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Effect of Interfacial Contact Forces in ACSR Dog Conductor

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Abstract

The mechanical behaviour of single layer cables used in engineering applications, have been studied for the past three decades and it varies widely depending on the numerical models adopted. Though these models predict the global response reasonably well, they differ widely in modelling the local contact conditions, the frictional effects at the interfaces and predicting the loss of stiffness of the single layer cable assemblies. The behaviour of the single layer cable can be well understood if the appropriate mode of contact prevalent at every stage of loading is adopted in the model. This paper analyses the contact modes present in a single layer cable assembly and considers its response under an axial tensile load and an axial twisting moment. Also this paper has formulated a sound theoretical model to find the response of a single layer cable considering all the interfacial forces in a coupled and radial contact mode and validate the experimental. Also proposes an arrangement to consider the axial and twist slip, by considering the tangential and the normal distributed forces at the contact interfaces. The effect of the friction and the associated slip of the wires have been included. Apart from consideration of the radial contraction of the wires due to the Poisson effect, as accounted by few authors, this paper considers the radial deformation due to contact forces, as a special feature. This has resulted in refined expressions for the curvatures and twist of the wire and the associated forces in the normal and binormal directions. The predictions with these inclusions are compared with the existing works and the importance of the refinements to the cable designers is highlighted.

Keywords: Cascade effect, Contact stress, Interfacial contact force, Overhead conductor, Single layer cable.

1. Introduction

The mechanical behaviour of cables used in different engineering applications has been studied for the past three decades by many researchers. As cited earlier the cables is used in a variety of applications ranging from overhead electrical power transmission, mooring cables in underwater platforms, anchoring elements in ship and other floating vessels, guy ropes for masts, antennas and tower structures, structural stay cables in bridges and hanging platforms, hauling, pulling and lifting ropes in winches, mechanical power transmission devices, and material handling and conveying equipment's, medical applications for endoscopic and other diagnostic tools and as filaments and yarns in textile applications. Depending on the loading conditions prevailing in these applications, the static, dynamic, impact and fatigue performance are of concern. The prediction and the precise estimation of the response of these cables play a vital contribution to the choice of an optimum cable and its arrangement.

However all the above said models, explain the wire as a thin three dimensional body, curved bent and twisted and the complete mechanics is governed within the elastic limits, by the equilibrium equations derived by Love[15]. Based on Love's equation of equilibrium of thin and slender rod, Phillips and Costello[3] presented a general nonlinear theory for a layer of helically wound wires without a core. The wire force in the normal direction had been accounted. The contact force along the hoop or lateral direction had been estimated, after duly evaluating the helix angle in the deformed state, through the nonlinear equations of equilibrium. The net clenching force in the normal (radial) direction of the strand was evaluated. The line contact stresses were evaluated through monograms connecting the applied tension and torsion on the strand. The work gained importance for identification of

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the lateral contact conditions and the corresponding contact stresses. However friction effects were not considered. Costello[3] contributed significantly to the analysis of the stranded cables due to axial twisting. A significant development of a six layered and cored strand was made Huang[10] to identify the contact modes prevailing with the geometrical arrangement of the helical wires. A hypothetical combined contact mode problem was considered with inclusion of interfacial forces due to friction at the contact locations. The radial contraction of the wires due to Poisson's effects was considered. A simultaneous radial contraction of the centre core due to Poisson's effects and the contact forces was also considered to define the helix radius in the deformed state. But this work did not consider the friction forces at the core-wire interface and their associated effect in the distributed moments in the helical wire. However this works paved way for modelling the contact modes in a single layered cored strand assembly. Knapp[13] used the energy method to derive the stiffness matrix for a cable assembly under the axial tension and torsion. The uniform radial contraction of the centre elastic core due to the contact forces acting on the lateral surface had been considered. However the wire forces in the normal and binormal direction were not considered and their effects on the strand force and strand twisting moment were not accounted. The contact forces, the interfacial friction forces were also not considered. However, the formulations were extended to a multilayered strand. The mechanics of stranded cables was extended to overhead transmission line conductors used in electrical power transmission by McConnell and Zemke[18]. Costello (1983), further presented a theory to extend the formulations of a single layered cable made earlier, to account for the multilayered cables. The axial force and the axial twisting moment were represented as linear combinations of the axial strain and rotational strain. A three layered cable had been considered and the effect of friction at the contact interfaces was neglected. It was found that the largest axial tensile stress occurred in the centre wire. Author in[20] extended the formulations of Costello[3] and the general equations of Love[15], to address a wire rope, as an assembly of strands. The response of the wire rope due to axial tension and torsion was predicted based on linear theory. The interfacial contact forces, frictional effects were not considered. The wire force in the normal direction, distributed moments in the normal, binormal and axial directions were also considered. The formulations adopted set a procedure to extend the equations of a stranded cable to a wire rope. Velinsky et al.,[24] is to develop the general nonlinear theory for complex wire rope Costello[3] had compiled all his decade old research and presented the salient formulations with relevant numerical examples in his book, which has become a ready reckoner for the cable and wire rope mechanics. All the research works hitherto carried out in the stranded cables though had undergone consistent improvements in one direction or the other, did not yield the principle of similarity of the stiffness elements, as expected in any linear elastic system. The types of contacts in a stranded cable were explained in detail and a new mathematical model to represent the effect of tangential and normal distributed forces in a combined contact was formulated by Parthasarathy[19]. The conditions that cause the inter-wire movements were studied and the effective stiffness of the stranded cable assemblies was established when subjected to axial tension and torsion. Labrosse et al.,[17] presented a new analytical approach to predict the global response of a cable subjected to bending, tension and torsion. In this theory the wires were considered as curved beams as presented by Love. The integrated stresses over the cable cross section and inter-wire efforts had been presented as a function of the cable axial strain. The inter-wire slippage had been accounted. Kumar and Botsis[14] had extended the Costello model to obtain the analytical expressions for the maximum contact stresses induced in the multi-layered strands with metallic wire core Gnanavel et al.,[5] have presented an analytical model to explain the importance of the interfacial loads and their effects in combined or coupled contact and identified the threshold limit at which the contact mode changes from a coupled arrangement to the arrangement of core-wire radial contact. In addition to Poisson's effects of the wire and the core, the radial contraction of the core due to the contact forces was considered. However the analysis was confined up to the combined contact arrangement only. In the later paper by the same authors[7], the analysis has been extended to the radial contact arrangement also. But this paper did not consider the influence of the cable under the combined contact mode, which existed prior to the radial loading. Gnanavel and Parthasarathy[8] presents exclusively the lateral contact mode modelling with its complete analytical development in the lines of the above authors but considers the effect of the frictional forces at the contact interface, hitherto not considered fully. The effect of the distributed contact force in the normal direction and their association in the tangential directions due to friction are the significant contributions of this paper. Further, the interaction of the distributed moments in the normal and axial (tangential) direction of the helical wires and their effects in the response of the cables are the distinct features of this work. Consideration of all these parameters brings out expressions for the wire force in the normal direction, which was generally treated as zero by the other investigators. Detailed experimental work has also been carried out in one of the research laboratories dealing with cables used for electrical power transmission. Gnanavel and Parthasarathy[6] have formulated a sound theoretical model to find the response of a wire rope considering all the interfacial forces in a coupled and radial contact mode. Also proposes an arrangement to consider the axial and twist slip, by considering the tangential and the normal distributed forces at the contact interfaces. A single layered stranded wire rope with six helical strands and a central stranded core assembly has been taken in to consideration. Each strand is made up of seven wires of which one wire forms a core for that strand surrounded by six helical wires. Equations of equilibrium of the helical wire, helical strand are obtained and transformed to find the axial and torsional response of the wire rope, about the rope axis. Ivan Argatov[11] an asymptotic modeling approach is employed for evaluating the mechanical response of a helical wire rope strand to axial and torsional loads with the effect of wire flattening taken into account. In order to evaluate the contact approach between the core and wires. Gnanavel and Parthasarathy[9] addresses a cable that has a combined contact mode arrangement by its construction, and has been found to retain that up to a certain strain level and then turning into a core-wire radial contact mode after that. The response of the cable has been studied in the complete strain range, following the influence of the first contact mode on the other. This brings a cascading influence on the net response. Further it brings out quantitative expressions to predict the response of the cables by taking into account the contact modes present at every stage of loading, and to estimate the contact forces developed at the interfaces, and also to evaluate the contact stresses and to identify the critical locations that cause probable failures of the wire strands. The curvature and twist expressions are refined with generalised strains theory. Four modes of contact can exist among the wires in a stranded multilayer cable assembly, i.e., the contact among the wires in the same layer (known as hoop or lateral contact), the contact among the wires in adjoining layers (radial contact), the combined contact of all the wires (combined lateral and radial contact) and trellis contact between the adjutant layers. The multilayer cables are hitherto modelled on the assumption of the presence of one of the contact modes only, though in reality the contact of modes change from one to the other, depending on the loading and the nature of contraction of the wires. Jiang Xu[12] is to explore the detection of broken wire flaws at multiple locations in the same wire of pre-stressing strands using guided waves below 400 kHz. Three broken-wire flaws in the same wire are detected using low frequency (50 kHz) guided waves, and only one broken-wire flaw is detected using high frequency (320 kHz) guided waves. Yuxin Peng[22] presented a method on computing the external diameter of individual strands and a parametric modeling method for the center curve of closed-end Stranded Wire Helical spring (SWHS). Ahmed Frikha[1] proposed a 2D microscopic model. Homogenization is first applied to helical single wire structures, i.e., helical springs. Next, axial elastic properties of a seven-wire strand are computed. The approach is validated through comparison with reference results: analytical solution for helical single wire structures and 3D detailed finite element solution for seven-wire strands. Kaitlin Spak[16] will focus on new and extended cable modeling methods, as well as the incorporation of damping mechanisms for helically twisted cables, included as damping terms describing variability in bending stiffness or as inter- or intra-wire friction. The authors' interest in this topic is for contracts to model cable harnessed satellites, and vibration suppression research has been included only if it can be applied to damping modeling of cables Biagio Carboni[2] proposed model, hysteresis is introduced in the constitutive equation between the bending moment and the curvature within the special Cosserat theory of shearable beams. Xing Enzhen[23] will focus on existing cable bending models and their applicable conditions are assessed in this study. 1×7 cable structure models are established, and finite element analysis is conducted with ABAQUS. Equivalent bending modulus is obtained at different helix angles of the cable models. The effects of contact and friction among the strands are analysed. The calculated and theoretical results from existing models are compared. Vladimir Ivanco[24] the creep of steel spiral strands with a construction of 1 × 7 and 1 × 19 round wires subjected to constant axial loads is studied numerically. Dabiao Liu et al.,[4] studied the effect of friction on the mechanical behavior of the wire rope with a multi strand cross-section consisting of both single-helix and double-helix wires. The principal aim of this contribution is to define and describe a novel design computational tool for the numerical simulation and prediction of creep strains in spiral strands. The present work is considered as follows, Stage 1: Radial contraction of the helical wires due to Poisson's effects and sliding due to friction, at the contact interfaces are considered. Stage 2: In addition to stage 1, the radial deformation of the core due to the contact forces and Poisson's effect are carried out. Stage 3: In addition to Stage 2, the wire curvature and twist expressions are refined to include with Poisson's effect. Stage 4: In addition to stage 3, the curvature and twist expressions are further refined with the generalised strain theory, that accounts for wire stretch effects. Based on the initial geometry, the contact mode is determined and depending on successive loading, the contraction of all the wires in the radial and lateral directions are ascertained and the threshold limits at which the contact modes change from one to the other are established. The overall response of the multilayer cables under the cascading effects of the presence of different contact modes is compared with the works of the other authors who have adopted one type of contact mode only during their study. This has resulted in an overall reduction in the stiffness of the cable assembly, compared to the existing models. The force and moments in the individual wires are studied and the contact forces and the resulting contact stresses are established as a function of applied loads.

2. Experimental Setup

The experimental setup consisted of a test rig of 40 m span with the end fixtures to support the specimen cable and exert a pulling force upto 100 kN. A double acting hydraulic actuator of 100 kN capacity was used to impart the tensile force in the strand. Figure 1 shows the tensile test rig. To measure the mechanical traction load and response of the strand specimens, a load cell type force transducer, and a dial gauge setup were used as shown Figures 1.

A test specimen of 11 m length was clamped by two sockets at its ends. A dial gauge set up had been mounted at the centre of the specimen as shown in Figure 1 to measure axial extension the axial extension of the cable. The least count of the dial gauge is ±0.01 mm. The measurement procedure as recommended by Bureau of Indian Standards (BIS) was adopted.

Figure 1. Tensile test rig.

3. Test Samples

Metallic single layered cables are used as samples used for the static axial tests.

4. ACSR Dog Conductor

A bimetallic single layer conductor assembly known as ACSR Dog conductor was subjected to static axial test using the test rig and the instrumentation shown in Figures 1. Table 1 shows the detailed specification of

Table 1. Specification of the ACSR dog conductor

Parameter	Value
Radius of the centre core, R_{0c}, mm	2
Radius of the helical wire, R_{0w}, mm	2
Helix angle of the wire, α_0, Degree	80
Young's modulus of elasticity of the core, E_c, GPa	207
Young's modulus of elasticity of the helical wire, E_w, GPa	69
Poisson's ratio of the core, í$_c$	0.3
Poisson's ratio of the helical wire, í$_w$	0.33
Number of wire	6
Coefficient of friction between the core-wire, ì$_{c\text{-}w}$	0.47
Coefficient of friction between the wire-wire interface, ì$_{ww}$	1.4

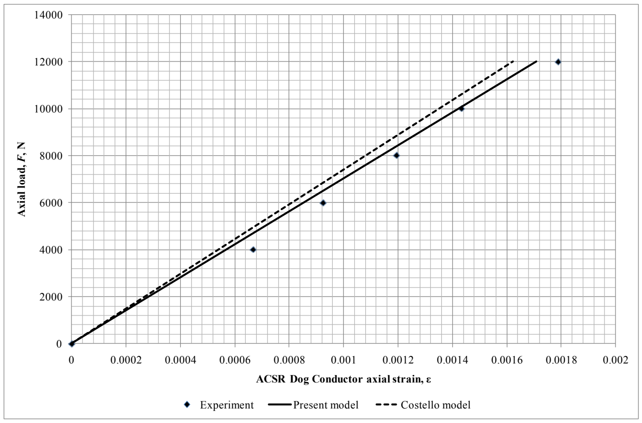

Figure 2. Axial force of ACSR dog conductor.

ACSR Dog Conductor. The samples mounting and the measurement procedures were adopted BIS Table 2 shows the applied axial loads and the corresponding strain values measured. The numerical computations made for these samples as per the analytical formulations mentioned in Gnanavel et al are also shown in the Table 1, for the present model and Costello model. The analytical model of the present model overestimates the axial stiffness by 4% as well as Costello model overestimates by 9%, there by confirming the accuracy of the present model, as per the refinements suggested.

5. Conclusion

The paper has addressed a proper methodology to identify the prevailing contact modes in a stranded cable system at each stage of loading, when it is subjected to axial tension and torsion. Analytical expressions to examine the prevailing geometry and to identify the proper contact mode during extension of a strand are derived with due consideration of Poisson's effects on the wires and the core and its consequences on the wire geometry and hence for the revised contact mode. The critical stress levels at which a cable changes its contact mode from one form to the other have been evaluated. The axial and the torsional response of the cables are evaluated under the prevailing contact modes for multilayered cables. Consideration of frictional effects at the contact interfaces, refined expressions for wire bending and twisting by adopting generalised strain theory, consideration of Poisson's effects and their inclusion in the wire bending and twisting and estimation of contact forces and deformation due to contact forces are the salient features included in the paper as compared to earlier researches of[3] who have done significant works except these new features. The cable axial response and the torsional response are predicted for typical assemblies of multi-layered cables and the results are compared with this researcher. The model adopted in the paper underestimates the cable axial stiffness but overestimates the torsional stiffness, due to the slip and other features considered. This paper has particularly addressed the existence of a combined contact mode in the initial stages of loading and has evaluated the corresponding stiffness of the cable assemblies. During successive stages of loading the contact mode changes to a core-wire radial contact and the corresponding stiffness changes are also evaluated. When many researchers have assumed the core-wire radial contact mode only to prevail from the initial stage of loading, this thesis has specifically taken note of the combined mode contact and has cited its cascading influence on the change of stiffness, when the cable transforms to the core-wire radial contact mode. The existence of the contact stresses during the short interval of loading is more than the contact stresses attributed by the other researchers, when the cable is handled in the core-wire radial contact mode. This increased stress value in the very initial stage of loading will have considerable influence on the design of cables for such applications.

6. Suggestions for Future Work

The axial response of multilayered cable assemblies is studied in this paper, under static loading conditions. Extension of the present model to consider the effects of dynamic loads under impact or vibratory conditions is future concern. Understanding the suitable modelling of the fatigue phenomena of wires at their contact interfaces is of prime importance to predict the wire breakages or wear pattern. Since the assemblies are often encountered with bending loads, when such cable are passed over pulleys, drums, sheaves etc., the global bending and the local bending and study of their effects will enable cable designer for proper life estimation and residual life in cables. The nonlinear studies of cable behaviour will enable future researchers for prediction of the response of cables in a more accurate way.

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