Experimental study on bearing capacity of single steel pipe column for fully united framework

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Abstract. It is analyzed and tested the substitution of triangular section columns for single steel outgoing line columns in the 500kV fully united framework based on the design, test and analysis with 18 specimens of single steel pipe. The theoretical calculation method of bearing capacity is put forward by analyzing the design theory. Through the experimental analysis and research, the computational model with bottom fixed, middle hinged and top hinged is obtained, which is consistent with theoretical values, thus providing valuable reference conclusions for the revision of the specification. It provides meaningful theoretical and experimental data for the analysis and calculation of substitution of single steel pipe outgoing line column for the original triangular section outgoing line column for the 500kV fully united framework.

1. Introduction

As a new achievement of the continuous development of the optimized design of the fully united framework, single steel pipe outgoing line column structure has the advantage of replacing the original triangular section outgoing line column, so as to further improve the mechanical performance, reduce the floor area and project cost.

Compared with triangular section outgoing line column single steel pipe column is simpler, but the technical research and relevant design specifications are still in the perfect stage. According to the existing design and calculation assumption of substation frame, the single steel pipe outgoing line column is analyzed and calculated with reference to the independent components with larger rigidity, and the results are certainly different from the actual situation.

Recently, some scholars have analyzed the structural properties of single steel pipe columns in fully united framework. For example, Gao Zhan [1] carried out the finite element simulation and load calculation of the single steel pipe in Yichang Jiangnan 500kV fully united framework; Yang Guofu [2] studied the breeze vibration phenomenon of the single steel pipe column in the fully united framework; Feng Renxiang [3] took Jinhua Wuning 500kV substation fully united framework project as an example, improved the A-type outgoing line column to a single column form, and performed a force analysis using finite element software.

From the research background above, it can be seen that the current research on single steel pipe outgoing line column of fully united framework is still at the stage of finite element simulation and software calculation, and the experimental research is almost blank. In this paper, a 500kV fully united framework is taken as an example, based on the study of the influence factor of the space effect of a single steel pipe column in a fully united framework [4] [5], the single steel pipe outgoing line column...
model is used instead of the 35m high triangular section outgoing line column for experiments, in order to study its bearing capacity characteristics and deformation stiffness, and to compare it with the theoretical ultimate bearing capacity, so as to lay a foundation for optimizing theoretical calculations.

2. Research and design of experiment

The purpose of the experiment is to obtain the ultimate bearing capacity and instability failure of the single steel pipe columns under three different constraint conditions, and to study the theoretical calculation method and mechanical characteristics of single steel pipe columns based on this.

2.1. Design of the Specimen

Taking a 500kV fully united substation framework as an example, from the theoretical calculation of equal stiffness and the numerical simulation, it is found that when the section moment of inertia at the height center of the original triangular section column is the same as that of the single steel pipe column, the relative deformation value at the top of the two columns is relatively close, and the error is small. Under the same external load, the stiffness of the two frame columns is close. Therefore, in this paper, the moment of inertia is calculated by using the section at 17.5m in the middle height of 35mA column to obtain the actual diameter of a single steel pipe column.

According to the similarity theory and experiment conditions, the geometric model similarity ratio is $S_l = 0.1$, the elastic model similarity ratio is $S_E = 0.1$. According to the physical similarity theory, the similarity ratio of other material parameters is calculated. Concentrated load similarity ratio is $S_P = S_l^2S_E = 0.01$, moment similarity ratio is $S_M = S_l^5S_E^4 = 0.001$. The stress similarity constant is equal to the strain similarity constant, $S_\sigma = S_\varepsilon$. The linear displacement similarity ratio is $S_x = S_l = 0.1$.

The length of the prototype in this experiment is 35m, the cross-sectional size is $\Phi 600mm \times 50mm$. Based on the geometric similarity ratio $S_l = 0.1$, the length of the specimen is 3.5m and the cross-sectional size is $\Phi 60mm \times 5mm$.

| Specimen | Sectional Size | Length | Steel Type | Elastic Modulus (GPa) | Design value of tensile and compressive strength (MPa) | Poisson Ratio $\mu$ |
|----------|----------------|--------|-------------|-----------------------|-------------------------------------------------------|---------------------|
| Specimen | $\Phi 60mm \times 5mm$ | 3.5m   | Q345        | 206                   | 310                                                   | 0.3                 |

Figure 1. Stress-strain curve of steel pipes test.
2.2. Material test and material properties
According to standard GB / T8162-2018 "Seamless steel tubes for structural purposes", the material mechanical properties of the specimen are sampled and tested. The test results and the stress-strain curve of steel pipes are obtained in Figure 1 and Table 2.

Table 2. Details of the properties test of steel pipes

| No. | OD (mm) | Thickness (mm) | Yield Load (kN) | Ultimate Load (kN) | Elasticity Modulus (MPa) | Yield Intensity (MPa) | Tensile Strength (MPa) | Load Rate (kN/S) |
|-----|---------|----------------|-----------------|-------------------|--------------------------|---------------------|----------------------|-----------------|
| 1   | 60      | 5              | 69.77           | 94.63             | 226000                   | 388                 | 527                  | 0.5             |
| 2   | 60      | 5              | 72.39           | 98.40             | 388                      | 527                 | 0.5                  |                 |
| 3   | 60      | 5              | 70.44           | 95.91             |                          |                     |                      |                 |

2.3. Number of the Specimen
In the original project, there were three ways of restraining the outgoing line columns: ①Support at 20m in the plane; ② Support at 26m in the plane; ③ Support at 26m in the plane, stay cable at 26m out of plane. Therefore, the test specimens were also divided into three types. The corresponding boundary conditions of the specimen numbers are shown in Table 3. The diagrams of the specimens are shown in Figures 2 to 4. At least 6 specimens were made for each boundary condition.

Table 3. Specimen number and boundary conditions.

| Number of the Specimen | The corresponding boundary conditions |
|------------------------|--------------------------------------|
| S20-X00-#a             | Support at 2.0m and 3.5m in the plane, No stay cable out the plane. |
| S26-X00-#a             | Support at 2.6m and 3.5m in the plane, No stay cable out the plane. |
| S26-X26-#a             | Support at 2.6m and 3.5m in the plane, stay cable at 2.6m out of the plane. |

* In order to facilitate comparison of experiment data, the specimens are numbered in the following way: S ###-X ###-#, S ## is the support height position except for the in-plane support of 3.5m; X ## is the stay cable height out of the plane. The last # is the serial number of the specimen.
2.4. Loading device and measuring point arrangement

2.4.1. Loading system of experiment. This experiment adopts monotonic loading, 40kN for each stage. Each stage load is maintained for 5 minutes, and then the next stage load is added. The instability failure is sudden, so the load holding time should be changed according to the strain growth in the vicinity of instability failure. When the value of the strain meter increases greatly, that is, when the load is not proportional to the increase in strain, the holding time is reduced to cope with the sudden instability failure.

2.4.2. Loading device. The experiment used a reinforced concrete reaction wall as a support point for the in-plane support to provide lateral support in the plane for the specimen. The specimen was fixed on the test bench by the base plate through anchor bolts, and the lateral support was connected to the reinforced concrete reaction wall through the processed support rods and hoop to provide bidirectional restraint support in the plane for the specimen. The out-of-plane stay cable was connected with the lateral node by steel wire rope through the drilling on the small welded steel plate out of the plane of the specimen.

The experiment device diagram is shown in Figure 5. The axial load was applied by a 500kN hydraulic jack. The calibrated pressure sensor and the static resistance strain meter were connected to a computer for each stage of load control. Two pre-loads were performed before the formal experiment to check whether the experiment device and measuring equipment were working properly.
2.4.3. Location of strain gauges. According to the analysis results of the theoretical model, the strain at each support of the model was relatively large. Therefore, strain gauges were arranged on the front and back of the column base, column top and mid-span of the test piece respectively. Through static resistance strain meter connected with right angle strain gauges, the strain changes of column base and supporting point were measured. All the strain gauges and load sensors used the TST3822EW static signal test analysis system for signal acquisition and control.

2.5. Experiment process
The specimens were loaded with 40kN per stage and 6 stages in total. During the experiment, according to the estimated load, when the load is applied near the theoretical calculated load, the loading speed was slowed down to capture the instability load. Specifically, when the load was applied, it was strictly applied in accordance with the loading system, each stage was 40kN, and when the load was controlled to the control load, the load was held for 5min to make the plastic deformation of the material sufficient. As the ultimate instability load was approached, the strain value of the specimen increased rapidly. When the ultimate instability load was reached, the load was continued to increase. At this time, the in-plane deformation of the specimen increased sharply, indicating that the specimen has been damaged. When the load dropped to 80% of the ultimate instability load, no more load was applied.

3. Calculation of theoretical ultimate bearing capacity of Single steel pipe under specific boundary conditions

3.1. Boundary conditions and calculation diagrams
The specimens were rigidly connected at the column base, and there are two supports at the top and middle position, so the structural calculation diagrams were shown in Figure 7. Due to different positions of the intermediate support, the models were divided into two sizes, namely S26-X00-#, that is, the intermediate support position is at 2.6m and S20-X00-#, that is, the intermediate support position is at 2.0m. The structure was fixed at point A without deflection and rotation. Point B and point C were hinged without deflection but rotation. The calculated lengths of the AB and BC segments and the critical load of instability were calculated according to the analytical formula.

3.2. Parameter Settings

\[\nu_{ij}, \varphi_{ij}, M_{ij}, \text{ and } Q_{ij}\] respectively represented deflection, angle, bending moment and shear force. \(i\) indicated the number of segments in the structure from bottom to top, and \(j\) indicated the number of nodes in the segment. \(L_1\) and \(L_2\) represented the length of AB and BC segments, \(P_i\) and \(P_j\) represented the pressure of the AB and BC segments respectively.
3.3. Stability equations

For position A, $V_{10}$ and $\phi_{10}$ were basic initial parameters, $M_{10}$ and $Q_{10}$ indicated the bending moment and shear. The basic initial parameters derived from the equilibrium conditions can be expressed as:

\[
\begin{align*}
V_{10} &= V_{10} \\
\phi_{10} &= \phi_{10} \\
M_{10} &= -\gamma V_{10} - \alpha \phi_{10} \\
Q_{10} &= -\beta \phi_{10} - \gamma \phi_{10}
\end{align*}
\]

(1)

There was coefficient matrix.

\[
[H] = \begin{bmatrix}
1 & 0 \\
0 & 1 \\
-\gamma & -\alpha \\
\beta & \gamma
\end{bmatrix}
\]

(2)

It can be known from the boundary conditions that the point A was fixed, then $V_{10} = 0$, $\phi_{10} = 0$, $Q_{10} = 0$, and the coefficient matrix $[H]$ was simplified as

\[
[H] = \begin{bmatrix}
0 \\
1
\end{bmatrix}
\]

The parameter of point B,

\[
\begin{align*}
V_{ii} &= V_{10} + \phi_{10} \frac{\sin v_i}{k_i} - M_{10} \frac{1 - \cos v_i}{P_i} - Q_{10} \frac{v_i - \sin v_i}{k_i} \\
\phi_{ii} &= \phi_{10} \cos v_i - M_{10} \frac{k_i \sin v_i}{P_i} - Q_{10} \frac{1 - \cos v_i}{P_i} \\
M_{ii} &= \phi_{10} \frac{P_i}{k_i} \sin v_i + M_{10} \cos v_i + Q_{10} \frac{\sin v_i}{k_i} \\
Q_{ii} &= Q_{10}
\end{align*}
\]

(3)

\[k_i = \sqrt{\frac{P_i}{EI_k}}, v_i = k_i l_i\]

For continuous beams supported by rigidly connected hinges, the deformation continuity conditions for adjacent spans were:

\[
\begin{align*}
V_{i+1,0} &= V_{ii} = 0 \\
\phi_{i+1,0} &= \phi_{ii} \\
M_{i+1,0} &= M_{ii} \\
Q_{i+1,0} &= Q_{ii} + R_i
\end{align*}
\]

(4)

$R_i$ was the reaction of the No.$i$ support.

For the hinged position, $V_{ii} = V_{10} = 0$, so from the 2nd equation of formula (3),

\[
\phi_{ii} \sin v_i - M_{10} \frac{1 - \cos v_i}{P_i} - Q_{10} \frac{v_i - \sin v_i}{k_i} = 0
\]

(5)

\[
Q_{10} = \frac{P_i \sin v_i}{v_i - \sin v_i} \phi_{ii} - \frac{k_i (1 - \cos v_i)}{v_i - \sin v_i} M_{10}
\]

(6)

Substituting formula (6) into the 2nd and 3rd equations in formula (3) :
\[ \varphi_0 = \varphi_{\alpha 0} \left[ \cos v_1 \frac{1 - \cos v_1}{v_1 - \sin v_1} \right] + M_{\alpha 0} \left[ \frac{k}{P_1} \sin v_1 + \frac{k}{P_1} (1 - \cos v_1)^2 \right] \]

\[ = \varphi_{\alpha 0} \frac{v_1 \cos v_1 - \sin v_1}{v_1 - \sin v_1} + M_{\alpha 0} \frac{k}{P_1} (-v_1 \sin v_1 + 2 - 2 \cos v_1) \]

\[ M_{ii} = \varphi_{\alpha 0} \left[ \frac{P_i}{k_1} \sin v_1 + \frac{P_i}{k_1} \sin^2 v_1 \right] + M_{\alpha 0} \left[ \cos v_1 - (1 - \cos v_1) \frac{v_1 \cos v_1 - \sin v_1}{v_1 - \sin v_1} \right] \]

By using the deformation continuity boundary conditions of the point B which was at the junction of the AB and BC segments, the point B starting parameters of BC segment can be represented by the point B end parameters of the AB segment, \(v_{1i}, \varphi_{1i}, M_{1i}, Q_{1i}\), that is,

\[ v_{20} = b_1 v_{1i} + b_2 \varphi_{1i} + b_3 M_{1i} + b_4 Q_{1i} \]

\[ \varphi_{20} = b_3 v_{1i} + b_2 \varphi_{1i} + b_3 M_{1i} + b_4 Q_{1i} \]

\[ M_{20} = b_3 v_{1i} + b_2 \varphi_{1i} + b_3 M_{1i} + b_4 Q_{1i} \]

\[ Q_{20} = b_3 v_{1i} + b_2 \varphi_{1i} + b_3 M_{1i} + b_4 Q_{1i} \]

\([B]\) was represented the corresponding coefficient matrix.

For continuous beams supported by rigidly connected hinges, then \(\nu = 0, Q = 0\), the coefficient matrix was simplified as \(B = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\).

If the specimen had \(n\) segments, the boundary condition of the end point of the No.\(n\) segment was

\[ -\gamma_1 \nu_{1n} + \alpha \varphi_{1n} + M_{1n} = 0 \]

\[ -\beta \nu_{1n} + \gamma \varphi_{1n} + Q_{1n} = 0 \]

There was the coefficient matrix \(K = \begin{bmatrix} -\gamma_1 & \alpha & -1 & 0 \\ -\beta & \gamma_1 & 0 & -1 \end{bmatrix}\).

If the end point of the No.\(n\) segment was also a hinged support, then \(M_{1n} = 0\), so the coefficient matrix was simplified as \(K = \begin{bmatrix} 0 & 1 \end{bmatrix}\).

Since the stability equation \([HA, B_1, A_2, B_2, \ldots, A_n, K] = 0\) and \(B = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\), the critical condition of the entire continuous beam was \([HA, A_2, \ldots, A_n, K] = 0\).

Since the model of this experiment had only two segments, the equilibrium equation was simplified as \([HA, A_2, K] = 0\).

\[ \frac{P_2}{K_2} \frac{v_2 \sin v_2}{v_2 - \sin v_2} \frac{2 - 2 \cos v_1 - \sin v_1}{v_1 - \sin v_1} + \frac{P_1}{K_1} \frac{v_1 \cos v_1 - \sin v_1}{v_1 - \sin v_1} = 0 \]

\[ P_1 = \frac{\pi^2 E I}{(u_1 l_1)^3}, K_1 = \frac{\pi}{u_1}, P_2 = \frac{\pi^2 E I}{(u_2 l_2)^3}, K_2 = \frac{\pi}{u_2} \]

\(u_1\) and \(u_2\) was the length coefficient.

Then the stability equation of this experiment model was
According to formula (12), using the numerical solution, the length coefficients \( u_1 \) and \( u_2 \) of the AB and BC members can be obtained. Then, the axial ultimate bearing capacity of the two sections is calculated by Euler formula \( \frac{\pi^2 EI}{(\mu d)^2} \), and the larger of which was used as the critical load for destabilization and the theoretical ultimate bearing capacity of the specimens.

\[
\frac{l_1}{l_2} \left( \frac{\pi}{u_1} \sin \frac{\pi}{u_2} - 2 \cos \frac{\pi}{u_1} \cos \frac{\pi}{u_2} + \frac{\pi}{u_1} \sin \frac{\pi}{u_2} \right) + \frac{\pi}{u_2} \left( \frac{\pi}{u_1} \sin \frac{\pi}{u_2} - \frac{\pi}{u_1} \cos \frac{\pi}{u_2} - \sin \frac{\pi}{u_1} \right) = 0
\]  
\begin{equation}
(12)
\end{equation}

4. Comparative analysis of experimental results and theoretical calculations

As shown in Table 5, the experimental data was compared with the theoretical calculation results. The instability failure load of the 6 steel pipes of the S26-X00-# series is basically consistent with the theoretical calculation results. The average error was about 4%, and only the experiment value of S26-X00-5 differed from the theoretical value by 17%. The instability failure load of 6 steel pipes of the S20-X00-# series differed from the theoretical calculation result by about 15%. The failure loads of S26-X26-# series steel pipes with stay cables were similar to that of S26-X00-# series without stay cables, and the experiment results can be used as a reference.

| Table 4. Calculation results of theoretical ultimate bearing capacity |
|-----------------------------------------------|
| Theoretical ultimate bearing capacity (kN) |
| S26-X00-# | 226.22 |
| S20-X00-# | 322.65 |

| Table 5. Experiment result in instability and failure of steel pipes. |
|-----------------------------------------------|
| (a) S26-X00-# steel pipes instability failure load results |
| Number of the Specimen | Instability Failure Load (kN) | Theoretical Ultimate Bearing Capacity(kN) | Experimental/Theoretical Value |
|--------------------------|-----------------------------|--------------------------------------|-------------------------------|
| S26-X00-1                | 224.2                       | 226.22                               | 1.00                          |
| S26-X00-2                | 217.7                       | 0.96                                 | 1.05                          |
| S26-X00-3                | 237                         |                                      | 1.07                          |
| S26-X00-4                | 242                         | 0.81                                 | 1.07                          |
| S26-X00-5                | 189                         | 0.83                                 | 0.83                          |
| S26-X00-6                | 218                         | 0.96                                 | 0.96                          |

| (b) S20-X00-# steel pipes instability failure load results |
|----------------------------------------------------------|
| Number of the Specimen | Instability Failure Load (kN) | Theoretical Ultimate Bearing Capacity(kN) | Experimental/Theoretical Value |
|-------------------------|-------------------------------|--------------------------------------|-------------------------------|
| S20-X00-1               | 275.5                         | 322.65                               | 0.85                          |
| S20-X00-2               | 280.0                         | 0.86                                 | 0.86                          |
| S20-X00-3               | 263.0                         | 0.81                                 | 0.81                          |
| S20-X00-4               | 258.0                         |                                      | 0.80                          |
| S20-X00-5               | 301.5                         | 0.93                                 | 0.93                          |
| S20-X00-6               | 273.8                         | 0.85                                 | 0.85                          |

| (c) S26-X26-# steel pipes instability failure load results |
|----------------------------------------------------------|
| Number of the Specimen | Instability Failure Load (kN) |
|-------------------------|-------------------------------|
| S26-X26-1               | 189                           |
| S26-X26-2               | 210                           |
| S26-X26-3               | 202                           |
| S26-X26-4               | 262                           |
| S26-X26-5               | 199                           |
| S26-X26-6               | 215                           |
It can be known from the static loading experiment data that the maximum strain occurred at the connection between the column foot and the base plate or at the top support point of the column. Taking specimens S26-000-3 and S20-000-1 as examples, the strain-load relationship at the foot and the top of the column was shown in Figure 8. Before the specimen S26-000-3 reached 250kN and S20-000-1 reached 300kN, the strain growth was approximately linear. The strain at the column foot and the column top was obviously larger than the column body strain. All specimens were subjected to in-plane bending.

5. Conclusion
From the analysis of the above experiment data, it can be concluded that:

1. By comparing the experimental data with the theoretical calculation results, it is known that the instability failure loads of the S26-X00-# steel pipes were basically consistent with the theoretical calculation result. The instability failure loads of the S20-X00-# steel pipes were about 15% different from the theoretical calculation result.

2. The instability failure loads for in-plane instability with support at 2.6 m and 3.5 m in the plane was relatively stable, with an average value of 221.3 kN. The average instability failure load for in-plane instability with support at 2.0 m and 3.5 m in the plane was 275.216 kN, and that average with support at 2.6m and 3.5m in the plane and stay cable out-of-plane at 2.6m was 212.8 kN.

3. The simplified analysis of the outgoing line frame column model to the single consolidated steel pipe model at the bottom can provide a reference for studying the overall structural forces and optimizing the design of the substation.

4. The model of outgoing line columns can be simplified to the model of single steel pipe with bottom fixed, and the deformation is within the allowable range. It can be used as a reference for the study of fully united framework and the optimization of substation design.

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