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Performance Analysis of a Overhead Power Transmission Line Tower Using Polymer Composite Material

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Abstract

For technical, aesthetic and economic reasons, our next generation overhead power transmission lines will be built with new materials and new design concepts in order to reduce the dimensions of the support structures. This paper discusses the mechanical performance tests carried out on a 66 kV overhead power transmission line tower built with Fiber Reinforced Polymer (FRP) composite material for the first time in India. The details of development of composite tower and its performance during full scale test carried out at Central Power Research Institute (CPRI) Bangalore, India are presented

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1. Introduction

The increasing demand for power requires construction of new power plants and additional transmission lines. The planning and erecting of new overhead power transmission lines have become a major problem in many countries, not only because of environmental impacts but also to the limited space in densely populated areas. Thus new technologies have to be developed and introduced. In the last few decades many concepts have emerged in overhead power line designs mainly considering growing environmental constraints.

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One of the concerns is the Right of Way (ROW), the strip of land accommodating the transmission line which depends on the voltage and technical specification of the line. The increasing demand for power requires construction of new power plants and additional transmission lines. The planning and erecting of new transmission lines have become a major problem in many countries, not only because of environmental impacts but also to the limited space in densely populated areas. Thus new technologies have to be developed and introduced. In the last few decades many concepts have emerged in overhead power line designs mainly considering growing environmental constraints. One of the concerns is the Right of Way (ROW), the strip of land accommodating the transmission line which depends on the voltage and technical specification of the line.

In recent times, public opposition to the construction of new power lines has increased due to awareness of environmental implications which is limiting the space for transmission lines. In addition, conventional metallic tower with heavy ceramic insulators tend to corrode fast and become damaged. New types of support structures for a transmission line are to be developed to reduce the dimension of the line, in both horizontal and vertical directions. Thus technology of compact transmission lines is being increasingly adopted by the power industry to effectively make use of the ROW. Therefore, it could be possible to build towers in transmission lines by using composite materials for resolving the above problems. Hsein-Yang Yeh et. al [1] studied the feasibility of building a transmission tower from composite material, E-glass and Vinyl ester.

Hsein- Liang Yeh et.al [2] carried out the failure analysis of a composite transmission tower and compared their results various failure criteria. Alipour et.al [3] introduced a polymer cross arm to make overhead transmission lines more compact and studied its influence on decreasing the ROW of transmission lines. Izumi et.al [4] developed line post type polymer insulation arm for 154 kV and tested its mechanical and electrical performance through a full scale model with hollow FRP elements made by filament winding process. Brian C. W et. al [5] studied modifying the existing 132 kV transmission tower to 230 kV with insulated cross arm to reduce the ROW. Heidari & Heidari [6] investigated the effect of land price on the power transmission line design in urban areas and listed the factors to be considered for compact transmission towers. According to the above, the design and development of transmission towers with polymer composite materials is a new concept being attempted. These materials are more economical in view of inherent properties such as electrical insulation, corrosion resistance, high strength to weight ratio.

The present study is intended to be a significant step in understanding the performance of a 66kV FRP composite material tower built from pultruded structural sections for first time in India. The performances of the FRP composite material tower under mechanical loading are presented in this paper.

2. Development of composite cross arm

The composite cross arm has been basically designed to replace steel cross arm with ceramic insulators. The composite cross arm consists of four pultruded structural elements fabricated for a 66 kV double circuit transmission line as per recommendations in IS:5613 (Part-2/Sec-1):1985 and IS :802 (Part-1/Sec-1):1995 RA 2006 [7][8]. Each element comprises of a solid core, metal end-fittings and silicone rubber housing with sheds. The core is a composite pultruded rod which sustains mechanical loads. The reinforcing fiber used is E-glass (75% by weight) and the matrix (25 % by weight) is epoxy resin. The composite rod is manufactured by pultrusion process where reinforcement is impregnated with resin and pulled through a heated die which delivers final shape for cross section. The silicone rubber housing provides electrical insulation and protects the composite rod. The sheds are provided to increase the insulator performance under wet and polluted conditions. The rubber housing is laid on composite rods to have sufficient adhesion and chemically bond to prevent damage from water contamination at the interface. The metal end fittings are attached to the end of rod by the crimping process. The material properties of different FRP sections are determined through experiments and compared with manufacturer's value are shown in Table 1.

Table 1. Material properties.

Properties	Suppliers' value	Tested value	ASTM Test method
Specific gravity	2.0	2.2	D792
Water absorption %	0.03	0.02	D570
Compression strength N/mm ²	406	416	D349
Tensile strength N/mm ²	851	750	D638
Flexural strength N/mm ²	1190	1182	D349
Impact strength kJ/m ²	488	472	D256
Dielectric strength in oil kV/mm	40	43	D149

The assembly of four structural elements, which is considered for the present study, is shown in Fig.1. The two horizontal elements with an open angle of 53° in horizontal plane resist longitudinal loads and transverse loads. The two suspension tie elements at an angle of 24° in vertical plane resist vertical loads and also avoid any uncertainty of the amount of stress distribution between two closely spaced members. Suitable end fittings were developed to enable fixing the composite cross arm on the tower body.

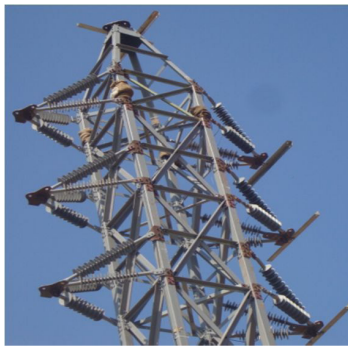


Fig.1(a) Photograph showing assembly of FRP cross arm on FRP tower body;

(b) Connections at base portion of the cross arm.

3. Development of composite tower

The composite tower consists of leg members, bracing and cross arm members having different cross sections. They are assembled with suitable structural connections with steel plates and end clamps. Mechanical fasteners are used to join both the leg members of the tower and the cross arm to the pulling plate and to the tower body.

The pultruded connections of this composite tower are typical pinned truss connections that have the line of action of the axial force in the truss members meeting at a point (Fig.2). The connections consist of mechanical fasteners that join square hollow tubular sections in single or double shear planar configurations. Spacer elements are used to improve the geometric fit-up and to allow members to pass through each other to create symmetric double shear connections. Small plate and tube inserts are used in the leg joints to improve the local bearing strength of individual highly loaded members as shown in Fig. 3.



Fig.2. Photograph showing leg member joint



Fig.3. Photograph showing pultruded connection on a composite tower

4. Development of composite tower

In the analysis and design of the composite tower, a number of theoretical assumptions are made. Only actual tower tests show how well the theoretical model correlates with the actual structure. The composite tower is a highly indeterminate structure and to ensure the reliable performance of composite material, a proto-type test is essential. The tests are conducted to know the structural behavior and performance of the composite tower under different loading conditions. The composite tower is erected vertically on rigid footings at the Tower Testing Station of Central Power Research Institute, Bangalore, India as can be seen in Fig.4; the loads are applied according to the rigging arrangement through steel wire rope attachments. Standard transverse, vertical and longitudinal loads are applied gradually through the electrically operated winches by avoiding the jerks as observed in Fig.5. The 66 kV double circuit composite tower is tested for the design loads as presented in Table 2 according to IS: 802 (Part-III): 1978.

Table 2. Summary of external loads on 66 kV composite tower.

Wind zone-4 (47 m/s)	Design loads (kN)					
	Reliability condition			Security condition		
	V	T	L	V	T	L
Span 200 m						
ACSR Dog	1.4	5.0	0	0.9	2.2	8.4
Conductor	(0.8)	(3.0)	(0)	(5.5)	(1.3)	(10.6)

V- Vertical, T- Transverse, L- Longitudinal, Earth wire loads are in brackets

4.1 Method of load application

In order to ensure the correctness and reliability of all measuring instruments and in turn the validity of the tests the calibration of all instruments before the test is conducted. Load cells used for tower testing are calibrated in a systematic manner with the help of 600 kN capacity Universal Testing Machine. The calibration of load cells is carried out up to the maximum anticipated load to be applied during tower testing. To enable the application of the external loads in the most representative manner and simulate tower design conditions, the tower structure is rigged suitably. Impact of any variance in inclination of rigging wires with respect to the directions accounted for in design is considered while preparing rigging arrangement. The calibrated load cells are attached to the cross arm through the rigging wires positioned as close to the test tower so that frictional losses do not cause impact on the load cells during testing as illustrated in Fig.5. The electrically operated winches are connected to the control panel and they are operated by a remote from a centralized control room for applying loads at different points of tower structure.



Fig. 4. Rigging arrangement of composite tower on the tower test bed



Fig. 5. Calibrated load cells attached to the composite cross arm

During the tests, the loads are applied at the cross arm of the tower through pulley block system by means of flexible steel ropes; the tension is adjusted by electrical winches.

4.2 Tower Testing Procedure

The prototype composite tower is examined carefully to prove that all the bolts and nuts are tightened properly. The tower is made truly plumb and square. All its members are checked for freedom from any visible defects. Four graduated metallic scales are fixed at peak, top, middle and bottom cross arm levels on the transverse and longitudinal face. Readings on these scales with reference to the plumb line are taken by an optical theodolite. The tower deflection values are measured with an accuracy of 5 mm. The deflections at the cross arm levels in transverse and longitudinal directions are recorded at different stages of loading under all test conditions which are presented in Table 3.

4.3 Bolt Slip test

In order to eliminate as far as possible, the play between the bolts and the holes throughout the structure. Bolt take up test is done in the beginning. Under this test all the transverse and vertical loads are increased simultaneously as far as possible to 50 % of the reliability condition loads. The loads on the tower are held for one minute. Deflection readings are taken for NO LOAD and LOADED conditions. The loads on the tower are then reduced to zero or to as low a value as possible. The deflection reading is again taken for this zero loading. The differences between the two zero loading are the permanent deflection on the composite tower. For subsequent test purposes, the readings with zero loads taken after the bolt slip test are considered as the initial readings.

4.4 Tests under Security Conditions

Under this condition (all conditions involving longitudinal loads in addition to transverse and vertical loads) all the transverse and vertical loads are first increased to about 100 %. Longitudinal loads are then increased in steps of 50 %, 75 %, 90%, and 95% of the ultimate loads. At all stages of loading it is ensured that the transverse and vertical loads are not less than the values for corresponding step of the longitudinal load. At each step the loads are maintained for one minute and the deflections are noted. All loads are then increased to 100%. At this final 100 % loading stage, the tower is observed for 2 minutes and deflections are noted. After every test the loads are brought down and deflection readings are taken for no load condition as recorded in Table 3.

4.5 Tests under Reliability Conditions

The transverse and vertical loads are applied as far as possible simultaneously at all points in steps of 50,75,90 and 95 %. The waiting period of two minute is maintained in each step and five minutes waiting period observed at the final 100 % loading. Throughout the process of loading under all tests, the tower is closely observed for any visible sign of failure of deformation. The deflections are monitored for each stage of loading whose values are shown in Table 4.

Table 3. Tower deflection under security condition.

Load %	Deflection in mm			
	Peak	Top cross arm	Middle cross arm	Bottom cross arm
Initial reading	0	0	0	0
50	30	30	20	20
75	95	65	60	60
90	160	110	90	80
95	180	130	110	100
100	210	150	130	120

Table 4. Tower deflection under reliability condition.

Load %	Deflection in mm			
	Peak	Top cross arm	Middle cross arm	Bottom cross arm
Initial reading	0	0	0	0
50	20	130	100	80
75	50	130	100	80
90	80	135	105	85
95	160	140	110	90
100	170	140	110	90

4.6 Strain Measurements

In order to study the structural performance of the composite tower under mechanical load, three rosette strain gauges (16 Nos. with 48 channels) are mounted on the critical members of the composite tower as seen in Figure 6.

The lead wires of the strain gauges are connected to the 64 channel MCE 1000 DAQ system, the data acquisition is through Lab View software with a sampling rate of 300 samples per second. Zero reading of the strain gauges recorded prior to actual loading of the tower. The load cycle test is carried out with 25 % of design loads before the actual test. The loads are applied gradually through load cell in an incremental fashion till the full loading is attained under each loading conditions. The strain variations with respect to change in the magnitude of loads are continuously monitored through DAQ system.

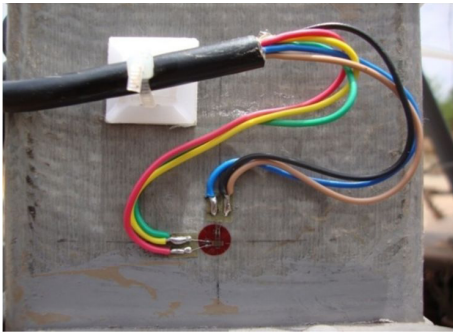


Fig.6 (a) Three rosette strain gauges mounted on the leg member;



(b) On the cross arm members

5. Results and Discussion

The composite tower successfully withstood recommended design loads as per IS: 802 without any visible sign of failure. From the Fig. 10 and 11, it shows that the maximum deflection at the peak of the tower is 210 mm under security condition and 170 mm under reliability condition. When the loading is continued up to 31.885 kN (3 times the design loads) one of the leg member developed crack near the top of cross arm indicating first visible signs of failure.

The Right of Way (ROW) requirement for a typical 66 kV tower is effectively brought down by about 17 % when composite tower is used in place of steel towers and also the weight of composite tower is brought down to 10500 N as against 24000 N of steel tower. The height of composite tower reduced by about 16 % compared to steel towers as shown in Fig.12.

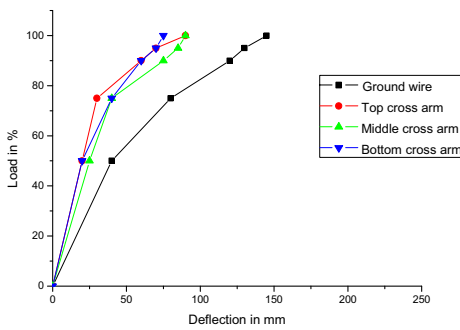


Fig.10. Load Vs. Deflection (Reliability condition)

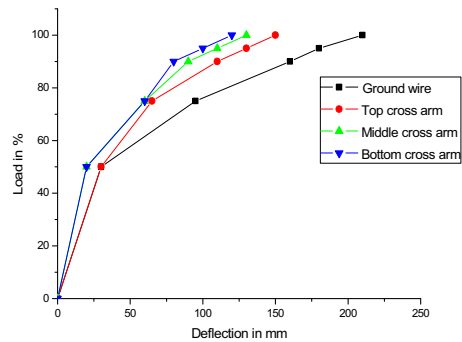


Fig. 11. Load Vs. Deflection (Security condition)

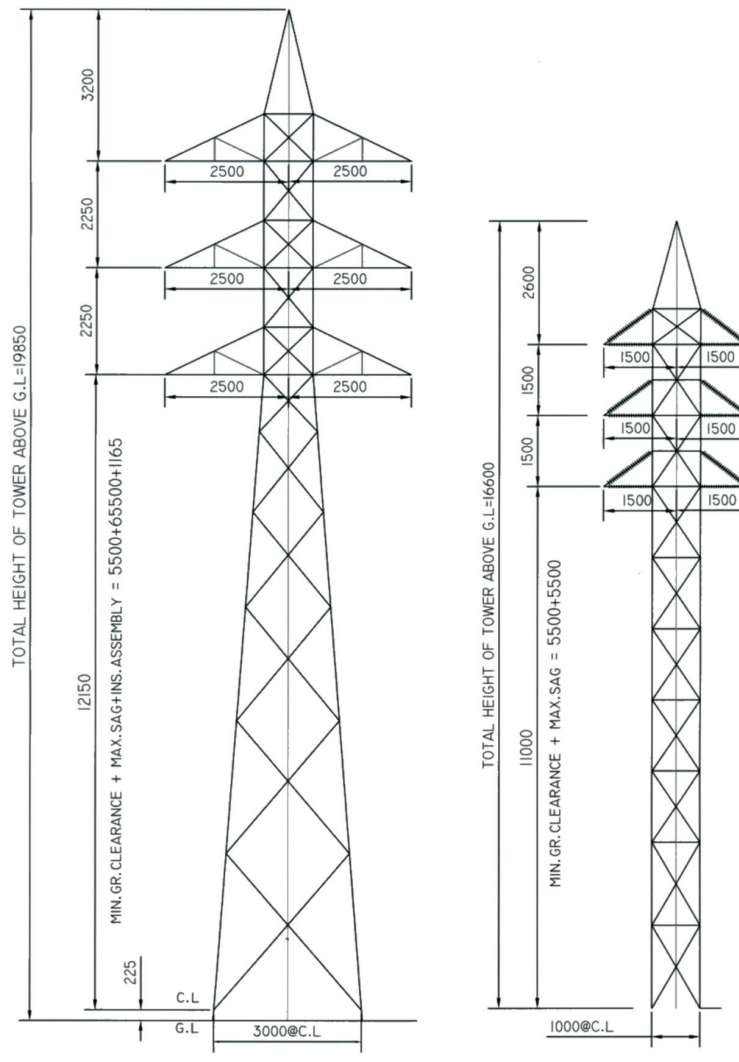


Fig. 12. (a) Conventional steel tower; (b) Proposed tower with composite members

6. Conclusion

Building a transmission line tower from E-glass and Epoxy resin that meets the same mechanical requirement than a steel tower is feasible. 17 % saving is achieved in ROW requirement for 66 kV lines. The tower height reduction of 16 % is achieved compared to steel towers. The composite cross arm can be used for up-rating the existing overhead transmission lines. Because of the light weight, this type of towers can be used for earthquake prone zones as well as for Emergency Restoration System (ERS) towers. Hence, the result of the study encourages the possibility of using composite cross arm either with steel tower body or FRP composite tower body to reduce the horizontal phase distance to build compact transmission lines.

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