500kV substation as background. In this paper, Fengnan 500KV substation fully united framework was taken as the engineering background for analyzing the effect of load on the bearing characteristics of triangular frame columns and variable-section steel columns under different working conditions to save materials and facilitate construction by replacing the triangular columns with variable-section columns.

2. Engineering load analysis
Frame columns are important vertical members in the united framework. The main loads include:
(1) Dead load of frame columns and other structural weights transmitted to frame columns;
(2) Wind load of the frame column itself;
(3) The acting force (moment) of the beam on the frame column by wind load;
(4) The acting force (moment) of the wire load on different working conditions;

According to the theory of structural mechanics and the study of the inflection point, the loads acting directly on the frame columns and the loads transmitted by the beams and wires to the frame columns were equivalent to the concentrated forces and moments of the three nodes of 20m, 26m and 33.6m. The beam-column node at 20m was hinged, which can transmit forces and bending moments, and the beam-column nodes at 26m and 33.6m were rigid nodes, which can only transmit forces and
cannot transmit bending moments. There were differences in the loads on the frame columns under different winds. Therefore, 0°, 90°, 180°, and 270° wind direction angle frame column mechanical models were established, as shown in Figure 1 to Figure 4.

This article mainly used ANSYS to model and analyze the bearing characteristics of the frame columns. The weight of the frame columns was represented by the acceleration of gravity, which was not shown in the figure. Other loads include:

1) Dead load

\( G_{ki} \) —— The weight of the beam was equivalent to the vertical force of the nodes of the frame columns (i means 1, 2, 3, corresponding to the nodes at 20m, 26m, and 33.6m, respectively, the meaning of i is the same later, and will not be repeated).

\( G_{k} \) —— The weight of the ground wire column was equivalent to the vertical force of the frame column.

2) Wind load

\( W_{ki} \) —— The wind load of the frame column was equivalent to the horizontal concentrated force of each node according to the inflection point.

\( W_{k4} \) —— The ground column wind load was equivalent to the horizontal concentrated force on 33.6m node.

\( W_{k5} \) —— The beam wind load was equivalent to the horizontal concentrated force of each node of the frame column.

\( M_{wk} \) —— The wind load of the ground column was equivalent to the bending moment of the frame column.

\( M_{wk5} \) —— The beam wind load was equivalent to the moment of the frame column.

3) Wire load

\( D_{ki} \) —— The horizontal tension of the wire was equivalent to the horizontal concentration of each node \( (D_{1ki} \) was the maximum wind condition value, \( D_{2ki} \) was the maximum icing condition value, and \( D_{3ki} \) was the installation condition value and will not be repeated).

\( D_{k5} \) —— The vertical load of the wire was equivalent to the vertical concentrated force of each node.

\( D_{k6} \) —— The wind pressure on the wire was equivalent to a horizontal concentrated force of each node.

\( M_{Dk} \) —— The horizontal tension of the wire was equivalent to the torque of the frame column.
3. Finite element model analysis

3.1. Establishment of finite element model
In this paper, ANSYS was used to analyze the bearing characteristics of triangular columns and variable-section columns, and the force and deformation characteristics of the two types of frame columns were studied. The Beam188 element type of 2-node beam element was used for modeling. The structural column was made of Q345B steel, with a density of 7850kg/m³ and a Poisson's ratio of 0.3. The material was simplified into an ideal elastoplastic material when modeling. The pedestal restraints of the frame columns were completely rigid.

3.1.1. Dimensions of Triangular Columns. Taking the dimensions of the triangular columns of Fengnan 500KV substation as an example, the triangular columns were divided into 0-20m, 20-26m and 26-33.6m sections from bottom to top.

![Figure 5. Diagram of triangular column](image)

![Figure 6. Diagram of variable section column](image)

3.1.2. Equal stiffness method to determine the size of a variable-section column. In order to make the variable-section columns and triangular columns have the same deformation under the same external load, the bending stiffness $K = EI$ of the two types of frame columns need to be consistent. Since the materials are Q345B steel, the size of the variable-section column can be determined according to the moment of inertia. Details were shown in the Figure.6.

![Table 1. Variable-section steel columns dimensions](image)

3.2. Finite element analysis results

3.2.1. Finite element analysis maps. Taking the maximum wind condition of 0° wind direction at the limit of load carrying capacity as an example, the results of the finite element analysis were shown in the figure below.
Figure 7. Linear displacement cloud map of triangular column

Figure 8. Angular displacement cloud map of triangular column

Figure 9. Mises stress cloud map of triangular column

Figure 10. $M_x$ distribution map of triangular column

Figure 11. $M_y$ distribution map of triangular column

Figure 12. $M_z$ distribution map of triangular column

Figure 13. Linear displacement cloud map of variable-section column

Figure 14. Angular displacement cloud map of variable-section column

Figure 15. Mises stress cloud map of variable-section column

Figure 16. $M_x$ distribution map of variable-section column

Figure 17. $M_y$ distribution map of variable-section column

Figure 18. $M_z$ distribution map of variable-section column
The distribution of displacements, stresses, and bending moments and the numerical values of the linear and angular displacements of the triangular column and variable-section column were shown in Table 2 and Table 3.

**Table 2. Linear displacement and angular displacement on each node of triangular column**

| Load Working conditions | Wind direction | Node linear displacement (m) | Node angular displacement (m) |
|-------------------------|----------------|-----------------------------|-------------------------------|
|                         | 20m node       | 26m node                    | 33.6m column top              | 20m node | 26m node | 33.6m column top |
| Bearing capacity Limit state | Maximum wind conditions | 0° | 0.015 | 0.026 | 0.099 | 0.014 | 0.019 | 0.039 |
|                         | 90° | 0.019 | 0.035 | 0.133 | 0.014 | 0.021 | 0.046 |
|                         | 180° | 0.013 | 0.026 | 0.100 | 0.010 | 0.014 | 0.034 |
|                         | 270° | 0.008 | 0.016 | 0.063 | 0.009 | 0.013 | 0.028 |
| Icing conditions | 0° | 0.015 | 0.027 | 0.105 | 0.013 | 0.018 | 0.040 |
| Installation conditions | 90° | 0.015 | 0.029 | 0.111 | 0.013 | 0.019 | 0.041 |
|                         | 180° | 0.014 | 0.027 | 0.105 | 0.012 | 0.018 | 0.039 |
|                         | 270° | 0.014 | 0.026 | 0.100 | 0.012 | 0.017 | 0.038 |
| Normal use Limit state | 0° | 0.010 | 0.018 | 0.068 | 0.008 | 0.012 | 0.025 |
|                         | 90° | 0.010 | 0.019 | 0.072 | 0.008 | 0.012 | 0.026 |
|                         | 180° | 0.010 | 0.018 | 0.068 | 0.008 | 0.011 | 0.025 |
|                         | 270° | 0.009 | 0.017 | 0.064 | 0.008 | 0.011 | 0.024 |
| Maximum wind (standard) | 0° | 0.011 | 0.020 | 0.076 | 0.010 | 0.014 | 0.029 |
|                         | 90° | 0.012 | 0.023 | 0.088 | 0.010 | 0.014 | 0.031 |
|                         | 180° | 0.010 | 0.020 | 0.076 | 0.008 | 0.012 | 0.027 |
|                         | 270° | 0.009 | 0.017 | 0.064 | 0.008 | 0.011 | 0.025 |

**Table 3. Linear displacement and angular displacement on each node of variable-section column**

| Load Working conditions | Wind direction | Node linear displacement (m) | Node angular displacement (m) |
|-------------------------|----------------|-----------------------------|-------------------------------|
|                         | 20m node       | 26m node                    | 33.6m column top              | 20m node | 26m node | 33.6m column top |
| Bearing capacity Limit state | Maximum wind conditions | 0° | 0.014 | 0.029 | 0.100 | 0.001 | 0.005 | 0.024 |
|                         | 90° | 0.020 | 0.041 | 0.136 | 0.002 | 0.006 | 0.030 |
|                         | 180° | 0.014 | 0.030 | 0.100 | 0.001 | 0.005 | 0.024 |
|                         | 270° | 0.007 | 0.016 | 0.058 | 0.001 | 0.003 | 0.017 |
| Icing conditions | 0° | 0.015 | 0.031 | 0.105 | 0.001 | 0.005 | 0.026 |
| Installation conditions | 90° | 0.015 | 0.033 | 0.110 | 0.001 | 0.005 | 0.027 |
|                         | 180° | 0.015 | 0.031 | 0.105 | 0.001 | 0.005 | 0.026 |
|                         | 270° | 0.014 | 0.029 | 0.099 | 0.001 | 0.005 | 0.025 |
| Normal use Limit state | 0° | 0.009 | 0.020 | 0.067 | 0.001 | 0.003 | 0.016 |
|                         | 90° | 0.010 | 0.021 | 0.071 | 0.001 | 0.003 | 0.017 |
|                         | 180° | 0.009 | 0.020 | 0.067 | 0.001 | 0.003 | 0.016 |
|                         | 270° | 0.009 | 0.019 | 0.063 | 0.001 | 0.003 | 0.016 |
| Maximum wind (standard) | 0° | 0.010 | 0.022 | 0.075 | 0.001 | 0.004 | 0.018 |
|                         | 90° | 0.012 | 0.026 | 0.088 | 0.001 | 0.004 | 0.021 |
|                         | 180° | 0.010 | 0.022 | 0.075 | 0.001 | 0.004 | 0.018 |
|                         | 270° | 0.008 | 0.018 | 0.061 | 0.001 | 0.003 | 0.016 |
3.2.2. Result analysis. It was shown that:

1. The maximum linear displacement and angular displacement of the triangular column and the variable-section column both appeared at the top of the column.

2. The displacement of the top line of the frame column in each working condition was less than the allowable deflection value of the code \( \frac{H}{200} \).

3. The deflection and rotation angle of the triangular column top with the maximum wind direction angle of 90° are the largest. The main reason was that the horizontal tension direction of the wire was consistent with the direction of wind load and the resultant force (distance) was large.

4. Under various working conditions, the linear displacement of each node of the variable-section column was close to that of the triangular column, and the angular displacement was much smaller than that of the triangular column.

5. According to the Mx distribution map, the 26-33.6m section of the triangular column bore a large bending moment and is the main bearing part.

6. According to the My distribution map of the triangular column, when subjected to the action of torque, the internal force of the end brace was large, and it was the main load bearing member. The most dangerous point was at the pedestal.

7. According to the Mz distribution map, when the triangular column was subjected to the xoy plane moment, the bending moment value of the end brace was very small and can be almost ignored. The main load bearing members were located in the 26m-33.6m section.

8. According to the Mx, My, Mz distribution maps, the internal force distribution of the variable section column was simpler than that of the triangular column, and the position of the maximum bending moment and torque appeared at the pedestal.

9. The maximum stress of the triangular column appeared at the 26m node, it was 155MPa. The maximum stress of the variable-section column appeared at the 26m node, it was 154MPa. They did not reach the yield point.

4. Comparative analysis of triangular columns and variable-section columns

In order to facilitate the comparison of triangular columns and variable-section columns, the column was divided into three sections. Δ1, Δ2 and Δ3 were defined as the relative deformation values of 0-20m section, 20-26m section and 26-33.6m section respectively. Relative deformation values of various working conditions were shown in Table 4.
| Load conditions | Wind direction | Δ1 | Δ2 | Δ3 |
|-----------------|----------------|------------------|------------------|------------------|
| Maximum wind conditions | 0° | 0.015 | 0.014 | 0.011 | 0.015 | 0.073 | 0.071 |
| | 90° | 0.019 | 0.020 | 0.016 | 0.021 | 0.098 | 0.095 |
| | 180° | 0.013 | 0.014 | 0.013 | 0.016 | 0.074 | 0.070 |
| | 270° | 0.008 | 0.007 | 0.008 | 0.009 | 0.047 | 0.042 |
| Icing conditions | 0° | 0.015 | 0.015 | 0.012 | 0.016 | 0.078 | 0.074 |
| | 90° | 0.015 | 0.015 | 0.014 | 0.018 | 0.083 | 0.077 |
| | 180° | 0.014 | 0.014 | 0.013 | 0.016 | 0.078 | 0.074 |
| | 270° | 0.014 | 0.014 | 0.012 | 0.015 | 0.074 | 0.070 |
| Installation conditions | 0° | 0.010 | 0.009 | 0.008 | 0.011 | 0.050 | 0.047 |
| | 90° | 0.010 | 0.010 | 0.009 | 0.011 | 0.053 | 0.050 |
| | 180° | 0.010 | 0.009 | 0.008 | 0.011 | 0.050 | 0.047 |
| | 270° | 0.009 | 0.009 | 0.008 | 0.010 | 0.047 | 0.044 |
| Normal use limit state | Maximum wind (standard) | 0° | 0.011 | 0.010 | 0.009 | 0.012 | 0.056 | 0.053 |
| | | 90° | 0.012 | 0.012 | 0.011 | 0.014 | 0.065 | 0.062 |
| | | 180° | 0.010 | 0.010 | 0.010 | 0.012 | 0.056 | 0.053 |
| | | 270° | 0.009 | 0.008 | 0.008 | 0.010 | 0.047 | 0.043 |

1. According to the data in Table 4, the relative deformation values of the variable section column and the triangular column in the three section of 0-20m, 20-26m, and 26-33.6m are relatively close, and the error is small. Under the same external load, the stiffness of each section of the two types frame column was relatively close, which verified the rationality of the equal stiffness method to design the variable-section column.

2. Although the linear displacement of the two kinds of frame columns were close, the angular displacement was quite different. According to Tables 2 and 3, the angular deformation of the variable-section columns were much smaller than the triangular columns. It was because the triangular columns rely on the transverse braces to connect the three main vertical members. The sizes of the transverse braces and vertical members were smaller. When the frame columns were subjected to torque, the transverse brace not only received tensile pressure, but also underwent bending deformation, which weakened the torsional strength of the vertical member and increased the angular deformation.

3. According to Figures 2 and 3, under the same external load, the maximum values of Mises stress were very close to each other, and they both appeared at the 26m node. It was due to the large stiffness change at 26m.

4. According to the internal force distribution diagram, it can be seen that the internal force distribution of the variable-section column was relatively simple, and the location of the larger internal force was located at the pedestal. The internal force distribution of the triangular column was more complicated. Under the action of torque, the pedestal was the position where the My was largest. Under the action of bending moment, the 26-33.6m section was the main bearing member.

5. It can be seen that it was feasible to replace triangular columns with variable-section column.

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