Structural Design of 35kV Composite Cross-arm Transmission Tower

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Abstract. For a long time, steel has occupied the most of the market for transmission towers because of its high strength, stable performance and easy connection. In recent years, Fiber Reinforced Polymer (FRP) has become the focus of the power industry due to its advantages of high strength, light weight, corrosion resistance, easy processing and good insulation performance. Based on the overhead transmission line design specifications, design requirements, research and engineering practice experience, the structural design of the 35kV composite cross-arm tower is completed in the paper. The design of the cross-arm frame, the joint design and the dimensional design are considered. The finite element static analysis is carried out in ANSYS, and results show the maximum deflection of the cross-arm is 36.8mm in the condition of loads long-term effects. According to the national design code for overhead transmission lines, the maximum node displacement of the 35kV FRP cross-arm tower meets requirements of the national code. In addition, the maximum stress of the 35kV composite cross-arm tower is 242MPa, which is far less than the FRP strength values 1130MPa listed in the Mechanics of composite materials, so its design strength also meets the design requirements. Subsequently, through economic analysis, it shows that there are good economic benefits, social benefits and broad application prospects in the 35kV composite cross-arm tower.

1. Introduction

High-performance fiber reinforced composites are characterized by high strength, light weight, corrosion resistance, durability and electrical insulation properties, making them ideal for manufacturing transmission towers [1]. The composite cross-arm is a cross-loader that uses composite materials instead of the steel used in the original transmission line, making full use of the advantages of composite insulation, high specific strength, light weight, excellent corrosion resistance and easy installation[2]. Composite cross-arm is another innovative application of the new composite materials in transmission lines after the composite insulators.

At present, FRP has been widely used in lattice and single-pole tower design for 220kV and below low voltage transmission lines at China and abroad. However, for transmission lines with large load and high voltage levels, it is more difficult to use composite materials in the whole tower [3].

In the design of the composite cross-arm tower, the tower body still adopts the traditional steel structure, and the FRP structure is adopted only in the tower head or the cross-arm portion [4]. This is the so-called partial insulation tower technology. This not only saves steel resources, but also reduces
the line corridors. At the same time, it is also avoided that a special grounding lead is required for the full composite tower. This is of great significance for the construction of a resource-saving and environment-friendly transmission line [5].

So far, they are not perfect enough that the national offshore transmission line design specifications, design requirements, research and engineering practice experience about the FRP cross-arms. Therefore, the consummation of the design for the 35kV FRP transmission rod is a necessary and basic work for the further research on the finite element static analysis problem.

2. Design for 35kV Composite Cross-Arm Tower

2.1. Basic Design Requirements

For the design of the 35kV composite cross-arm, the relevant design requirements are shown in Table 1 and Table 2.

Table 1. Basic design conditions.

| Parameters              | Conditions          |
|-------------------------|---------------------|
| Altitude                | Less than 1000m     |
| Terrain                 | Plains              |
| Maximum wind velocity   | 30m/s               |
| Ice thickness           | 10mm                |
| Conductor               | JL/G1A-240/30       |
| Ground                  | OPGW-24B1-70        |
| Cross-arm material      | FRP                 |

Table 2. Application conditions of the 35kV FRP tower.

| Tower type | Horizontal span | Vertical span | Number of loops |
|------------|-----------------|---------------|-----------------|
| ZN         | 220m            | 250m          | Single loop     |

2.2. Dimensional Design

The formula for determining the nominal height is as follows:

\[ H = \lambda + f_{\text{max}} + h_x + \Delta h \]  \hspace{1cm} (1)

where \( \lambda \) is the insulator string length, \( f_{\text{max}} \) is the maximum sag, \( h_x \) is the minimum distance from the wire to the design ground when the maximum sag occurs, and \( \Delta h \) is the construction allowance.

In view of the self-insulation and experimental demonstration of the composite tower, the design no longer uses the insulator string, and the wire is directly connected to the cross-arm by the fitting, so \( \lambda = 0.3 \text{m} \). It can be seen from the calculation of the stress sag that the maximum sag of the wire is 5.42m when the gear pitch is 250m. The tower body is designed to be safe according to the residential area. The vertical distance between the designed conductor and the ground is 7.0m, and the span of the working distance is 250m. Therefore, the nominal height is 13.02m. The nominal height is rounded to 14m.

When the wire is not synchronized, the center of the wire is close to the gear, which will cause the air gap between the wires to break down [6], resulting in flash over between the wires. For this reason, the gear distance below 1000m can be calculated as follows:

\[ D_m = 0.4\lambda + \frac{U}{110} + 0.65\sqrt{f_{\text{m}}} \]  \hspace{1cm} (2)
Where $\lambda$ is the suspended insulator string length, $U$ is the transmission line rated voltage, and $f_m$ is the maximum sag of the wire. Therefore, the gear distance is 2.77m.

When the two-phase wires are vertically arranged, the factors that make the distance between the wires close are mainly: the wire is not uniformly covered with ice or the wire is detached to cause jumping or the wire dancing causes a large up and down movement. In the procedure, the distance between the vertical lines is taken as three-quarters of the horizontally inter-line distance calculation:

$$D_v = 0.75D_m$$

Therefore, the distance between the vertical lines is 2.08m.

The height of the ground bracket is mainly determined by the minimum distance between the wire and the ground at the position of the central section of the span. Since there is no relevant composite material tower design specification, based on the above calculations, the following values are obtained with reference to the relevant design parameters: the upper cross-length is 1.1m, the lower cross-length is 1.5m, the vertical spacing of the grounding line is 1.5m, and the vertical spacing of the wires is 2.5m. Draw a sketch of the composite rod design as shown in Fig.1.

![Figure 1. FRP cross-arm tower head dimensions.](image)

### 2.3. Cross-Arm Architecture Design

The 35kV composite cross-arm is mainly composed of the line-post composite insulator and the connection fit of tip. The line-post composite insulator is composed of a composite insulating tube, an umbrella sleeve, an internal insulating medium and an end connecting fitting. It is mainly subjected to pressure and bending moment in the cross-arm structure.

| Part of the cross-arm | Diameter /mm | Length /mm | Length of metal parts /mm | Length of the insulating part /mm |
|------------------------|--------------|------------|---------------------------|----------------------------------|
| Upper cross            | $\Phi 90$    | 1100       | 204                       | 896                              |
| Lower cross            | $\Phi 90$    | 1500       | 279                       | 1221                             |
The connection fit of tip is used to connect the end metal parts of the line-post composite insulator, the suspension composite insulator, and the wire suspension metal string [7, 8]. The resin and fiber materials of the line-column composite insulator should be reasonably selected with reference to the structural importance, structure type, connection method and environment in which the structure is located. Then, the resin and fiber are optimized for material design.

The FRP cross-arm with the silicone rubber umbrella group [9] is used as the 35kV transmission tower cross-arm. The composite cross-arm parameters are shown in Table 3. Fig. 2 is the composite cross-arm product.

2.4. Node Connection Design
The composite cross-arm tower has attracted the attention and interest of the power industry due to its high strength, light weight, corrosion resistance and fatigue resistance [10, 11], durability and electrical insulation performance.

However, there are few studies on the node connections for composite cross-arm towers. The fixed connection of the composite cross-arm tower body to the cross-arm and the cross-arm to the diagonal tie rod still uses the conventional metal connecting member. The metal connecting members are mainly metal embedded parts and metal sleeves.

The linear expansion coefficient of the composite material is higher than that of the steel and the anisotropic characteristics are prominent. In the key connection design, the metal sleeve with resin-bonded flexible joining technology or structural adhesive [12, 13] is selected to solve the problem caused by the large difference between the expansion coefficient of the composite material and the steel.

3. Structural Analysis and Economic Comparison
Compared with the steel, FRP has a small modulus of elasticity, which determines its large deformation characteristics. The loads applied to the crossbar hanging point under different conditions (such as 90° max wind condition and loads long-term effects condition) are shown in Table 4 and Table 5.

Table 4. External force on conductor.

| Working conditions               | Along the cross direction/N | Along the transmission line/N | Vertically with the cross direction/N |
|----------------------------------|-----------------------------|-------------------------------|--------------------------------------|
| 0° max wind                      | 0                           | 787                           | 2397                                 |
| 45° max wind                     | 1575                        | 472                           | 2397                                 |
| 90° max wind                     | 3149                        | 0                             | 2397                                 |
| One lower conductor disconnected | 0                           | 11494                         | 1267                                 |
| The thickest ice                 | 898                         | 0                             | 4472                                 |
| Loads long-term effects          | 82                          | 0                             | 2397                                 |

Figure 2. Products of 35kV composite cross-arm.
Table 5. External force on ground.

| Working conditions                  | Along the cross direction/N | Along the transmission line/N | Vertically with the cross direction/N |
|-------------------------------------|-----------------------------|--------------------------------|--------------------------------------|
| 0° max wind                         | 0                           | 416                            | 858                                  |
| 45° max wind                        | 832                         | 249                            | 858                                  |
| 90° max wind                        | 1663                        | 0                              | 858                                  |
| One lower conductor disconnected    | 0                           | 0                              | 858                                  |
| The thickest ice                    | 890                         | 0                              | 1122                                 |
| Loads long-term effects             | 39                          | 0                              | 858                                  |

In order to analyze the displacement and stress characteristics of the composite cross-arm, the mechanical finite element simulation calculation of the composite cross-arm was carried out by ANSYS software, the load combination working conditions in Table 4 and Table 5 were applied to the finite element model. Displacement contour in 90° max-wind condition is shown in Fig. 3.

Table 6. Displacement and stress data of the composite cross-arm.

| Working conditions                  | Displacement/mm | Stress/MPa |
|-------------------------------------|-----------------|------------|
| 0° max wind                         | 89.6            | 50.4       |
| 45° max wind                        | 150.6           | 50.6       |
| 90° max wind                        | 274.6           | 50.8       |
| One lower conductor disconnected    | 434.4           | 242.1      |
| The thickest ice                    | 376.9           | 157.9      |
| Loads long-term effects             | 36.8            | 48.2       |

According to the national design code for overhead transmission lines [14], the maximum deflection of the cross-arm shall not exceed \(3h/1000\) (\(h\) is the ground to the calculation point height) in the long-term load operating conditions (wind speed \(v = 5\) m/s, ice thickness \(b = 0\)). And Table 6 shows...
that the maximum node displacement of the 35kV FRP composite cross-arm designed is 36.8mm in the condition of loads long-term effects, which meets the requirements of the national code above. In addition, the maximum stress of the composite cross-arm listed in the following Table 6 is 242MPa, which is far less than the FRP strength values 1130MPa listed in the Mechanics of composite materials [15], so its design strength also meets the design requirements.

In order to analyze the economics of the composite cross-arm tower, the 35kV composite cross-arm tower was compared with a conventional angle steel tower. The cross-arm structure of the composite cross-row linear tower is simpler. Compared with the conventional 35kV single-circuit tower, the composite cross-arm tower height is reduced by 0.8m. When the distance to the ground is equal, the descent index is 5.4%. The horizontal span between the wires is reduced by 0.2m, and the descent index is 11.8%. The use of the suspended insulator is eliminated, and the descent index is 100%.

Since the overhanging insulator is eliminated, the wire and the composite cross-arm end are directly connected by the metal fitting, and the wire has no space for the wind to oscillate. Therefore, the tower width and the corridor can be effectively reduced under the condition that the phase spacing is satisfied.

The reduction in the width of the corridor reduces the load on the wires, reducing the tower weight and the foundation force. The reduction in tower weight and the reduction of the foundation concrete result in a corresponding reduction in cost of construction.

4. Conclusion

Based on the existing national overhead transmission line design specifications, design requirements, research and engineering practice experience, the structural design of the 35kV composite cross-arm tower is completed in the paper. The design of the cross-arm frame, the joint design and the dimensional design are considered.

The 35kV composite cross-arm is constructed using a line-post composite insulator and a connection fit of tip. The metal connecting member is made of a metal embedded member and a metal sleeve. Through the external dimension design, the vertical spacing between the height of the call, the length of the cross-arm, the vertical spacing of the wires and the ground wire are determined.

The finite element static analysis is carried out in ANSYS, and results show the maximum deflection of the cross-arm is 36.8mm in the condition of loads long-term effects. According to the national design code for overhead transmission lines, the maximum node displacement of the 35kV FRP cross-arm tower meets the requirements of the national code. In addition, the maximum stress of the FRP cross-arm is 242MPa, which is far less than the FRP strength values 1130MPa listed in the Mechanics of composite materials, so its design strength also meets the design requirements.

Subsequently, through economic analysis, it shows that there are good economic benefits, social benefits and broad application prospects in the composite cross-arm tower.

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