

Structure Design and Analysis for 110kV FRP Transmission Pole

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Abstract— As an important class of special load-bearing structure, transmission pole affects the security, economy and reliability of transmission lines running directly. With the implementation of domestic major projects in recent years, such as UHV project, smart grid and transformation of rural grid, transmission pole of composite materials (referring to fiberglass reinforced composites in this paper) becomes one focus of attention in electric power industry for its lightweight, high strength, good electrical insulation, easy maintenance and good environmental adaptability, etc. Based on the existing national code for design of overhead transmission lines, design requirements, research and engineering practical experience, the structure design of a 110kV FRP pole is completed in the paper. Subsequently, the problem of small elastic modulus and large deflection are solved by mainly considering the pole's structure, material and cross section, etc. Then, the finite element static analysis is carried out in ANSYS. Result shows that the transmission pole meets the requirements of stress and deflection in the national code, which provides a theoretical reference for a further research.

Keywords-FRP; 110kV transmission pole; Structure design; Finite element static analysis.

I. INTRODUCTION

As an important load-bearing structure of overhead transmission lines, the present materials of transmission pole are mainly steel, concrete and wood. It is reported that, the traditional pole of steel, concrete or wood commonly has many defects, such as large quality and power loss, being easy to be corrosive and cracking, being hard and be expensive of transportation, construction and maintenance^[1], which consumes a lot of mineral resources and destroys environment. So FRP (Fiberglass Reinforced Plastic) transmission pole becomes one focus of attention in electric power industry and has made a significant progress in a number of domestic research applications^[2], as a low-carbon, energy-saving, environmentally friendly and new structures meeting the technical aesthetics for its lightweight, high strength, good electrical insulation, easy maintenance and good environmental adaptability, etc.

China has started research on composite transmission structure since the 1950s, but failed to promote application for the limit to material properties and technological level^[3]. In recent years, especially since 2009, the State Grid has begun to promote the construction of resource-saving,

environment-friendly, new technology, materials and technology transmission lines, with the improvements in manufacturing process and properties of fiber and resin materials. Subsequently, many domestic companies and research institutes start laboratory for exploration and research on composite transmission structure.

At present, pilot projects of FRP transmission structure at voltage level of 110kV, 220kV, 500kV and 750kV are running in China^[4]. Wherein, those of 220kV and below are commonly single-rod or lattice, but for a higher voltage level or heavier load line, adopt partial insulating of FRP cross-arm. Subsequently, latticed structures made from FRP have gradually attracted many attentions^[5].

However, there is no national or industry technical code of FRP transmission structure published in China, the paper will solve the problem of small elastic modulus and large deflection of the FRP transmission pole by considering to optimize material and cross section, etc., basing on the existing national code for design of overhead transmission lines, design requirements, research and engineering practical experience. Then, complete the design for 110kV FRP transmission pole and summarize the issues to consider for a further study in the design by finite element static analysis.

II. DESIGN FOR 110 kV FRP POLE

A. Design Parameters

1) Design Requirements

- a) Environment:
 - meteorological conditions: typical region VI
 - altitude: less than 1000m
 - contamination level: class III
 - terrain: plains.
- b) Voltage level and number of loops: 110kV, double-loop.
- c) Conductor: LGJ240/30, Ground: JL/LB1A-95/55.
- d) Design span: horizontal span $l_h=200\text{m}$, vertical span $l_v=250\text{m}$.
- e) Weather conditions: maximum wind velocity $V_{\max}=25\text{m/s}$, ice thickness $\delta=10\text{mm}$, the highest temperature $t=40^\circ\text{C}$.
- f) The main pole adopts FRP.

2) Design Parameters

According to the conductor and ground type in design requirements above, the design parameters of them are found or calculated, and listed in the following Table I.

TABLE I. PARAMETERS OF CONDUCTOR AND GROUND

Design Parameter	Conductor	Ground
Calculated sectional area A (mm ²)	275.95	100.88
Diameter d (mm)	21.60	12.48
Linear elastic coefficient E (MPa)	73000	103600
Thermal expansion coefficient α (1/°C)	19.6×10^{-6}	15.5×10^{-6}
Tensile strength σ_p (MPa)	260.324	612.014
Safety coefficient k	2.5	3
Calculated tensile force (N)	75620	61740
Allowable stress $[\sigma_0]$ (MPa)	104.13	204.005
Annual operational stresses $[\sigma_p]$ (MPa)	65.08	153.003
Nominal weight per km (kg/km)	922.2	474.6

According to the design requirements above and design parameters in Table I, the unit-load (means unit-length & unit-area weight) of conductor and ground is calculated in the following Table II.

TABLE II. UNIT-LOAD OF CONDUCTOR AND GROUND

Unit-load category (10 ⁻³ MPa/m)	Conductor	Ground
Own weight load $\gamma_1(0,0)$	32.75	46.14
Icing weight load $\gamma_2(10,0)$	31.75	61.79
Vertical total load $\gamma_3(10,0)$	64.50	107.93
$\gamma_4(0,10)$	5.38	9.28
$\gamma_4(0,15)$	9.08	15.67
No icing wind load $\gamma_4(0,25)^*$	28.59	49.29
$\gamma_4(0,25)^{**}$	20.52	35.37
$\gamma_4(0,5)$	1.01	1.74
Icing wind load $\gamma_5(10,10)$	10.36	22.14
$\gamma_6(0,10)$	33.19	47.06
$\gamma_6(0,15)$	34.91	48.72
No icing complex load $\gamma_6(0,25)^*$	43.47	67.52
$\gamma_6(0,25)^{**}$	38.65	58.14
$\gamma_6(0,5)$	32.77	46.17
Icing complex load $\gamma_7(10,10)$	65.33	110.18

Notes: * used in strength check

** used in wind deviation check

B. Structure Design

1) Calculate the Maximum Sag

Those may be the control meteorological conditions are the lowest temperature, maximum wind, icing wind and annual average temperature. Because maximum wind and icing wind are of the same temperature and allowable stress, the one has smaller unit-load can not be the control meteorological condition. Therefore, maximum wind is no longer possible to be the control meteorological condition, according to Table II. Comparison of the other three meteorological conditions is in Table III.

TABLE III. COMPARISON OF METEOROLOGY

Meteorology	The Lowest Temperature	Icing Wind	Annual Average Temperature
$[\sigma_0]$ (MPa)	104.13	104.13	65.08
t (°C)	-20	-5	10
γ ($\times 10^{-3}$ MPa/m)	32.75	65.33	32.75
$\gamma / [\sigma_0]$ ($\times 10^{-3}$ /m)	0.3145	0.6274	0.5032
Number*	a	c	b

Notes: *Number of $\gamma / [\sigma_0]$ from small to large

Critical span is calculated as follows:

$$l_{ij} = \sqrt{\frac{24[[\sigma_0]_j - [\sigma_0]_i + \alpha E \cos \beta (t_j - t_i)]}{E[(\frac{\gamma_j}{[\sigma_0]_j})^2 - (\frac{\gamma_i}{[\sigma_0]_i})^2] \cos^3 \beta}} \quad (1)$$

Assuming no elevation, $\cos \beta = 0$. The data in Table III into the Formula (1), critical spans are calculated in the following Table IV.

TABLE IV. DISTINGUISH OF EFFECTIVE CRITICAL SPAN

Control conditions	a (The lowest temperature)	b (Annual average temperature)	c (Icing wind)
Critical span	$l_{ab}=90.8\text{m}$ $l_{ac}=154.7\text{m}$	$l_{bc}=202.9\text{m}$	—

The Table IV above shows, $l_{ab}=90.8\text{m}$ and $l_{bc}=202.9\text{m}$ are effective critical spans. So the lowest temperature will be the control condition at horizontal span $l_h < l_{ab}$, annual average temperature at $l_{ab} < l_h < l_{bc}$, and icing wind at $l_h > l_{bc}$. Apparently, annual average temperature is the control meteorological condition in this paper.

Calculate the stress σ_0 and sag f under unknown conditions of the highest temperature, external overvoltage no wind, and icing no wind using the following state equation, with annual average temperature known. Stress σ_0 and sag f under different spans are listed in Table V.

State equation:

$$\sigma_{c2} - \frac{E\gamma_2^2 l^2}{24\sigma_{c2}^2} = \sigma_{c1} - \frac{E\gamma_1^2 l^2}{24\sigma_{c1}^2} - \alpha E(t_2 - t_1) \quad (2)$$

Sag equation:

$$f = \frac{\gamma_0 l^2}{8\sigma_0} \quad (3)$$

TABLE V. STRESS σ_0 AND SAG f UNDER DIFFERENT SPANS

Span (m)	The highest temperature		External overvoltage no wind		Icing no wind	
	σ_0 (MPa)	f (m)	σ_0 (MPa)	f (m)	σ_0 (MPa)	f (m)
100	44.35	0.92	70.17	0.58	103.88	0.78
150	46.60	1.98	65.62	1.40	103.68	1.75
200	48.15	3.40	61.80	2.65	103.50	3.12
202.9	48.22	3.50	61.61	2.74	103.49	3.21
250	51.35	4.98	62.31	4.11	107.21	4.70
300	53.90	6.84	62.87	5.86	110.50	6.57
350	55.86	8.98	63.30	7.92	113.19	8.73
400	57.39	11.41	63.63	10.29	115.38	11.18

Results show that the maximum sag $f=3.5\text{m}$ occurs at the highest temperature conditions.

2) Material and Dimension Design

Transmission pole generally adopts resin-based composite materials, mainly composed of resin and reinforcing fibers, and the reinforcing fibers commonly is fiberglass.

In order to prevent conductor cross-arm from bending and narrowing the safety gap excessively, foam-filled hollow tube is used for cross-arm to improve its flexural rigidity, which makes up for its deficiencies of small elastic modulus and large deflection effectively [6]. And increase FRP insulators rods, which is fixed to the pole via metal hoops [7,8]. Meanwhile, to prevent pollution and lightning flashover, silicone rubber sheath dressing with sheds is added to the hollow FRP tube, which will enhance the creepage distance of FRP cross-arm effectively.

For the main pole, use an all-composite tapered tube rod, which is fixed to the foundation anchor bolts by a metal sleeve flange. To make up for the difference of expansion coefficient between FRP and steel, adopt resin-casting flexible-connection techniques or structural adhesive between the metal sleeve flange and the FRP pole.

According to the literature [9], and referencing the dimensions of a double-loop FRP test pole in Panzi, Shenzhen, its top diameter of the preliminary design is 500mm, the root diameter is 700mm and the thickness is 20mm, and cancel suspension insulator strings. Dimensions of pole head are shown in Fig. 1.

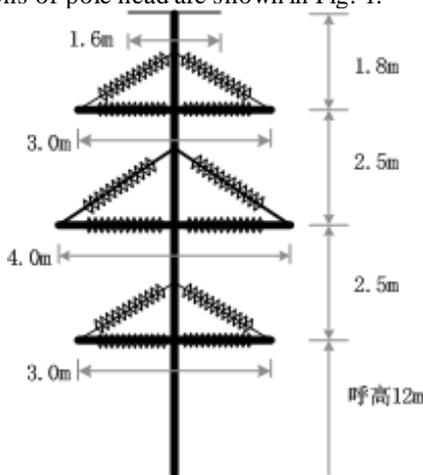


Figure 1. FRP pole head dimensions.

3) Main Pole Cross-section

For a single all-composite pole, in order to increase its flexural rigidity, it is necessary to design a reasonable cross-section or rib inside, to obtain a maximum moment of inertia for the same cross-sectional area. According to the literature [10], three main forms of cross-section are shown in Fig. 2. Among them, the triangular rib structure is superior to the others not only in terms of deformation but also stress. Therefore, choose the cross-section with triangular rib.

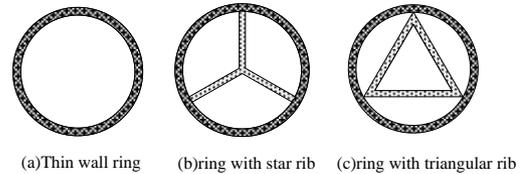


Figure 2. FRP pole cross-section.

III. STATIC ANALYSIS

A. Finite Element Modeling

As it is shown in Fig. 3, omit the cross-arm insulator sheds and pull rods, build the ground support, FRP cross-arm and the main pole as a whole model using SHELL99 element, since that stress and deformation of the main pole is mainly studied in the paper. And basic structure parameters of FRP are listed in the following Table VI, according to the literature [11].

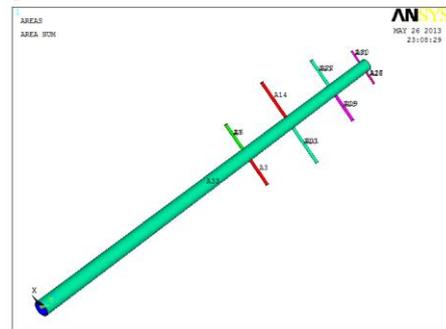


Figure 3. FRP pole finite element modeling.

TABLE VI. BASIC STRUCTURE PARAMETERS OF FRP.

Structure Parameter	Parameter Value
E_x (GPa)	39.8
E_y (GPa)	8.4
E_z (GPa)	8.4
μ_{xy}	0.25
μ_{xz}	0.25
μ_{yz}	0.25
G_{xy} (GPa)	4.2
G_{xz} (GPa)	4.2
G_{yz} (GPa)	4.2

B. Design of Ply Packing

The total ply numbers, thickness and orientation angle of each ply are shown in Table VII, dividing into three parts such as the main pole, cross-arm and ground support. Fig. 4 is the symmetrical ply packing of the main pole.

TABLE VII. PLY PACKING PARAMETERS OF FRP.

Structure	Numbers	Thickness	Orientation Angle (°)
Main pole	10	2	0/45/0/-45/0/0/-45/0/45/0
Cross-arm	10	1	0/45/0/-45/0/0/-45/0/45/0
Ground support	7	1	0/45/0/-45/0/45/0

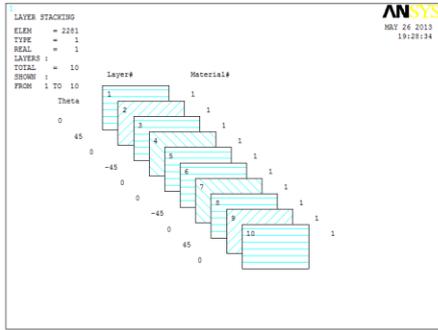
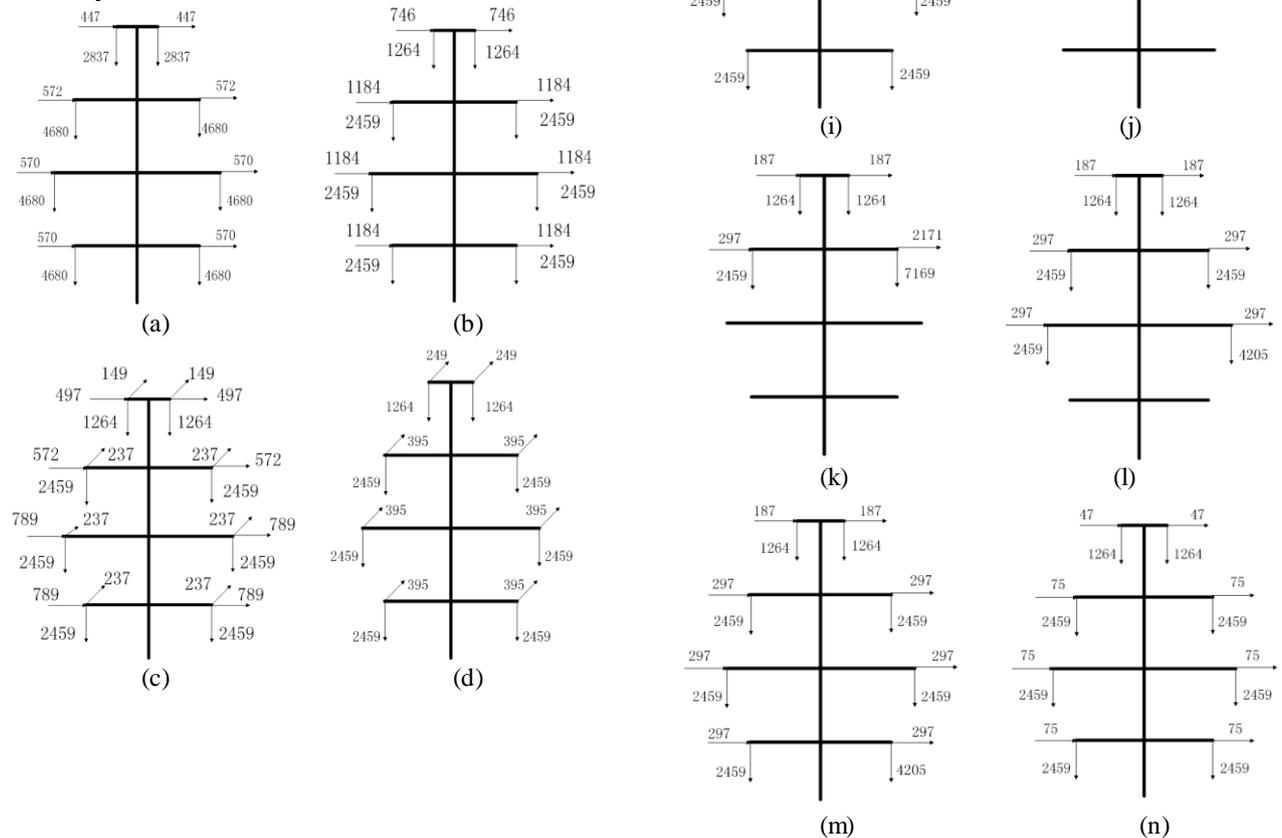


Figure 4. ply packing of the main pole.

C. Load Calculation

Whether the external loads combination on the pole is reasonable directly affects its safety and economy. According to GB 50545-2010 "Code for designing of 110~750kV overhead transmission line", the working conditions of operation, disconnection, installation and special load must be considered in the strength calculation and analysis.



(a-d) Operating conditions I (90°,60°,45° and 0° wind); (e) Operating conditions II;
 (f-i) One upper, middle, lower conductor, and ground disconnected
 (j-m) One ground, and upper, middle, lower conductor installed
 (n) Loads long-term effects

Figure 5. External load on the pole head

D. Analysis of Results

Apply the boundary and loads to the FRP pole, and calculate the working conditions of loads combinations in Fig. 5. Displacement contour in the 60° maximum wind condition is shown in Fig. 5. In order to analyze the internal forces and deformation of the main pole, a list of its maximum node stress and displacement is output in the following table VIII.

TABLE VIII. MAXIMUM NODE STRESS AND DISPLACEMENT OF THE MAIN POLE.

Working Conditions	Stress (MPa)	Displacement (mm)	Deflection	
Operating conditions I	0° max wind	36.08	129.89	0.68%
	45° max wind	36.88	351.36	1.85%
	60° max wind	37.16	531.67	2.80%
	90° max wind	37.63	708.41	3.73%
Operating conditions II	The thickest ice	69.60	272.67	1.44%
	One upper conductor disconnected	83.97	627.56	3.30%
Accident conditions	One middle conductor disconnected	135.25	472.83	2.49%
	One lower conductor disconnected	92.37	331.09	1.74%
	One ground disconnected	48.78	341.11	1.80%
	One upper conductor installed	70.35	268.87	1.42%
Installation conditions	One middle conductor installed	63.34	239.39	1.26%
	One lower conductor installed	36.13	223.41	1.18%
	One ground installed	69.60	111.00	0.58%
Loads long-term effects	35.85	34.05	0.18%	

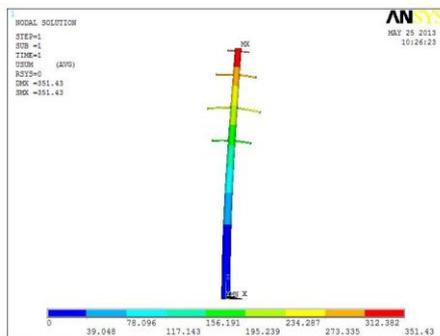


Figure 6. Displacement contour in 60° max-wind condition.

According to the current national code for designing of overhead transmission line^[12], the maximum deflection of the pole must not exceed 5‰ in the operating condition of loads long-term effects (wind velocity $v=5\text{m/s}$, ice thickness $b=0$). And Table VIII shows that the maximum node displacement of the 110kV FRP pole designed is 34.046mm in the condition of loads long-term effects, that is deflection of 1.79 ‰, which meets the requirements of the national code above.

In addition, the maximum node stress of the main pole is 152MPa, which is far less than the FRP strength values listed in the following Table IX^[11], so its design strength also meets the design requirements.

TABLE IX. BASIC PERFORMANCE PARAMETERS OF FRP

Basic Performance Parameter	Parameter Value
σ_{x+} (MPa)	1130
σ_{x-} (MPa)	612
σ_{y+} (MPa)	36.7
σ_{y-} (MPa)	0.25
τ_{xy} (MPa)	0.25

IV. CONCLUSION

Based on the existing national code for designing of overhead transmission line, design requirements, research and engineering practical experience, the structural design of a 110kV FRP pole is completed in the paper. And the problem of small elastic modulus and large deflection are solved by mainly considering the transmission pole's structure, material and cross section, etc. Finally, the finite element static analysis is carried out in ANSYS, results show:

(1)The maximum node displacement of the 110kV FRP pole is 34.046mm in the condition of loads long-term effects, that is deflection of 1.79‰, which meets the requirements of 5‰ in the national code.

(2)The maximum node stress of the main pole is 152MPa, which is far less than the FRP strength values, so its design strength also meets the design requirements.

In conclusion, studies show that the FRP transmission pole meets the requirements of stress and deflection in the existing national code, which provides a theoretical reference for a further research.

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