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FINITE ELEMENT ANALYSIS OF A JUMPER CONDUCTOR SET USED IN POWER TRANSMISSION TOWERS UNDER WIND EFFECT

Burak Talha Kılıç[1,3], Eray Baran[1], Mete Uzar[2]

Abstract: Jumper conductor sets are essential components in energy transmission lines, enabling the transfer of electrical energy between insulator strings positioned on either side of tension towers. In cases where the jumper conductor set is relatively long, it is secured to the tower cross-arm through an insulator arm at its mid-length to mitigate oscillations caused by wind. Additionally, counterweights are attached to the jumper conductor to reduce wind-induced lateral movements. However, the effects of counterweight quantity and positioning on the behavior of jumper conductors under lateral wind loads have not been fully investigated. Addressing this gap, the present study examines the behavior of a triple-bundle 1272 MCM ACSR jumper conductor set used in 420 kV energy transmission lines through finite element analysis (FEA). The primary objective is to assess how counterweight quantity and placement influence the lateral sway response of the conductor under wind-induced loading conditions. In the study, mechanical tests were conducted to determine the bending stiffness and sag behavior of jumper conductors, and the results were used to validate the FEA model. A parametric study on 1272 MCM ACSR jumper conductor set revealed that counterweights significantly reduce lateral sway from 32° without counterweights to 15° with 2 kN weights. Symmetrical counterweight placement further enhanced stability of the jumper conductor set. These findings emphasize the importance of counterweight placement in mitigating wind-induced oscillations and ensuring the stability of jumper conductor sets in high-voltage transmission lines. The study provides valuable insights for optimizing the design of counterweight systems to enhance the reliability and performance of transmission line structures.

Keywords: Conductor Oscillation, Finite Element Method, Hardware Set, Jumper Conductor, Numerical Simulation, Overhead Lines, Counterweight

INTRODUCTION

Overhead lines are exclusively used around the world for power transmission. In these lines, conductors are carried by steel tower structures with different dimensions and structural features. Moreover, geometry of tower structures usually varies depending on the energy capacity of the line, as well as the function of the tower within the line, such as suspension, tension and termination type towers. The main components of a typical power transmission line tower structure are shown in Figure 1a. Cross-arm members are generally made of steel profiles, and they are mainly used to support the conductors safely by providing enough distance between conductors to tower body, known as clearance distance. Conductors are usually connected to the tip of the cross-arms through insulators. Suspension and tension type insulators provide the required electrical insulation level by providing enough clearance distance from the tower structure.

In energy transmission towers, the energy flow on the conductors on either side spans are ensured by using a jumper conductor between the tension insulators attached to both sides of the tower. In the cases where the length of the jumper conductors in the tension tower is relatively long, these conductors are also attached to the tower cross-arm at their mid-lengths with the help of a suspension insulator in order to reduce the oscillations that will occur under the influence of wind. For the same purpose, a counterweight may also be used at the bottom of the suspension insulator. An example of jumper conductor application and details of its components are given in Figure 1b. In this particular example, the jumper conductor is connected to the main conductors on both sides of the tower with dead end clamps. Additionally, spacers made of aluminum are placed at regular intervals along the jumper cable to ensure that the distance between the individual conductors is maintained.

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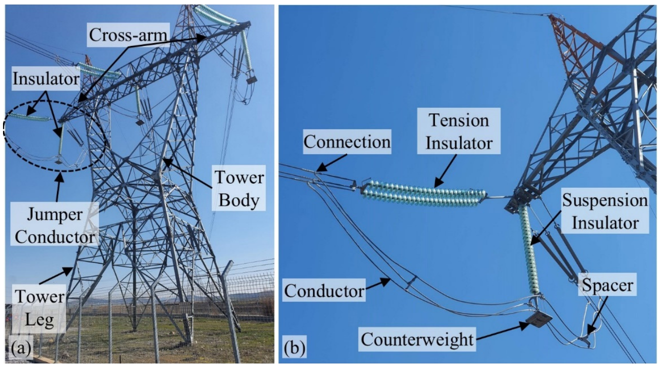

Figure 1: (a) Typical energy transmission line tower; (b) Jumper conductor and its components

The present study aims to investigate the effect of counterweight placement on the lateral sway response of jumper conductor sets used in 420 kV energy transmission towers in Türkiye. While counterweights are commonly used to mitigate wind-induced oscillations, their influence on the structural behavior of jumper conductors remains insufficiently explored. By incorporating experimental data into finite element analysis, this research provides a more accurate representation of conductor behavior under lateral wind loads. The findings offer valuable insights into optimizing counterweight configurations to enhance the stability and reliability of transmission line components, ultimately contributing to the safe and efficient operation of energy transmission systems.

1. LITERATURE REVIEW

Review of the current literature indicates that the behavior of conductors used in transmission lines has been generally investigated for situations that create unbalanced loading, such as conductor breakage and ice shedding. In a study conducted by Yan et al. in China, energy transmission towers and tower members with a capacity of 500 kV were analyzed dynamically under wind load by using the finite element method [1]. Within the scope of the study, it was aimed to evaluate the dynamic wind load coefficient in the specifications, considering stochastic wind fields. In a study conducted by Thomas and Peyrot, the breaking conditions of conductors located between towers considered to be rigid were investigated with the proposed numerical method [2]. In this study, insulators and conductors are modelled as cable elements. In addition to classical modeling, cable elements were assumed to carry some amount of compression forces in addition to its tensile capacity. In the study, wind load and load due to conductor breakage as well as vibration states of the conductors were examined using the dynamic analysis method. McClure and Lapointe examined two transmission line towers using the finite element method, taking into account the unbalanced loading caused by conductor breakage and ice shedding on the conductors [3]. In the numerical analysis model used in the study, conductors are modelled as linear elastic elements that can only carry tensile forces. In a study by Jamaleddine et al. [4], a small-scale, two-span transmission line model was established in laboratory and tested under a situation representative of ice shedding. A numerical analysis model of the physical model was also created and analyzed under static loading. During modeling, conductors were modelled as truss elements carrying only tensile force.

Song et al. [5] analyzed the response of large-span transmission lines using finite element methods and proposed dynamic vibration absorbers to reduce wind effects on suspension insulators, identifying critical wind speeds through parametric evaluations. Gayar et al. [6] adapted a revised version of the CIGRE working group equation to estimate the oscillation angles of suspension-type insulators in 400 kV lines, taking into account wind speed and clearance requirements under lightning, switching, and temporary overvoltage conditions. Zhou et al. [7] developed an improved model to estimate wind swing angles of insulators under varying wind directions, integrating multiple factors such as terrain and wind asymmetry. Their results showed better agreement with FE simulations compared to IEEE and design manual models. Similarly, Niu et al. [8] introduced a mathematical model to calculate jumper conductor sag and length for 800 kV lines, incorporating key parameters like stiffness and cross-sectional properties. In another approach, a simplified method was proposed to estimate the peak dynamic windage yaw angle of suspension insulators by combining average and fluctuating wind components through an improved rigid rod model [9]. Wind-induced yaw behavior was also examined in a 500 kV system by using FE simulations, where span length was found to significantly affect the yaw angle, prompting the recommendation of dynamic wind load factors for improved design accuracy [10]. Moreover, windage yaw flashovers were investigated through a systematic method combining wind–rain load simulation, yaw calculation, and flashover analysis [11]. This study introduced a key-node modeling approach and found that, particularly under typhoon conditions, conductors are more prone to flashovers than insulators, underlining the significance of rain effects in high-risk environments.

The current literature lacks a comprehensive examination of the behavior of conductors subjected to lateral wind loading, a scenario characterized by relatively complicated dynamic response. Furthermore, existing numerical investigations often employ truss elements that lack flexural stiffness and can only accommodate tensile forces. However, the flexural stiffness of conductors is a crucial parameter, influencing sag and lateral deformation behavior depending on the wind direction. The majority of studies are based solely on numerical models rather than physical testing, and it is noteworthy that there are very few studies utilizing numerical models validated with results from physical testing. The present study was conducted in an attempt to address these deficiencies in the related literature.

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2. EXPERIMENTAL AND NUMERICAL STUDIES ON 1272 MCM ACSR JUMPER CONDUCTOR

A three-stage study was carried out to ensure that the behavior of the jumper conductor was realistically reflected in the numerical analysis model. In the first stage, flexural stiffness of 1272 MCM ACSR conductor was obtained by performing a three-point mechanical bending test. In the second stage, the conductor was attached to two rigid supports in the laboratory in order to obtain the actual sag profile under self-weight. This profile was then used to validate the one numerically determined by the analysis program. In the third and final stage of the study, additional weights were attached at the mid-point of the same conductor in the laboratory and sag profiles due to self-weight and additional weights were obtained by taking displacement measurements along the length of the conductor. Following these experimental stages, a numerical model of the same conductor was constructed. The same loading scenarios were then simulated in the numerical model. Ultimately, the results obtained from the numerical model were compared and validated against the experimental findings obtained in the laboratory.

2.1. Determination of Flexural Stiffness of 1272 MCM ACSR Jumper Conductor

In the literature, cable elements are generally considered to have only axial tensile stiffness with no compression and flexural stiffness. This simplification greatly reduces the complexity of engineering calculations. However, depending on the investigated problem, flexural stiffness may significantly affect the conductor's behavior. The effect of flexural stiffness becomes especially important for conductors with a relatively large cross-sectional area, such as 1272 MCM type conductor. Although it is accepted that there is no bonding between the aluminum and steel wires that make up the conductor cross section, an acceptable level of stiffness against bending occurs due to mechanical interaction between individual wires resulting from spiral winding and friction.

Mechanical load testing for flexural stiffness of the 1272 MCM ACSR jumper conductor was carried out with a simply supported beam mechanism (Figure 2a) established in the Structural Mechanics Laboratory of the Middle East Technical University Civil Engineering Department. The cross-sectional view and geometric details of the tested conductor are provided in Figure 2b and Table I, respectively. The value of flexural stiffness (EI) basically depends on the elasticity modulus (E) of the materials forming the conductor and the moment of inertia (I) of the conductor cross section. During the experiment, the load levels applied to the conductor specimen and corresponding midspan displacements were recorded. Using the load (P) and displacement (Δ) values measured in the loading test, the flexural stiffness of the conductor was calculated according to Eq. 1. The flexural stiffness of the 1272 MCM ACSR conductor was determined as 1.854×10^8 kN/m.

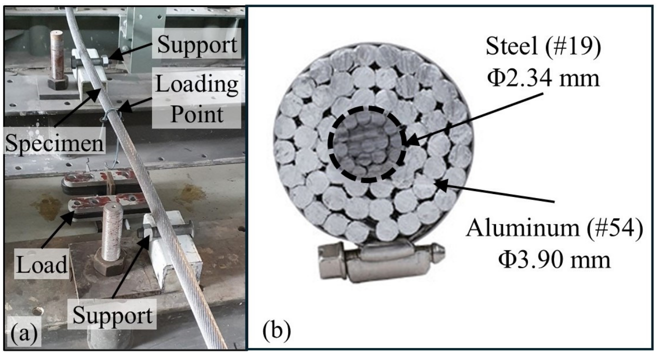

Figure 2: (a) Test setup and specimen used to determine the flexural stiffness of the conductor; (b) Cross-sectional view of 1272 MCM ACSR conductor

$$EI = \frac{PL^3}{48\Delta}$$

Table I: Geometric properties of 1272 MCM ACSR conductor

Diameter (mm)	35.10
Steel Area (mm^2)	81.71
Aluminum Area (mm^2)	645.10
Unit Weight (kg/m)	2.137

2.2. Verification of Numerically Determined Sag Profile with Experimental Measurement

In finite element analyses, the initial geometry (i.e., sag profile due to self-weight) of conductors significantly affects the response of these members under loading. For this reason, considerable effort was dedicated to accurately determine this sag profile. For this purpose, a 9 m length segment of 1272 MCM ACSR conductor was placed between two elevated rigid supports in the laboratory creating a clear span of 8 m. The sag profile was determined by carefully measuring the position of the conductor with respect to a reference line along the length. The picture of the experimental setup fabricated in the laboratory is given in Figure 3. The connection of the conductor to the supports was provided with dead end clamps, mirroring the end connections of jumper conductors on transmission line towers. With this type of connection method, the conductor's ends exhibit characteristics of a pin support in the vertical plane of the jumper conductor, while functioning as a fixed support in the perpendicular (i.e., transverse) direction. In simpler terms, although the conductor ends were free to rotate in-plane, rotation and translation were restricted in the out-of-plane direction. This aligns with the precise connection details employed in existing jumper conductors on energy transmission line towers.

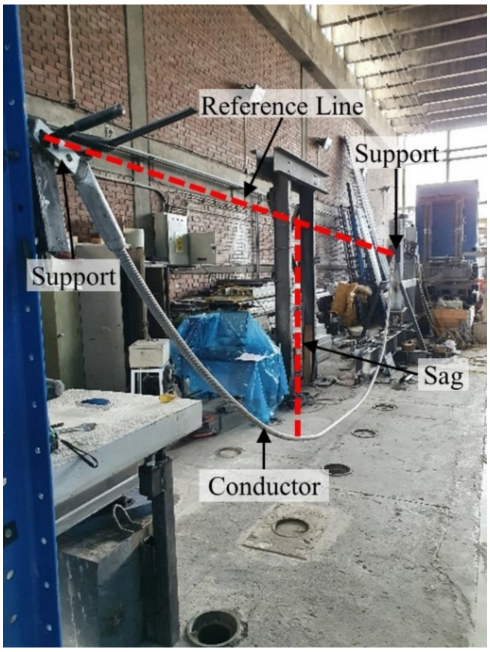

Figure 3: Test setup used to determine the sag profile of jumper conductor

A finite element analysis model was created using the SAP2000 computer program [12] to determine the sag profile of the conductor sample investigated in the laboratory. In the analysis model, cable elements and sag calculation module available in the library of the SAP2000 program were utilized. Realistic cross-sectional properties of 1272 MCM ACSR conductors, including the experimentally determined flexural stiffness, were assigned to the cable elements. A comparison of the sag profile determined numerically with the SAP2000 program, and the experimentally determined profile is given in Figure 4. As evident, both methods resulted in almost identical maximum sag at the midspan location. However, there is a slight difference between the two sag profiles near support locations. The main reason for this difference is attributed to dead end clamps used at the ends of the conductor segment in the laboratory model. The overall agreement between the two sag profiles validates the accuracy of the SAP2000 sag calculation module. Consequently, the sag profile obtained from this module was utilized in the numerical analysis of the jumper conductor on an actual transmission line tower.

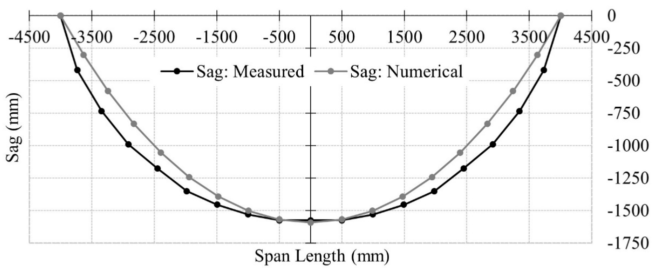

Figure 4: Experimental and numerically determined sag profiles for jumper conductor under self-weight

2.3. Finite Element Modeling of 1272 MCM Conductor and Verification of its Behavior under Additional Loads

The laboratory model of the 1272 MCM conductor segment of 9 m length was further studied under additional weights of different sizes hung at the midspan. The sag profile along the conductor was measured with respect to a horizontal reference line as indicated in Figure 5a. A detailed numerical model of the jumper conductor with a weight attached at midspan was created (Figure 5b) and analyzed using the general-purpose finite element analysis program Abaqus CAE [13]. While creating the FE model, the initial sag profile of the model was based on the geometry shown in Figure 4, which is the sag profile occurred under the self-weight. Since this initial geometry included the effect of the self-weight of the conductor, no additional self-weight was assigned to the conductor in the FE model.

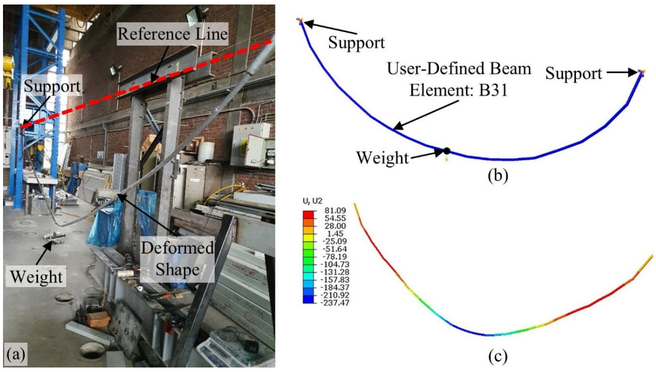

Figure 5: (a) Deformed shape of jumper conductor under additional weight; (b) Model used in FE analysis; (c) Deformed shape determined by the FE model

While creating the FE model, B31 type beam elements available in the program library were used to model the conductor. Pin and fixed boundary conditions were defined in the in-plane and out-of-plane directions, respectively, at both ends of the 9 m long conductor segment. The 1272 MCM ACSR conductor has a composite structure with a cross section consisting of both aluminum and steel wires. Therefore, the transformed section approach was used to calculate the axial and flexural stiffness of the conductor cross section. This approach allows an accurate calculation of the equivalent area and equivalent moment of inertia of the cross section. The equivalent cross section properties given in Table II were assigned to the relevant elements by creating a user-defined profile in the Abaqus program. “Dynamic, Implicit” analysis type was utilized with “Quasi-Static Loading”. Figure 5c shows a representative sag profile from the FE analysis with an additional load of 0.13 kN applied at the midspan of the conductor. The numerically predicted sag profiles are compared with the experimentally determined profiles for the cases of

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Table II: Material and geometric properties used in FE model for 1272 MCM ACSR conductor

E_s (GPa)	E_a (GPa)	A_s (mm²)	A_a (mm²)	$n=E_a/E_s$	A_t (mm²)	$(EA)_t$ (N.m)	I_t (mm⁴)	$(EI)_e$ (N/mm)
200	70	81.71	645.1	0.35	879	6.15E+07	2648	1.85E+08
a: Aluminum, s: steel, t: transformed, e: experiment								

0.13 kN and 0.24 kN midspan loading, respectively, in Figure 6 and Figure 7. Together with the sag profiles under midspan loading, each plot also shows the initial sag profile of the conductor. The close agreement between the numerically predicted and experimentally determined sag profiles proves the validity of the material and cross section information as well as the modeling assumptions used in the FE model for the 1272 MCM jumper conductor.

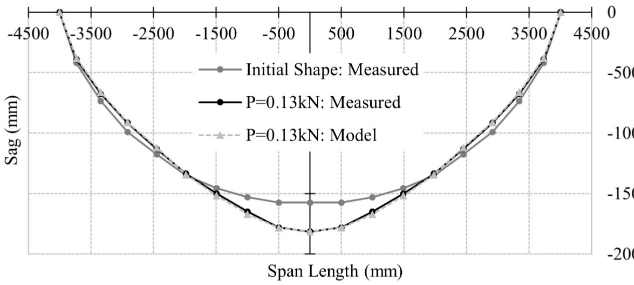

Figure 6: Experimental and numerically determined sag profiles under 0.13 kN midspan loading

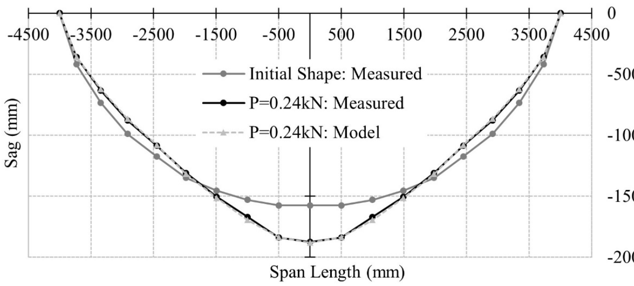

Figure 7: Experimental and numerically determined sag profiles under 0.24 kN midspan loading

3. RESPONSE OF JUMPER CONDUCTOR SET USED IN 420 KV TRANSMISSION LINE TOWERS UNDER DIFFERENT COUNTERWEIGHTS

Following the validation of the modeling approach and cross section properties of the 1272 MCM ACSR conductor, a detailed FE model of a representative jumper conductor subassembly used in 420 kV energy transmission towers in Türkiye was created. A picture of this model is given in Figure 8. As can be seen, three jumper conductors were supported at their ends and a composite suspension insulator rod was provided at conductor midspan. The conductors had pin and fixed boundary conditions, respectively, in-plane and out-of-plane directions. The top end of the insulator rod was modelled as a pin support in all directions. The material and cross-sectional properties used for the conductors were the same as those explained in earlier sections and summarized in Table II. Composite suspension insulator rod was included in the model using beam elements and user-defined cross section assignment. The modulus of elasticity for the insulator rod was taken as 77 GPa. To represent the spacers available between individual conductors along the jumper assembly, constraints were defined between the conductor nodes at respective locations. While these restraints do not affect the response of the conductor assembly under lateral motion, they maintain a constant relative distance between individual conductors. The loading considered for the analysis includes: (1) self-weight of conductors and insulator rod, (2) counterweight set attached at the bottom end of the insulator rod, and (3) lateral wind load. The wind load calculation procedure specified in the “Electrical High Current Facilities Regulation” [14] was followed and a distributed load of 0.024 kN/m was applied to the conductors. Additionally, the counterweight was included in the model as a non-structural mass at the relevant node.

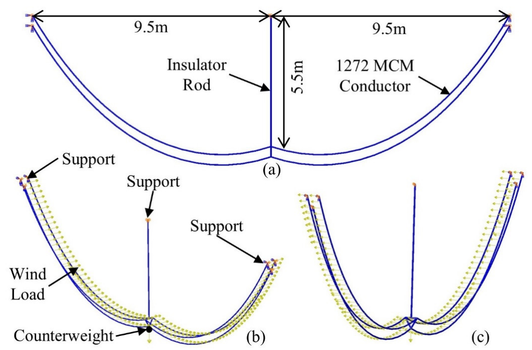

Figure 8: FE model details of the 420 kV jumper conductor assembly

3.1. Effect of Counterweight on Lateral Deformation Response of Jumper Conductor Assembly

The jumper conductor assembly model was first analyzed under self-weight and wind load only, without a counterweight. This analysis is shown as “Test-1” in Table III and Figure 9. In Test-2 case, the 1 kN counterweight currently used in 420 kV electricity transmission towers in Türkiye was attached at the bottom end of the insulator rod. The counterweight was increased to 2 kN in Test-3 case. Starting from Test-4 case, the 2 kN counterweight was included in the model as two separate 1 kN weights. These weights were placed on the jumper conductor on both sides of the insulator rod symmetrically. The location of these counterweights in each analysis case of Test-5 to Test-12 is indicated in Table III.

Table III: Counterweight cases used in FE model of jumper connductor set

TEST #	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12
Additional Counterweight (kN)	-	1	2	2x1	2x1	2x1	2x1	2x1	2x1	2x1	2x1	2x1
Location of Counterweight* (mm)	-	0	0	574	1163	1760	2360	2955	3540	4108	4656	5182

Two counterweights are symmetrically placed on either side of insulator rod.

For each analysis case, the deformation profile of the jumper conductor assembly was determined by recording the lateral displacement values at all nodes along the length of the jumper conductor. The lateral deformation profiles determined in this way are shown in Figure 9. Each curve in the plot reflects the top view of the deformed shape of the jumper conductor set under the combined effect of self-weight, counterweight and wind loading. As can be seen, the size of the counterweight and its location along the length of the jumper conductor have a significant impact on the lateral deformation behavior. In the absence of counterweight, the maximum lateral deformation on the jumper conductor is 3610 mm, with the deformation at the midspan of the conductor is 3330 mm. The level of lateral deformation in this case corresponds to an approximately 32º rotation of the insulator rod and has the potential to cause a short-circuit problem. In the cases where there is a 1 kN (Test-2) and 2 kN (Test-3) counterweights at the midspan of the jumper conductor assembly, the maximum lateral deformation is reduced to 2590 mm and 2190 mm, respectively. In these two cases, the lateral deformation at the bottom end of the insulator rod is 2050 mm (21º rotation) and 1450 mm (15º rotation), respectively.

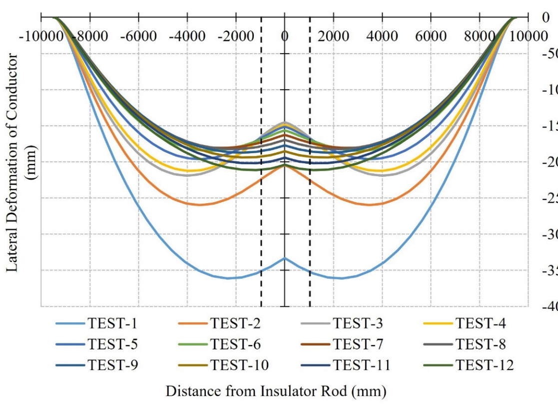

Figure 9: Effect of counterweight size and position on deformation response of jumper conductor: Lateral deformation profile

Dividing the total counterweight into two separate weights and placing them symmetrically with respect to the insulator rod resulted in a larger lateral deformation at the bottom end of the insulator rod. This behavior is better represented in Figure 10. The dashed light gray curve in the plot indicates the maximum lateral deformation on the conductor while the black curve indicates the lateral deformation at the bottom end of the insulator rod. When the counterweights are positioned away from the location of the insulator rod (i.e., the midspan of the conductor assembly) there is a constant increase in the lateral deformation at the bottom end of the insulator rod. However, a similar response is not valid for the maximum lateral deformation of the conductor assembly. The smallest maximum lateral deformation is obtained when the counterweights are placed at a distance of 2360 mm from the midspan of the conductor assembly (Test-7).

In ensuring safety against short-circuit condition, a critical criterion involves the proximity of the conductor to the tower body in the case of lateral deformation of the jumper conductor assembly. This criterion is explained in Figure 9, where the vertical black dashed lines indicate the location of the tower body, represented by a typical width of 2 m. As evident, for majority of the cases analyzed, the maximum lateral deformation of the jumper conductor assembly occurs outside the tower body. It is also evident that lateral deformation of jumper conductor at the bottom end of the insulator rod is a more valid parameter than the maximum lateral deformation for assessment of the short-circuit condition.

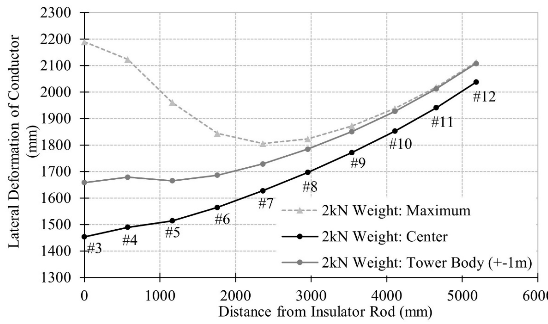

Figure 10: Effect of counterweight size and position on deformation response of jumper conductor: Maximum lateral deformation of conductor depending on counterweight location

4. CONCLUSION

This study presented a comprehensive investigation into the mechanical behavior of jumper conductor set used in power transmission lines, with a specific focus on their response to various loading conditions. The experimental and numerical analyses conducted as part of the study contribute valuable insights into the mechanical behavior of jumper conductors. The following conclusions can be drawn from the findings:

- The flexural stiffness of the 1272 MCM ACSR jumper conductor was accurately determined through a

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three-point mechanical bending test, considering the complex composition of aluminum and steel wires.

- The numerical model of the jumper conductor was validated against experimental data obtained from a laboratory setup, ensuring the accuracy of the finite element analysis. The model accurately predicted the sag profile under self-weight and additional weights.
- The inclusion of counterweights at the midspan of the jumper conductor assembly proved effective in reducing lateral deformation under wind load. The counterweight mass and its location significantly influenced the conductor's behavior, emphasizing the importance of considering counterweights for safety against short-circuit conditions.

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BIOGRAPHY

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