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Mechanical Design and Testing of a High Strength Composite Insulated Cross Arm

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SUMMARY

Compaction and refurbishment of overhead transmission lines with composite insulated cross-arms can help utilities to overcome modern day challenges by way of reducing the physical foot print of the line, squeezing the right-of-ways, produce aesthetically pleasing design with improved public acceptance all whilst minimizing environmental impacts and life cycle costs. Until recently, the main stream adoption of insulated cross-arm has remained mostly limited to braced line post assemblies. With the advancements in composite insulation technology there are now practical options to custom design high strength variants of braced post insulators in the form of spatial insulated cross-arm assemblies.

The work presented in this paper summarizes the mechanical design and testing of such a high strength composite insulated cross-arm developed for retrofitting and ground clearance mitigation of existing 230 kV transmission lines with lattice steel towers. Due to the fact that mechanical testing of insulated cross-arms is not covered by any existing standards, a test protocol for the cross-arm was devised in close collaboration with the end-user. In addition to the more common static load tests, cyclic load tests are also presented and summarized.

KEYWORDS

Composite insulated cross-arms, CICA, transmission lines, upgrading.

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1. INTRODUCTION

Composite insulated cross-arms are structures having two or more load bearing members made of composite insulating materials and subjected to not only tensile loads but also to bending and/or compression loads [1]. The application of insulated cross-arms allows the prospect of compact aesthetic transmission lines and the ability to upgrade, harden or refurbish existing lines via retrofitting. The most basic and commonly found insulated cross-arm for high voltage transmission lines is a 2-dimensional braced line post configuration which is composed of a rigidly connected line post insulator braced with a suspension insulator which imparts cantilever support. In situations when the longitudinal loads (which could be due to broken conductor(s), unsymmetrical ice or unbalanced wind/spans) reach higher levels, a common solution is to swap the rigid connection of the line post insulator with a hinge mechanism. This rotatable configuration which is often referred to as the pivoting horizontal Vee ensures that bending stresses on the cross-arm are avoided, however such a cross-arm design can be prone to wind stability issues if the line is incorrectly designed [2]. The use of pivoting horizontal Vee assemblies puts inherent limitations on the allowable span lengths and the number of permissible adjacent tangent spans between dead-ends. Moreover, such rotatable designs are often not compatible with the vintage loading criteria of existing structures in retrofit scenarios. Under these circumstances, all the necessary technical requirements can be fulfilled with 3-dimensonal high strength composite insulated cross-arms which do not require the aforementioned pivoting motion and can still resist the longitudinal loads. Shown in Figure 1 are some examples of these kinds of robust composite insulated cross-arms commissioned successfully for voltage levels upto 1000 kV AC and ± 800 kV DC, providing like-for-like replacement of conventional steel cross-arms without any compromises on allowable spans, conductor bundle design or longitudinal loading criteria.

Figure 1. Composite insulated cross-arms in-service on 750 kV EHVAC (left), ±800 kV UHVDC (middle) and 1000 kV UHVAC (right) transmission lines.

In this paper the mechanical design and testing of such a high strength double Vee composite insulated cross-arm with superior longitudinal load withstand characteristics in comparison to standard composite braced line post is reported.

2. APPLICATION DETAILS

The cross-arm described here has been developed primarily for retrofitting of existing 230 kV lattice steel towers to provide ground clearance mitigation. With the use of an insulated cross-arm the need for the traditional suspension insulator is eliminated and the attachment point of the phase conductor on the retrofitted structured is raised by an amount which is roughly equal to the length of the original insulator assembly (refer to Figure 2). Retrofits with insulated cross-arms are a highly cost-effective solution for ground clearance improvements and are easier to implement and maintain compared to other alternatives such as elevating the tower body or using floating dead-end insulator assemblies. The replacement of existing cross-arm requires only minimal modification of the existing tower and hardware. A key feature of this solution is that the composite insulated cross-arm is relatively light and modular making the installation safe and convenient with reduced machinery, man power and ground disruptions. The insulated cross-arm can be hoisted as a single piece assembly and then bolted in place. In areas with difficult access, line crews can perform the installation without the need for heavy lifting crane or helicopter.

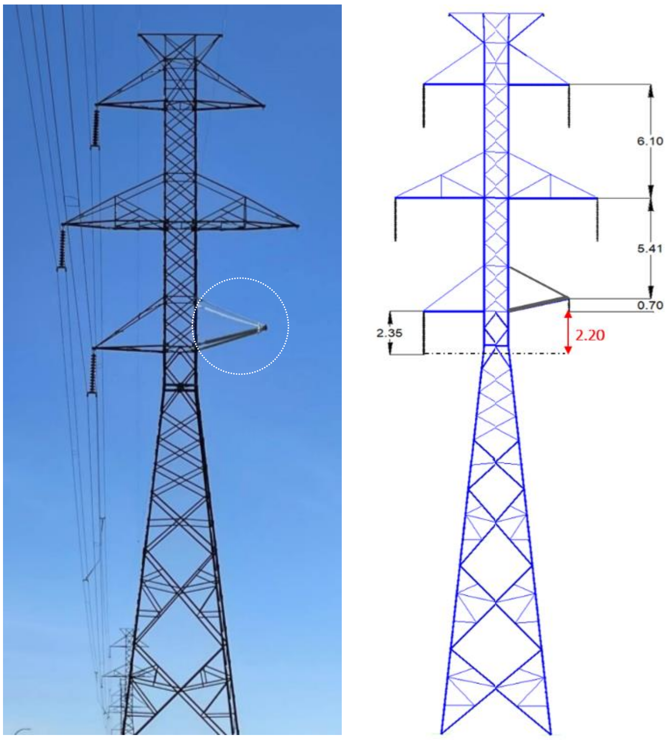
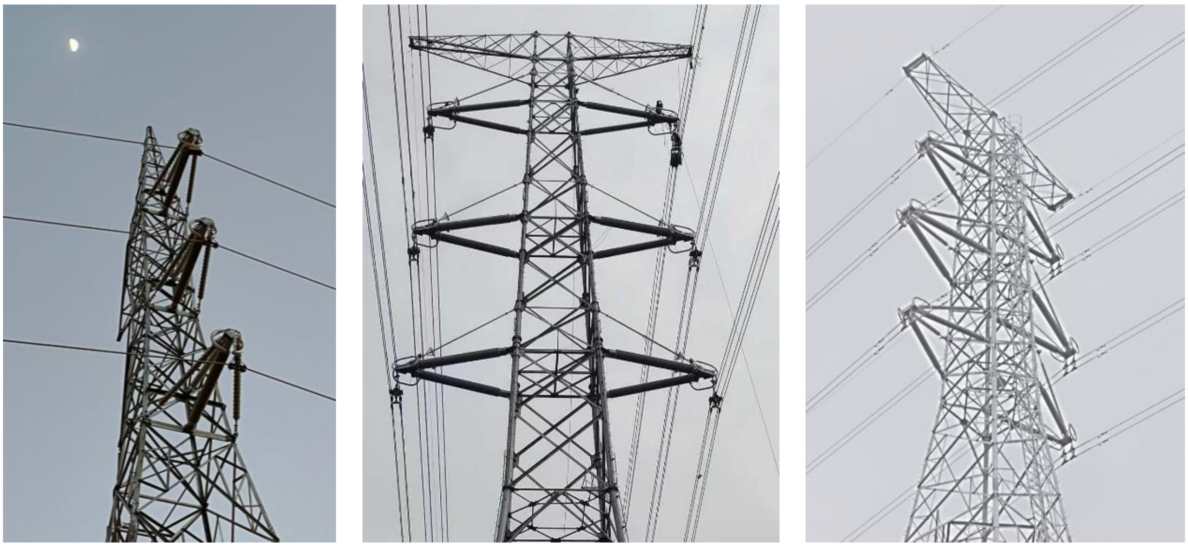


Figure 2. Ground clearance or allowable sag increase with insulated cross-arm retrofit (units: meters).

Other potential uses of the developed cross-arm include thermal uprating on lines where ground clearances are not an issue, overcoming right-of-way constrictions and use on compact new-build lattice towers as well as monopole designs that require greater load capacities than typical brace line post assemblies.

3. DESIGN REQUIREMENTS

In retrofit applications, the configuration and mechanical design of the insulated cross-arm needs to consider the structural design and load withstand capabilities of the existing tower. Common configurations of 3-dimensional spatial composite insulated cross-arms are shown in Figure 3 and these include: (1) Tetrahedron cross-arm featuring a single line post and three suspension long rod insulators, (2) Tripod cross-arm with two line post insulators braced by a single suspension insulator and (3) Double Vee cross-arm composed of two line post insulators braced by two suspension insulators. The optimal configuration amongst these options is chosen by balancing the loading withstand requirements alongwith the cross-arm weight and cost.



Tetrahedron Tripod Double Vee

Figure 3. Common configurations of high-strength composite insulated cross-arm with longitudinal withstand capabilities.

In this retrofit application, a double Vee design of insulated cross-arm was adopted to keep the tower structural modifications at a minimum and to retain the same reaction force pattern in the members of the lattice tower. The connection of insulated cross-arm was designed to ensure a simple interface with the tower body. The base of the cross-arm line post insulators were formed in shape of vertically aligned blade end fitting which attached to a vertically aligned plate connected to the tower body and matched the original bolt hole drilling pattern as shown in Figure 4.

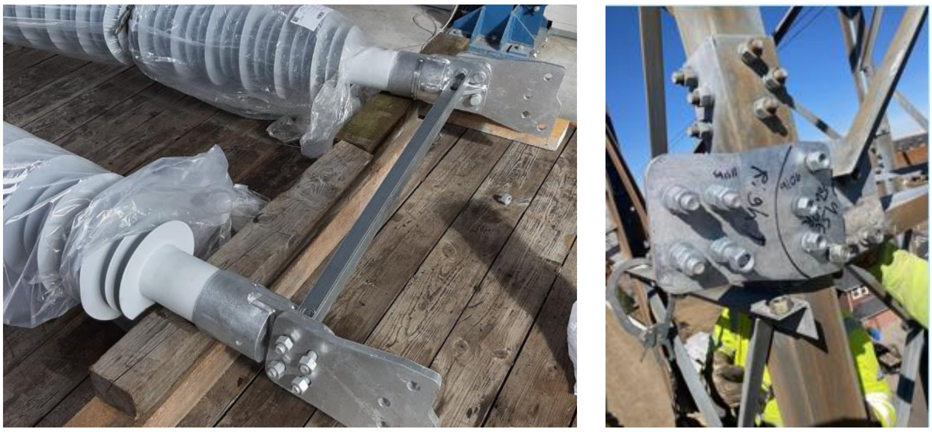


Figure 4. Connection of insulated cross-arm with tower body.

On the high voltage side, the twin conductor bundle was connected to the cross-arm node with a freely suspended fitting assembly of 700 mm length. This length of the suspension assembly was selected with consideration of the longitudinal load alleviation effect and to avoid physical interference of conductor clamp with the post insulator housing under extreme swing conditions (see Figure 5).

The design loads for the insulated cross-arm are summarized in Table 1. The cross-arm FRP cores, bolted connections and metallic hardware, should not be loaded beyond their damage limits for weather related repeatable loads (and for safety loads such as construction and maintenance) whereas, for security loads which involve longitudinal loading, the composite cross-arm may be utilized beyond its damage limit and upto its ultimate limit (due to the relatively low probability of occurrence), provided that damage experienced during such events does not impact on the integrity of the structure to which the assembly is connected. Thus, Loadcases 1, 3 and 5 would attract a strength factor of 0.5 as per NESC

[3]. The use of significant climatic loads in conjunction with a longitudinal conductor loadcase (Loadcases 2 and 4) is not prescribed by the NESC and is conservative in comparison to standard international design practice. For this reason, it was considered appropriate to use a strength factor 1.0 to determine the insulator capacity for Loadcases 2 and 4.

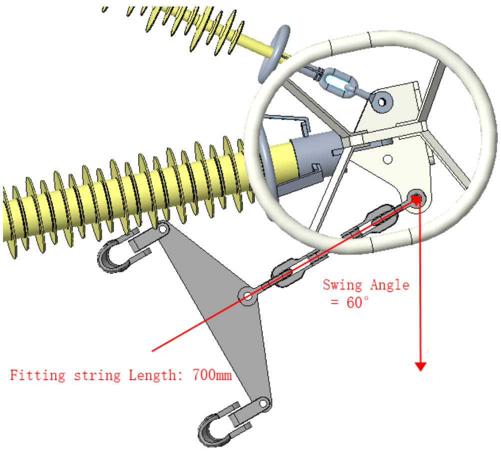


Figure 5. Sizing of conductor suspension assembly under swing condition.

Table 1. Design load cases and insulator damage limit considerations

Load Case	Condition	Vertical (kN)	Transverse (kN)	Longitudinal (kN)	Overload Factor	Strength Factor
LC-1	Ice	22.3	0	0	1.66	0.5
LC-2	Ice & Unbalanced Tension	22.3	0	17.8	1.0	1.0
LC-3	Wind	9.2	10.8	0	1.66	0.5
LC-4	Wind & Un-balanced Tension	9.2	10.8	17.8	1.0	1.0
LC-5	Ice & Wind	29.0	16.1	0	1.3, 1.25	0.5

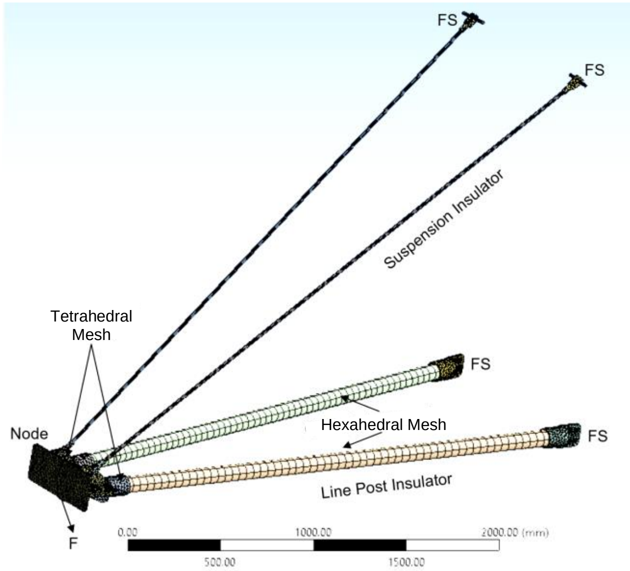
4. FEA SIMULATIONS

To specify and verify the mechanical design of the composite insulated cross-arm FEA simulations were carried out with the actual load cases of the tower in ANSYS Mechanical. The 3D model of the cross-arm needs to be simplified before it is analyzed in FEA simulations. Some unstressed parts such as the sheath of the post insulator and suspension insulator, the conductor suspension fitting string and grading rings are removed. At the same time, some of the link fitting hardware in series with the brace suspension insulator are omitted and directly replaced by the FRP rod. Theses simplifications of the model can make the finite element simulation analysis simpler and more efficient. The adopted material properties in the simulation model are given in Table 2.

Table 2. Simulation model material parameters

Material	Elastic Modulus (GPa)	Poisson Ration (-)	Density (kg/m^3)
Steel (ASTM A572)	210	0.3	7850
FRP	37	0.3	2150

In the simulation model, the interface between each component of the cross-arm is configured to reflect the actual connection design and degree(s) of rotational freedom. The FRP rod are set to be bonded with metallic end fittings and the bolted connection between the post insulator and cross-arm node is modeled by beam connection elements. The connection on either end of the suspension brace insulators is articulated and configured to revolve with two degrees of freedom. Two boundary conditions are applied to the cross-arm model: (1) Fixed Support (FS) at the back ends of each post insulator and suspension insulator, and (2) Force (F) loading at the front node end as depicted in Figure 6.



. **Figure 6.** Double Vee composite insulated cross-arm simulation set-up.

The results of FEA simulation showed that in terms of highest stress and compression load (85 kN) on the post insulator, the most critical loadcase is LC-2: Ice & Unbalanced Tension whereas, LC-1: Ice produces the highest tension load (33 kN) on the suspension brace insulators (see Figure 7). For the simulated cross-arm the bending stress on the 3.25 m long line post FRP cores remain low and it's sizing is governed by the buckling resistance requirement of 170 kN. At high transmission voltages, insulation coordination considerations demand longer dry arcing and creepage distances and thus the bucking load resistance of post insulator becomes critical. Today with the advancement and availability of high strength FRP cores with relatively large diameters in both solid and hollow core types means that composite insulated cross-arms can be practically applied on EHV and even UHV lines to minimize their foot print and environmental/community impacts.

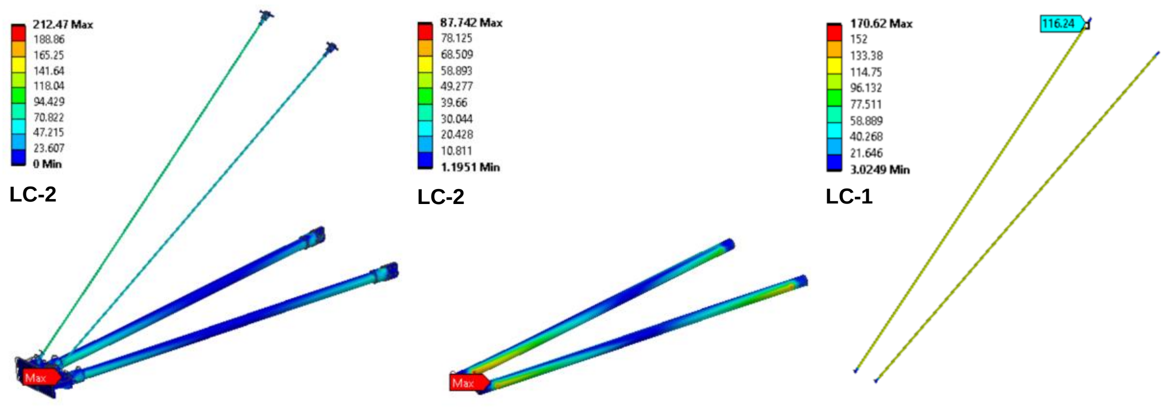


Figure 7. Stress distribution of insulated cross-arm in FEA simulation (units: MPa).

FEA simulation was also utilized to develop the combined load interaction curves of the insulated cross-arm. Extraction of strength curves of 3-dimensional insulated cross-arm is more complicated and cannot be derived according to the procedure [2] given for standard braced line post assemblies. Combined load curves for double Vee insulated cross-arm are shown in Figure 8 which were formulated by considering the capabilities and strength of the bolted connections, metallic hardware, FRP cores and the compression buckling stability of the line post insulator.

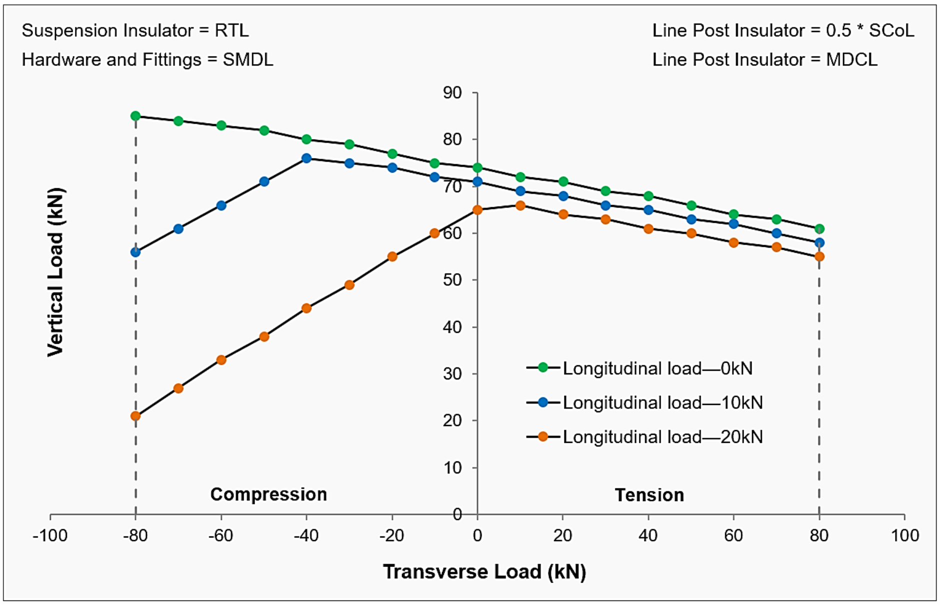


Figure 8. Combined load interaction diagram of double Vee composite insulated cross-arm.

5. DEVELOPMENT OF TEST PLAN

Testing of multi-component insulation arrangements is an essential part of insulator development where identified weak points and analysis of failure modes lead to improved designs. Moreover, standards such as NESC allow for strength factor adjustments where engineering studies have been performed paving the way for more optimized designs. It should be noted that as opposed to full-scale electrical (type) testing, no current standards or international guidelines address the subject of mechanical testing of insulated cross-arm. Guidelines for mechanical test requirements are now being developed in IEEE under P2833 – Guide for Overhead Transmission Lines with Composite-Insulated Crossarm Supports.

For this insulated cross-arm the objective of mechanical testing can be summarized as follows: (1) confirm buckling capacity of post insulator, (2) subject the insulated assembly to the most critical static design loads as identified by tower load cases and (3) confirm the integrity of insulator end fittings under cyclic loading conditions.

Following a series of workshops and extensive interaction between the stakeholders the following four tests where identified:

- Static Load Test 1: Post insulator ultimate capacity test
- Static Load Test 2: Assembly combined load test
- Cyclic Load Test 1: Post insulator 2 Hz high cycle test
- Cyclic Load Test 2: Assembly 0.03 Hz low cycle test

In addition to assembly tests, it was decided to test the post insulator individually due to its crucial function in the overall performance of the cross-arm. The post and suspension insulators as well as the metallic hardware of the cross-arm were also design and type tested at the component level according to their relevant IEC product standards.

6. STATIC LOAD TESTS

Post insulator ultimate capacity test
A compression test on the post component of the insulated cross-arm included loading to 100% of the ultimate load and then to failure. This test was performed three times with a new post component each time. The target loads summarized in Table 3 were identified from the peak compression force to be

contained. Conservative assumptions were made to simulate the end conditions for the post insulator with one end of the insulator being fully fixed and other pinned and allowed to rotate freely.

Table 3. Post insulator test loads

Strength Coordination	Compression Load (kN)	% of Ultimate Target
Damage limit	-85.0	50%
Ultimate limit	-170.0	100%

The end conditions of the post insulator and overall set-up extracted from the test report [4] is shown in Figure 9. The resulting minimum post insulator compression buckling load measured during the tests was 150% of the target ultimate limit.

Figure 9. Post insulator ultimate compression capacity test.

Assembly combined load test

Combined loading involved applying a combination of vertical, transverse, and longitudinal loads to the full cross-arm assembly. LC-2: Ice & Unbalanced Tension, identified as the critical load combination during FEA calculations was simulated in the laboratory. Following the application of the (known) vertical loads, the longitudinal load was applied to 100% of the ultimate load and then to failure in increments of 25% of the ultimate target (see Table 4).

Table 4. Cross-arm assembly combined static test loads

Strength Coordination	Vertical Load (kN)	Transverse Load (kN)	Longitudinal Load (kN)	% of Ultimate Target
Damage limit	Not specified			
Ultimate limit hold point	-22.3	0.0	17.8	100%
Ultimate limit	-22.3	0.0	26.7	150%

The test setup is shown in Figure 10 where the insulated cross-arm was fixed onto a reaction wall and the vertical load was applied by suspension of a weight equal to the design load of 22.3 kN, while the variable longitudinal load was applied up to the ultimate target load of 17.8 kN and then on to failure. Tip deflections were measured in 3 dimensions via a laser tracker. At the 100% targeted longitudinal load of 17.8 kN, the longitudinal tip deflection of the assembly was 41mm. Failure occurred following the application of a 49.9 kN longitudinal load, which equates to 175% of the resultant design load vector.

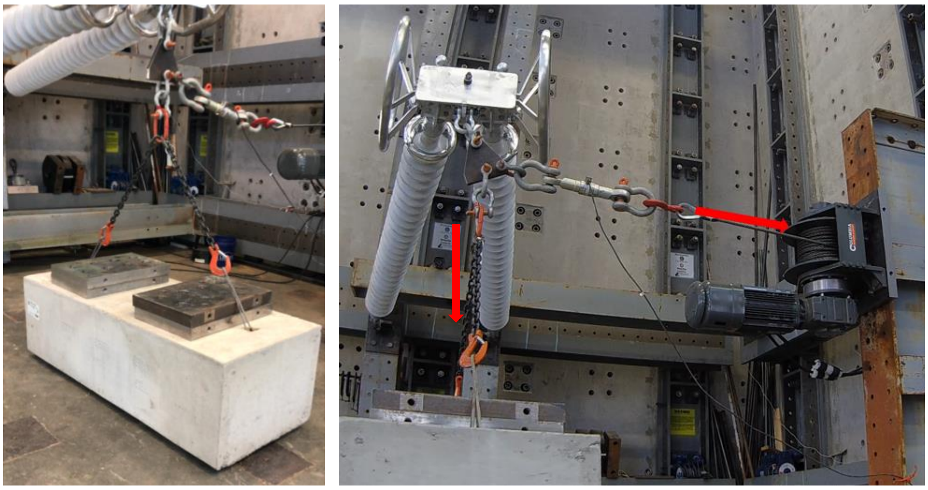


Figure 10. Cross-arm assembly combined static load application.

7. CYCLIC LOAD TESTS

The purpose of cyclic testing is to determine if end fittings remain firmly connected to the FRP core rods under expected repeated loads during the design life of the line. In addition, if any slippage does occur during the application of the cyclic load, the integrity of the seal between the silicone sheath and the end fitting becomes a primary concern, since this could lead to moisture ingress.

In order to determine whether any slippage between the end fitting and the composite post was evident, two methods were employed: Firstly, the outer sheath was removed near the end fitting and the FRP core was marked 45mm from the end fitting, before and after testing as illustrated in Figure 11. Secondly, deflection measurements were monitored at the start, mid-point and near the end of the test period to determine if any increase in the peak-to-peak deflection was evident.

Figure 11. End fitting slippage measurement before and after cyclic load tests.

Post insulator high cycle test
During this test a compression load at 2 Hz frequency was applied to the cross-arm post insulator for up to 300,000 cycles lasting for a duration of 41.7 hours. Since there are no standards defining the methodology for determination of cyclic loads, the cyclic load of -1.30 / -16.5 kN was conservatively determined with reference to prior similar testing experience. The test setup for the post insulator cyclic test is nearly identical to static compression load test with the exception of the lower end of the base which is fixed instead of being pinned.

Assembly low cycle test
The full assembly low cycle test was based on wind loading, with the wind component reversed every 33 seconds. During this test combined vertical and transverse loads at 0.03 Hz frequency were imposed

onto the insulated cross-arm for 3,000 cycles lasting upto 27.8 hours. The variable transverse load of +11.97 / -11.97 kN was applied sinusoidally via a hydraulic actuator and as with static load assembly test, the vertical load of 15.2 kN was applied via a dead weight attached to the cross-arm node. Deflection measurements were monitored through the built-in displacement transducer inside the hydraulic actuator at the start, mid-point and near the end of the test period to determine if any increase in the peak-to-peak deflection was evident.

The test set-up for post insulator high cycle and assembly low cycle test is shown in Figure 12. No relative slippage of the end fittings or change in deflection of post insulator or cross-arm assembly was evident after the performance of cyclic loading tests.

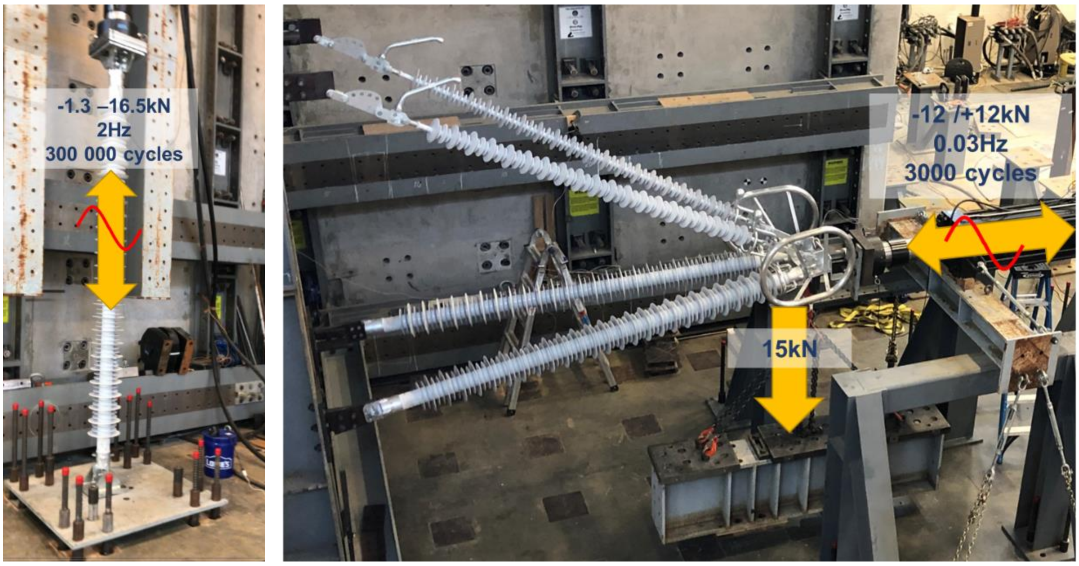


Figure 12. Test set-ups for cyclic loading test of post insulator and full cross-arm assembly. (Photo courtesy: Jean-Pierre Marie, EPRI)

CONCLUSIONS

High strength composite insulated cross-arms are the most advanced evolution of compact overhead transmission line insulation. Such insulated cross-arms overcome the limitations of standard braced line post assemblies and also facilitate grid upgradation needs through convenient retrofits. The most suitable configuration and design of cross-arm depends on the actual transmission line requirements. Mechanical design of insulated cross-arm takes into account the damage and ultimate limit considerations of the composite material and relies on FEA simulations which informs about the component reaction forces, stress distributions and deformations. Full-scale static and cyclic load tests are vital to provide the necessary validation of mechanical performance of the insulated cross-arm.

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