Experimental Study on Axial Pressure Stability Bearing Capacity of Transmission Tower Composite Rod of Circular Section

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Abstract. In order to further popularize the application of glass fiber reinforced resin matrix composite material in transmission tower, the axial compression bearing capacity test of two cross-section types of composite material rods, including solid round mandrel and hollow round pipe, was carried out, which provided data reserve for the standardization of calculation formula of axial compression bearing capacity of composite material rod. In this paper, the applicability and influence factors of Euler formula and yield criterion stability calculation method were analyzed, the test data were fitted, and the value of the key coefficient in the calculation formula of the axial pressure stability coefficient of composite material compression bar of circular section was proposed, which provided support for the standardization of the calculation method of the bearing capacity of composite material compression bar for transmission tower.

1. Preface
Applying the composite material into the transmission tower can bring the advantages of the composite material into play, and the advantages include high insulation, light weight and high strength, and good anti-corrosion property [1-4]. Compared with steel structure tower, the composite material rod is usually applied into the composite insulating cross arm of tower. In this case, the cross arm of tower can be shortened, thus saving the corridor space. The composite material rod mainly bears the pressure and tension loads in the composite insulating cross arm of tower, in which, the compression member is mainly selected according to the bearing capacity for stability in case of suffering from pressure. At present, the formulas for calculation of axial pressure stability of composite material rod mainly include Euler formula and stability coefficient method. Main points which the current design personnel pay attention to are the applicability of design method and accuracy of parameter value taking.

The composite material rod of transmission tower involved in this paper mainly adopts glass fiber reinforced resin matrix composite material of extrusion or filament winding technology. The solid mandrel refers to composite material rod manufactured according to traditional transmission tower structure and rod connection mode, and its both ends are connected with steel joints in actual application.

At present, the calculation methods of stability bearing capacity of hollow circular section composite material rod mainly include Euler formula [5] and stability reduction factor method [6-9].
The calculation method of stability bearing capacity of hollow D-type cross section composite material rod includes the “edge failure criterion” stability reduction factor method [10]. At present, there are not many researches on the calculation method of axial pressure stability bearing capacity of solid mandrel. In this paper, the analysis and comparison between the axial pressure test data of solid mandrel and the results of Euler formula and finite element analysis were conducted, and then the calculation method of axial pressure stability bearing capacity of composite material rod of power transmission tower was proposed.

2. Axial Pressure Test

2.1. Mechanical Property of Composite Material

With regard to the mechanical property, the composite material product is discrete to some extent; the performance indexes of composite materials manufactured of different formulas, technologies and batches are discrete to some extent, and the discreteness coefficient of fiber reinforced material is within 7%-10% generally. To guarantee the accuracy and reliability of test results, in this paper, the actual situations of different technologies and different manufacturers were taken into consideration during the selection of test samples for compression bar stability bearing capacity of composite material, and 4 batches of products of different specifications were selected.

The axial pressure specimens of solid mandrel this time referred to φ80, φ110 and φ150 in specification, and there were totaling 69 specimens.

The material characteristic test was conducted to samples of each specification, and the elastic modulus and compression strength of composite material specimen of each specification are as shown in Table 1.

| No. | Specification | Slenderness Ratio | Elastic Modulus/MPa | Compression Strength/MPa |
|-----|---------------|-------------------|---------------------|-------------------------|
| A   | φ80           | 20~150            | 55900               | 618                     |
| B   | φ110          | 80~120            | 55000               | 741                     |
| C   | φ110          | 20~150            | 49200               | 690                     |
| D   | φ150          | 80~140            | 51400               | 533                     |

Note: The first letter A, B, C or D in the specification number representatives 4 batches respectively.

2.2. Test Device

For the composite material rod, considering that the boundary condition of its both ends in the truss structure was hinge joint, both ends of the specimen adopted spherical hinge connection, simulating the actual constraint status [11] of both ends of the member bar. The calculation length of specimen was the sum of spherical hinge height and specimen length.

Both ends of the specimen adopted connection of flange disc and spherical hinge. The solid mandrel was crimped together with the casing pipe (see Figure 1).

Figure 1. End Connection of Solid Mandrel Specimen

The test was completed in the steel framework loading device of the part laboratory of the ultra-high-voltage tower test base, and according to the bearing capacity of specimen, the horizontal test device and the vertical test device with bearing capacities of 3,000kN and 10,000kN were selected respectively. The test device is as shown in Figure 2.
2.3. Test Result
See Table 2 for the maximum test load of the solid mandrel specimen. Taking the φ110 solid mandrel specimen for example, the typical failure modes under different slenderness ratios are as shown in Figure 3.

The specimen with slenderness ratio of 40 below had no obvious deformation, showing strength failure form, with instantaneous failure at the end. The specimens with large slenderness ratios including 40, 60, 80 and 120 had obvious deflection change in the rod in the later period of the test, showing stability failure form. For specimens with slenderness ratio of 120 above, the deflection in the middle of the specimen was too large, and there would be collision of edges of test spherical hinges. From above situations, it can be known that the solid mandrel rods with slenderness ratios of 120 and above have relatively large deformation in the later period of bearing, and in case of being applied into the tower, there may be large deformation of the whole tower if the rod suffers from too large stress. This kind of members with large slenderness ratio shall not be used in main bearing members, and the influence of the deformation after suffering from stress on the deformation of the whole tower shall be taken into consideration. It can be known that the limit value for slenderness ratio of solid mandrel member of composite material for tower should be 120.

3. Euler Formula
In the transmission tower of truss structure, the critical load of compression bar is calculated as per the hinge joint of two ends when the rod is under compression. At the early stage of application of composite material rod on the transmission tower, the design personnel usually adopt the Euler formula, and this formula is the calculation method of stability bearing capacity [12] proposed targeting elastic axial pressure rod of ideal line, and its expression is shown as below:
In the formula: $F_{cr}$ refers to the critical load (or ultimate stability bearing capacity) of compression bar; $E$ refers to the elastic modulus; $A$ refers to the cross section area of rod; $\lambda$ refers to the slenderness ratio of member.

The Euler formula is established according to the approximate differential equation of the curved axis, and this equation is only applicable to the situation that the internal stress does not exceed the critical stress $\sigma_p$ at the elastic-plastic buckling stage of proportional limit, and its scope of application is shown as below:

$$\lambda \geq \pi \left( \frac{E}{\sigma_p} \right)^{\frac{1}{2}} = \lambda_p$$

In the formula: $\lambda_p$ refers to the ultimate value of slenderness ratio; $\sigma_p$ refers to the critical stress of compression bar.

For solid mandrel members of different slenderness ratios, the comparison between the value of bearing capacity of composite material pipe calculated through the Euler formula and the test result is as shown in Table 2.

### Table 2. Comparison among Test Value of Solid Mandrel, Finite Element Analysis Value, Calculated Value of Euler Formula and Calculated Value of Fitting Formula

| Specimen No. | Actual Slenderness Ratio | Test Value/kN | Finite Element Calculation Result/kN | Calculation Value of Euler Formula/kN | Calculation Result of Fitting Formula/kN |
|--------------|--------------------------|---------------|--------------------------------------|-------------------------------------|----------------------------------------|
| A80-20       | 25.5                     | 3323          | 2813                                 | 4265                                | 2332                                   |
| A80-40       | 45.5                     | 2269          | 1259                                 | 1340                                | 1128                                   |
| A80-60       | 65.5                     | 2157          | 626                                  | 646                                 | 586                                    |
| A80-80       | 85.5                     | 1134          | 371                                  | 379                                 | 354                                    |
| A80-100      | 105.5                    | 648           | 244                                  | 249                                 | 236                                    |
| A80-120      | 125.5                    | 465           | 171                                  | 176                                 | 168                                    |
| A80-140      | 145.5                    | 205           | 128                                  | 131                                 | 126                                    |
| A80-150      | 155.5                    | 153           | 112                                  | 115                                 | 111                                    |
| B110-80      | 84                       | 1207          | 731                                  | 731                                 | 686                                    |
| B110-100     | 104                      | 637           | 473                                  | 477                                 | 454                                    |
| B110-110     | 114                      | 436           | 395                                  | 397                                 | 379                                    |
| B110-120     | 124                      | 377           | 331                                  | 336                                 | 322                                    |
| C110-20      | 24                       | 5264          | 5802                                 | 8012                                | 4719                                   |
| C110-30      | 34                       | 4296          | 3660                                 | 3992                                | 3143                                   |
| C110-40      | 44                       | 2937          | 2272                                 | 2384                                | 2055                                   |
| C110-60      | 64                       | 2401          | 1099                                 | 1127                                | 1033                                   |
| C110-80      | 84                       | 1148          | 645                                  | 654                                 | 614                                    |
| C110-100     | 104                      | 1015          | 420                                  | 427                                 | 406                                    |
| C110-120     | 124                      | 623           | 296                                  | 300                                 | 288                                    |
| C110-150     | 154                      | 289           | 190                                  | 195                                 | 188                                    |
| D150-80      | 82.9                     | 1912          | 1269                                 | 1303                                | 1208                                   |
| D150-90      | 92.9                     | 1108          | 1018                                 | 1038                                | 972                                    |
| D150-100     | 102.9                    | 895           | 824                                  | 846                                 | 798                                    |
| D150-120     | 122.9                    | 521           | 561                                  | 593                                 | 565                                    |
| D150-140     | 142.9                    | 431           | 429                                  | 439                                 | 421                                    |
In Table 2, the slenderness ratios of both A80-20 and C110-20 are smaller than $\lambda_p$ (the limit value $\lambda_p$ of slenderness ratio of the manufacturer A is 29.9, and that of the manufacturer C is 26.5), and the test proves that the calculation with the Euler formula has a certain scope of application. For members with slenderness ratio of above $\lambda_p$, the theoretical bearing capacity calculated with the Euler formula is smaller than the test result, and the test results show that for members with slenderness ratio of above $\lambda_p$, the formula 1) and the formula 2) are reasonable for calculation.

4. Finite Element Analysis

4.1. Finite Element Modeling
For test member, the general finite element software ANSYS shall be selected to establish finite element model, and the solid mandrel shall adopt BEAM188 unit for simulation. Add X-direction and Y-direction constrained translation freedom degree at the top of specimen, and release the Z-direction translation constraint; add X-direction, Y-direction and Z-direction constrained translation freedom degree at the bottom of specimen, and constrain the rotating freedom degree along with the axial direction of two ends of the member. The calculation model of finite element is as shown in Figure 4.

In case of calculating the axial pressure bearing capacity, considering the influence of initial bending, the overall initial bending of the member refers to a half-sinusoid, and the peak value is the 1/1,000 of member length. Considering the characteristics of composite material, but not considering the influence of residual stress during the calculation, the material performance shall be subject to actually measured value of test member, as shown in Table 1.

4.2. Calculation Result of Finite Element
The finite element model was conducted to the test member according to measurement data of test, and then the non-linear buckling analysis was conducted, thus obtaining the ultimate load of member, as shown in Table 2.

For many members were calculated, only the finite element calculation result of axial pressure bearing capacity of solid mandrel Bφ110-80 when the slenderness ratio is $\lambda$=80 is listed, as shown in Figure 5.

![Figure 4. Finite Element Calculation Model of Solid Mandrel Specimen](image)

![Figure 5. Calculation Result of Finite Element of Solid Mandrel Bφ110-80](image)
4.3. Conformance of Finite Element Analysis

Compared with the calculation result of Euler formula (except the situation that the limit value of slenderness ratio is \( \lambda_p \) below), the stability coefficient \( \phi \) value calculated through finite element analysis is smaller than the calculated value of finite element by 0.01%-8.31%. It can be known that the finite element model established in this paper is high is accuracy and reliability.

5. Test Fitting Formula

Fibers inside the composite material are arranged differently in direction, and the arranged amounts of fibers in various directions are also different; in addition, the material performances in various directions are different. Meanwhile, the differences in processing technology and raw material performances of various manufacturers cause large discreteness of material performances [13]. The differences of fiber arrangement, processing technology and raw material performances of composite material are main factors which influence stability performance of rod bearing capacity.

Through test, it is found that the solid mandrel will keep the linear elasticity characteristic approximately before the axial pressure reaches the ultimate strength. During the test, there will be abnormal sound once or twice generally, and this is usually caused by local failure of edge organization of composite material, but this will not influence continued bearing of member. When the member deformation becomes severer, there will be unstable failure of member. The axial pressure instability of composite material belongs to elastic-plastic state instability, and the stability coefficient determined by ultimate load theory should be adopted.

Through above analysis, it can be known that the calculation method of bearing capacity of the maximum buckling criterion is suitable. To facilitate calculation, based on the calculation formula of steel member stability bearing capacity of the maximum buckling criterion, the reference [14] determined the stability calculation of axis pressure member of composite material refer to formulas (3) to (6).

\[
\frac{N}{\phi \cdot A} \leq f_c
\]  

(3)

In the formula:  
- \(N\) - axial pressure stability bearing capacity of composite material rod, kN;  
- \(\phi\) - Stability coefficient of axis pressure member, calculated as per formulas 4) to 6);  
- \(f_c\) - Design value of compressive strength of composite material, MPa.  
- \(\lambda_n \leq 0.215\)

\[
\phi = 1 - \alpha_1 \lambda_n^2
\]  

(4)

\(\lambda_n > 0.215\)

\[
\phi = \frac{1}{2 \lambda_n^2} \left[ \left( \alpha_2 + \alpha_3 \lambda_n + \lambda_n^2 \right) - \left( \left( \alpha_2 + \alpha_3 \lambda_n + \lambda_n^2 \right)^2 - 4 \lambda_n^2 \right)^{1/2} \right]
\]  

(5)

\[
\lambda_n = \frac{K \lambda}{\pi} \left( f_c / E \right)^{1/2}
\]  

(6)

In the formula:  
- \(K\)-Component slengerness ratio correction coefficient.

The test value of specimen, calculated value of Euler formula and calculated value of finite element were listed into Figure 6, and the data was mixed in a relatively uniform way, with the fitting stability curve as shown in Figure 6. This curve not only guarantees accuracy and reliability of the test, but considers convenience of calculation. Through calculation, the obtained 3 parameters in calculation formulas (4) to (5) of axial pressure stability coefficient of composite material member take the following values: \(\alpha_1 = 0.56, \alpha_2 = 0.990\) and \(\alpha_3 = 0.188\).
Figure 6. Comparison between the Calculated Value of Recommended Formula for Stability Bearing Capacity of Composite Material and the Test Value

From Figure 6, it can be known that the regularization slenderness ratio-stability coefficient curve fitted with test value is close to the calculated value of finite element and the calculated value of Euler formula, and is lower than the test value, calculated value of finite element and calculated value of Euler formula. This curve is high in envelope, and the calculation result is safe and reliable when it is used in the design. Meanwhile, it can be known that with the increasing of slenderness ratio, the calculated results of Euler formula and finite element are closer to the test result, which means that the initial defect has greater influence on the overall stability bearing capacity of short slenderness ratio specimen. In case of considering initial defects such as performance instability of material, the fitting formula can be adopted for calculation for it is more all-around, with greater applicability and higher reliability.

6. Conclusions

By combining the axial pressure test of solid mandrel, this paper analyzed the applicability of main calculation method of axial pressure stability of composite material member at present, and proposed the calculation method of axial pressure stability bearing capacity of composite material member of circular cross section. Main conclusions are shown as below:

1) The slenderness ratio of the solid mandrel member of composite material for tower should be 120.

2) The Euler formula is applicable to the calculation of bearing capacity of the member whose slenderness ratio is greater than \( \lambda_p \).

3) The calculation of axial pressure stability coefficient of solid mandrel member of composite material should adopt the maximum buckling criterion formulas (4), (5) and (6); in which, \( \alpha_1 = 0.56 \), \( \alpha_2 = 0.990 \), and \( \alpha_3 = 0.188 \).

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