Research on the Application of High Strength Steel for 750kV Combined Framework

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Abstract: With the high strength steel being used widely in engineering, it’s certainly meaningful to research the application of high strength steel to substation frameworks. Using high strength steel of different grades including Q420, Q460, Q550 and Q690 for a 750kV combined framework instead of common steel, researchers have run its finite element analysis with different steel materials by SAP2000 and preliminarily designed its section, as well as valued its cost. The result demonstrates that the application of high strength steel in substation frameworks has certain economic and social benefits.

1. Introduction

The 750kV substation is a special ultra large substation in the nation's power grid, a very important role in the main UHV grid. As the main structure of the substation, the frame occupies a large area and costs amount of labor force, which consequently have a great influence on the layout and cost of the whole substation. For a long time, the steel’s grades used for transmission and transformation stations in our country are limited to Q235 and Q345, and the scarce types and the low strength of steel have led to a larger cross-section of frame, as well as increased the workload on installation, the investment and the waste of resources. High strength steel has the advantages of high strength and good bearing capacity, which can effectively smooth these above contradictions [1-2].

With a substation project in Xinjiang as the object, the SAP2000 as a calculation and analysis software, respectively adopting common steel and high strength steel such as Q420, Q460, Q550, Q690 steel, and carrying out finite element modeling and analysis with reference to the actual traverse load, local wind pressure and earthquake influence, as well as under the condition that the bearing capacity and displacement can meet the requirement of specifications, this paper analyzes the benefits of the employment of high strength steel for the substation frame and provides a theoretical basis for relevant researches.

2. Introduction to the calculation model

The overall schematic diagram of this 750kV substation frame is shown as Figure 1. Take the typical parts to study on and the related dimensions are shown in Table 1. The structure’s form is a lattice construction. The open root modeled and analysed is a square of 9.0m long and 4.0m wide. And high strength steel of four grades---Q420, Q460, Q550 and Q690 are used.
Figure 1. The whole diagram of the substation frame.

Table 1. Dimension Information of a Substation Project in Xinjiang

| project                                      | Dimension information |
|----------------------------------------------|-----------------------|
| Lower chord elevation of the busbar beam     | 27.000m               |
| Lower chord elevation of the beam containing inlet and outlet lines | 40.000m               |
| Top chord elevation of the column containing land-lines | 58.000m               |
| Span of the beam containing inlet and outlet lines | 42.0m                 |
| Span of the busbar beam                      | 41.0m                 |

Considering the small sizes of the frame beam members and their small internal force mainly controlled by deflection rather than strength, the use of high strength steel is restricted by the aspect ratio and size specification, so the frame beam continues to use common steel. While the materials used for lightning rod, as well as frame columns containing inlet and outlet lines and generatrix that bear larger load all are high strength steel.

Generally, there are two ways to integrally model a combined frame: practical modeling method and simplified modeling method. The former is to establish models of frame beams and columns and land-line columns according to the real situation, while the latter is to simplify a beam to a single member under the principle of equal rigidity and weight, and then model and calculate the beam separately. In order to make the calculation model more paralleled to the practice, actual modeling method is used in this paper by the SAP2000 [3]. All members are set as beam elements, and the connections between beams and columns are hinged.

3. Select the cross section

The cross section of each model member with steel and high strength steel are respectively compared as shown in Table 2. All sizes and materials used can meet the relevant provisions to steel structure.

Table 2. Comparison of the cross section of each model with steel and high strength steel

| Component | Common iron | Φ25×10 | Φ325×8 | Φ299×8 | Φ273×7 | Φ230×6 |
|-----------|-------------|--------|--------|--------|--------|--------|
| Gear of the inlet and outlet line Frame column Main material | Φ89×5 | Φ121×5 | Φ121×5 | Φ121×5 | Φ121×5 | Φ121×5 |
| Cross bar | Φ180×5 | Φ180×5 | Φ180×5 | Φ180×5 | Φ180×5 | Φ180×5 |
| Diagonal bar | Φ121×5 | Φ121×5 | Φ121×5 | Φ121×5 | Φ121×5 | Φ121×5 |
| Frame beam Chord member | Φ114×5 | Φ114×5 | Φ114×5 | Φ114×5 | Φ114×5 | Φ114×5 |
| Web member | Φ95×5 | Φ95×5 | Φ95×5 | Φ95×5 | Φ95×5 | Φ95×5 |
| Diagonal bar | Φ245×7 | Φ245×7 | Φ245×7 | Φ245×7 | Φ245×7 | Φ245×7 |
| Gear of the busbar Frame column Main material | Φ76×5 | Φ76×5 | Φ76×5 | Φ76×5 | Φ76×5 | Φ76×5 |
| Cross bar | Φ89×5 | Φ89×5 | Φ89×5 | Φ89×5 | Φ89×5 | Φ89×5 |
| Diagonal bar | Φ140×5 | Φ140×5 | Φ140×5 | Φ140×5 | Φ140×5 | Φ140×5 |
| Frame Chord member | Φ76×5 | Φ76×5 | Φ76×5 | Φ76×5 | Φ76×5 | Φ76×5 |
Note: the cross sections are all circular steel pipe and the unit is mm.

4. Load calculation of the frame

4.1. Conductor load

The conductor load is concentrated at three fixed points of the beams containing inlet and outlet lines and the busbar beams, among which the busbar beams on both sides settle wires in their side faces. (the load perpendicular to the frame beams) is the larger one between \( R_A \) and \( R_B \). The schematic diagram of conductor load is shown as figure 2, obtained from electrical engineering and the traverse load is shown in Table 3 and 4.

![Figure 2. Conductor load schematic diagram](image)

Table 3. The calculation results of the load on inlet and outlet lines (750 sideways)

| Status                        | Horizontal tension(H) | Unit | Perpendicular(RA) | Load (RB) | Unit |
|-------------------------------|-----------------------|------|--------------------|-----------|------|
| Max load                      | 96008.562             | N    | 3639.616           | 3210.904  | kgf  |
| Max wind velocity             | 77735.717             | N    | 3034.084           | 2711.896  | kgf  |
| Min temperature               | 59054.274             | N    | 2496.056           | 2245.484  | kgf  |
| Construction installation     | 5877.931              | N    |                    |           | kgf  |
| Three-phase weight of workers | 61131.675             | N    | 2548.292           | 2403.480  | kgf  |
| One-phase weight of workers   | 74527.804             | N    | 2688.716           | 2863.052  | kgf  |
| Lateral wind pressure         | 1161.418              | kgf  |

Table 4. The calculation results of the load on gears of busbar (750 lengthways)

| Max load                      | 47662.97              | N    | 1884.76            | 1884.76   | kgf  |
| Max wind velocity             | 39541.59              | N    | 1611.496           | 1611.496  | kgf  |
| Min temperature               | 32670.38              | N    | 1401.248           | 1401.248  | kgf  |
| Construction installation     | 32427.50              | N    |                    |           | kgf  |
| Three-phase weight of workers | 35727.51              | N    | 1457.860           | 1548.768  | kgf  |
4.2. Wind load
According to Code for load on Building structures (GB50009-2012) [4], the standard value of wind load is calculated by formula 1:

\[ \omega_K = \beta_Z \mu_Z \mu_S \omega_0 \]  
(1)

\( \omega_K \) (kN/m²) is the standard value of wind load; \( \beta_Z \) is a vibration factor; \( \mu_Z \) is a variable coefficient of wind pressure height; \( \mu_S \) is the structural shape factor of wind load; \( \omega_0 \) (kN/m²) is the fundamental wind pressure.

Considering different kinds of wind speed, the basic wind pressure can be approximately calculated by formula 2.

\[ \omega_0 = \frac{\nu^2}{1600} \]  
(2)

\( \nu \) (m/s) is the wind speed.

Referring to the Design Manual for Substation frame [5], the basic wind pressure corresponding to the wind speed of 10 m/s is taken under the small wind conditions (0.063 kN/m²) and the wind pressure of the region once in 50 years under gale conditions, but not less than 0.3 kN/m². According to Code for load on Building structures, the basic wind pressure in this area is 0.85 kN/m² once in 50 years.

For the herringbone columns, the latticed columns and the frame columns, the windshield coefficient can be calculated according to the net and contour area of bars and nodes. Then search for the wind load body size coefficients through the Table 3-3 and 3-4 in the Manual for the Design of Substation frame. The shape coefficients of the wind load on the herringbone column structures are listed in Table 3-2.

The value of the wind-induced vibration factor is determined by referring to the Article 5 of Code for the Design of Building structures (4.4.2): the wind vibration coefficient of the herringbone columns is 1.2, the lattice type tower structures 1.5, the single Steel pipe columns (h > 8 m) 2, and the steel pipe concrete columns 1.7.

As for the variable coefficient of wind pressure height, considering the geographical environment of substation, it can be adopted according to the type-A ground (desert) and by the Table 3-5 in the Design Manual for substation frame in detail.

Value of the wind load acting on the frame columns equals to the standard one on each column section multiplied by its member diameter. Then convert it into the line load on each column segment, which is applied in the form of uniform line load in SAP2000. And value of the wind load acting on the busbar beams equals to the windshield area multiplied by the standard value. After discounted by the windshield coefficient, the wind load is symmetrically distributed to the upper and lower chords of the truss beams, and finally applied in the form of uniform line load. The effects are shown in Figure 3.

\[ \text{(a) X direction} \quad \text{and} \quad \text{(b) Y direction} \]

Figure 3. Wind load effect diagram
4.3 Earthquake action
According to Code for Seismic Design of buildings\(^6\) (GB50011-2010, Partial revision), the seismic fortification intensity of the site is 8 degrees, and the basic design seismic gravity acceleration is 0.2 g (the second group).

5. Bearing capacity and displacement analysis

5.1 Bearing capacity analysis
Fig. 4 is a cloud diagram of stress ratio between common steel and high strength steel generated by the SAP2000. It can be seen that the maximum stress ratio appears in the position where the land-line columns are connected with the lightning rod, and the stress ratio at the bottom of frame columns is also large, while the stress ratio of frame beams are relatively small. The maximum stress ratio and the control conditions with the common steel and the high strength steel are shown in Table 5, which show that all the schemes are competent in bearing capacity.

![Figure 4. The stress ratio cloud diagram](image)

| Steel type | Max stress ratio | Control condition     |
|------------|-----------------|-----------------------|
| Common     | 0.739           | great wind, unfavorable-X |
| Q420       | 0.746           | great wind, unfavorable-Y |
| Q460       | 0.783           | great wind, unfavorable-Y |
| Q550       | 0.805           | great wind, unfavorable-Y |
| Q690       | 0.771           | great wind, unfavorable-Y |

5.2 Displacement analysis
According to the Technical Specification for structural Design of Substation buildings\(^7\) (DL/T 5457-2012), the displacement of a substation frame should be calculated under the load of serviceability limit states. For latticed tower structure (750kV), it is mainly controlled by the following two aspects:

(1) The allowable deflection in the middle of frame beams is \(H/400\). For busbar beams, it's 102.5mm (41000/400), while for beams containing inlet and outlet lines, it is 105mm (42000/400).

(2) The allowable deflection of independent lightning rods is \(H/70\) (Steel Tube). For framework lightning rods, it's 614mm (43000/70).

The calculated displacement of lightning rods and the maximum displacement in the middle of beams are shown in Table 6 to 8 and both can meet the requirements of code.

| Steel type | Direction x | Direction y |
|------------|-------------|-------------|
|            | Max displacement | Control condition | Max displacement | Control condition |
| Common     | 40.4        | Gale condition | 15.2 | Gale condition |
| Q420       | 29.2        | Gale condition | 28.6 | Gale condition |
| Q460       | 25.3        | Gale condition | 33.6 | Gale condition |
Q550 17.3 Gale condition 43.5 Gale condition
Q690 13.8 Gale condition 56.3 Gale condition

Note: units in the table are all mm.

Table 7. The displacement in the middle of the beams containing input and outlet lines

| Steel type | Direction x Max displacement | Control condition | Direction z Max displacement | Control condition |
|------------|-----------------------------|-------------------|-----------------------------|-------------------|
| Common     | 25.5 Gale condition         | 27.7 Gale condition |
| Q420       | 28.9 Gale condition         | 28.6 Gale condition |
| Q460       | 30.2 Gale condition         | 29 Gale condition  |
| Q550       | 35.1 Gale condition         | 30 Gale condition  |
| Q690       | 42.7 Gale condition         | 32.1 Gale condition |

Table 8. The displacement in the middle of the beams of the busbar beams

| Steel type | Direction-y Max displacement | Control condition | Direction-z Max displacement | Control condition |
|------------|-----------------------------|-------------------|-----------------------------|-------------------|
| Common     | 71.3 Gale condition         | 49.1 Gale condition |
| Q420       | 75.2 Gale condition         | 50.4 Gale condition |
| Q460       | 76.7 Gale condition         | 50.9 Gale condition |
| Q550       | 82.4 Gale condition         | 52.7 Gale condition |
| Q690       | 87.1 Gale condition         | 53.9 Gale condition |

6. Economic analysis

Referring to relevant databases[8], the unit prices when using common steel and various high strength steel are shown in Table 9. With this model, the consumption and the cost of different steel are shown in Table 10.

Table 9. The unit prices when using different steel

| Steel type | Detailed | Unit price |
|------------|----------|------------|
| Common     | Q235     | 4050       |
|            | Q345     | 4470       |
| High strength | Q420     | 4640       |
|            | Q460     | 5060       |
|            | Q550     | 5410       |
|            | Q690     | 6560       |

Note: the price unit is yuan / ton

Table 10. The quantity and cost of steel

| Steel type | Steel quantity | Steel cost Percentage decrease of cost |
|------------|----------------|----------------------------------------|
|            | Common steel | High-strength steel | 96.05 | 0 |
|            | Q235    | Q345        | 0.00 | 7.2% |
|            | Q420    | Q460        | 75.82 | 6.9% |
|            | Q460    | Q550        | 70.10 | 11.5% |
|            | Q550    | Q690        | 55.31 | 4.5% |
|            | Q690    | Q345        | 53.57 | 0 |

Note: quantity unit is t, cost unit is ten thousand yuan. The percentage reduction in cost is based on the amount of common steel used.

According to the table, using high-strength steel can obviously reduce the amount of steel used and reduce the total cost. Among them, the cost of Q550 steel is the lowest, which is lower than that of the common steel by 11.5%. It is economically more competent. From the economy, because the high-strength steel has the characteristics of high strength and outstanding bearing capacity which can meet
the engineering requirements well, the corresponding reduction of steel will not only save the cost, but also significantly reduce the cost of transportation and installation. From the social benefits, the use of high-strength steel conforms to the national reforms to save energy and reduce emission. In the long run, the use of high-strength steel will generate obvious economic and social benefits.

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