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Modelling and simulation of power lines made of composite structures

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ABSTRACT

The paper presents our new Functionally Graded Material (FGM) beam finite element that can be used for elastic-static, modal and buckling analysis of single beams or spatial beam structures. The material properties in a real beam can vary continuously in the longitudinal direction, while the variation with respect the transversal and lateral directions is assumed to be symmetric in a continuous or discontinuous manner (Murín et al., 2016). An application to elastostatic and modal analysis of high-voltage lines (single, double and triple bounded) with heterogeneous cross-sections is presented. The heterogeneous material properties of the cross-section are homogenized using the extended mixture rules. A linearized elastostatic analysis of power lines with the effect of tensile axial forces is proposed. Further, the axial, flexural and torsional eigenfrequencies and eigenmodes are calculated. The corresponding results of simple and bundle power lines obtained by our proposed finite element are compared with the ones obtained with standard beam finite elements. Further, the accuracy and efficiency of our proposed beam finite element is evaluated and studied. The results of the chosen analyzed case are verified by measurements on real electric conductor.

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1. Introduction

One of the most used multi-wire conductors in overhead power lines is Aluminum Conductor Steel Reinforced (ACSR) – Fig. 1. The outer strands of ACSR are made of aluminum, chosen for its excellent conductivity, low weight and low cost. The center strands are made of steel for the strength required to support the weight without stretching the aluminum due to its ductility. This gives the power lines an overall high tensile strength.

The power line is from a mechanical point of view a 3D system. It can be loaded in longitudinal, horizontal and vertical direction. Also torsional loading is possible as well. However, in the technical calculations the problem is frequently simplified to a one dimensional system. In the literature, e.g. [2], an analytical method is presented for elastic-static analysis or free vibration in its vertical plane. However, analytical methods are not effective for general spatial analyses and numerical methods, like the finite element method, are used. For the simple elastic-static analysis the geometrically nonlinear link finite element can be used that is able to analyze the tensional forces and stresses, and the elongation of the line. For dynamic analysis, the standard beam finite element is preferable.

Power lines under certain conditions are exposed to external loads:

- Static ones – e.g. accumulation of ice on the power line. Icing is one of the main external loads, frequently threatening the reliability and mechanical security of overhead power lines situated in cold regions. Excessive accretion of ice on conductors can induce electric faults, such as flashovers, due to insufficient clearances, and mechanical damages to transmission line systems, such as hardware/insulator component failure, cable breakage, tower deformation and collapse [3–5].
  In [6], the tensile strength and critical stress states of a complete conductor under extreme design conditions is investigated and a sensitivity study explored the importance of friction effects between conductor wires on the mechanical response.
- Dynamic ones – e.g. vibrations and oscillations induced by air flow, ice-shedding, etc. Vibrations and oscillations of overhead power lines (aeolian vibration, galloping and subspan oscillations) are a very dangerous problem because it can cause mechanical damage of the conductors, insulators, armatures and power line pylons. They can negatively influence the whole

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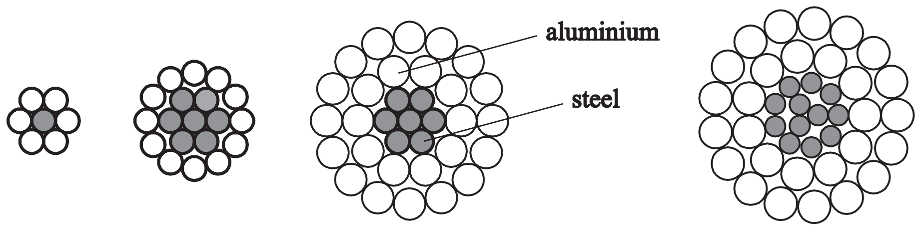

Fig. 1. Different heterogeneous cross-section of the used ACSR conductor.

power transmission system and can make a power transmission system collapse.

Ice-shedding is investigated with experimental, numerical and theoretical methods by many authors. Approximate practical models of ice-shedding were suggested in the early 1940 s, reported in [7]. With the improvement of computational mechanics, numerical simulation methods (over all the finite element method – FEM) are used to study ice-shedding from power lines. E.g. in [8] the dynamic response of bundle conductors and five-span line section is analyzed, while in [9] the dynamic response of transmission lines with different parameters after ice-shedding is numerically simulated. In [10], a new theoretical method to calculate the jump height of the overhead power line after ice-shedding is presented. Dynamic models of multi-span lines for analyzing ice-shedding are compared to experimental measurements, see [11].

Large amplitude vibrations of long-span transmission lines with bundled conductors in gusty wind are studied in [12]. In [13] the impact of wind-induced vibration coefficients on transmission towers is presented. The issue of line vibration and galloping of power lines is presented e.g. in [14], and in [15] numerical simulation of galloping by means of ABAQUS software is presented.

The proposed contribution is a continuation of our previous paper [1] that is extended to elastostatic analysis of FGM beam structures. In [1], a brief overview of current state of the art solutions of FGM beams is provided together with a list of the current literature on this topic. In Chapter 2, the new composite beam finite element equations suitable for static, modal and buckling analyses of single beams or spatial beam structures made of spatially varying FGMs in longitudinal, transversal and lateral direction are presented. From the differential equations of axial, flexural and torsional deformation of the FGM beam with longitudinally varying material properties the transfer relations and the local and global finite beam element matrices are established. Effects of axial and shear forces are included. The inertial forces and moments are considered as well. Homogenization of the radially varying material properties of the power line is introduced in Chapter 3. The heterogeneous material properties of the cross-section are homogenized using the extended mixture rules [1]. An application to elastostatic and modal analysis of high-voltage lines (single, double and triple bounded) with heterogeneous cross-section is presented in Chapter 4. The numerical calculations of the linearized elastostatic problem and the axial, flexural and torsional modal analyses of power lines with tensile axial forces are performed. The results of the numerical analyses of simple and bundle power lines obtained by our proposed finite element are compared with the ones evaluated using standard beam finite elements in ANSYS [16]. To confirm the suitability, the efficiency and the accuracy of our numerical models, an experimental measurement realized on selected ACSR power line is done in Chapter 5.

2. Composite beam finite element equations

Let us consider a 3D straight finite beam element (Timoshenko beam theory and Saint-Venant torsion theory) of doubly symmetric cross-section – Fig. 2. The nodal degrees of freedom at node i are the displacements u_i, v_i, w_i in the local axis direction x, y, z, and the cross-sectional area rotations $\varphi_{x,i}$, $\varphi_{y,i}$, $\varphi_{z,i}$. The degrees of freedom at the node j are denoted in a similar manner. The internal forces at node i refer to the axial force N_i, the transversal shear forces $R_{y,i}$ and $R_{z,i}$, the bending moments $M_{y,i}$ and $M_{z,i}$, and the torsion moment $M_{x,i}$.

Furthermore, $n_x = n_x(x)$ denotes the axial force distribution, $q_z = q_z(x)$ and $q_y = q_y(x)$ are the transversal and lateral force distributions, $m_x = m_x(x)$, $m_y = m_y(x)$ and $m_z = m_z(x)$ are the distributed moments, $\mu_x = \rho A = \mu_y = \mu_z = \mu$ denote the mass distribution, $\overline{\mu}_y = \rho I_y$, $\overline{\mu}_z = \rho I_z$ and $\overline{\mu}_{xT} = \rho I_p$ refer to the distributions of mass moments of inertia, $\rho = \rho_L^H(x) \equiv \rho_L^H$ is the homogenized effective mass density distribution, A is the cross-sectional area, I_y and I_z are the second moments of area, $I_p = I_y + I_z$ denotes the polar moment of area and ω is the circular frequency. The effective homogenized and longitudinally varying stiffnesses read as follows: $EA = E_L^{NH}(x)A$ is the axial stiffness ($E_L^{NH}(x) \equiv E_L^{NH}$ denotes the effective elastic modulus for axial loading), $EI_y = E_L^{M_yH}(x)I_y$ is the flexural stiffness about the y-axis ($E_L^{M_yH}(x) \equiv E_L^{M_yH}$ is the effective elastic modulus for bending about axis y), $EI_z = E_L^{M_zH}(x)I_z$ is the flexural stiffness in axis z, ($E_L^{M_zH}(x) \equiv E_L^{M_zH}$ is the effective elastic modulus for bending about axis z), $G\overline{A}_y = G_{Ly}^H(x)k_y^{sm}A$ is the reduced shear stiffness in y-direction ($G_{Ly}^H(x) \equiv G_{Ly}^H$ is the effective shear modulus and k_y^{sm} is the average shear correction factor in y-direction [17]), $G\overline{A}_z = G_{Lz}^H(x)k_z^{sm}A$ is the reduced shear stiffness in z – direction ($G_{Lz}^H(x) \equiv G_{Lz}^H$ is the effective shear modulus and k_z^{sm} is the average shear correction factor in z – direction), $G_L^{M_xH}(x)I_T$ is the effective torsional stiffness, $G_L^{M_xH}(x) \equiv G_L^{M_xH}$ denotes the torsional elastic modulus and I_T is the torsion constant – $I_p = I_T$ for the circular and the ring cross-section). The derivatives with respect to x of the relevant variables are denoted with an apostrophe "′" throughout the paper.

The differential equations for axial, transversal, lateral and torsional deformation and their solutions are established according to Fig. 2 – Definition according to the Transfer Matrix Method [18]. The finite element equations of the 3D FGM beam are established from the transfer matrix relations according to Fig. 2 – Definition according to the Finite Element Method.

2.1. Axial deformation

Eq. (1) results from the axial deformation problem of the FGM beam, including the specific case of harmonic oscillations ($u = u(x)$ is the axial displacement distribution, $u' = u'(x)$ is its first derivative and $u'' = u''(x)$ denotes its second derivative, $N = N(x)$ is the axial force distribution, $N' = N'(x)$ is its first derivative):

$$N' = n_x - \mu_x\omega^2 \; u \tag{1}$$

$$u' = \frac{N}{EA}. \tag{2}$$

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