Effective Inelastic Bending Behavior of Multi-Wire Cables Using Finite Elements Accounting for Wire Contact

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ABSTRACT

This contribution focuses on the investigation of inelastic structural effects occurring during the bending deformation of cables using detailed finite element models of helix wire strands. Due to the complex structure of cables usually consisting of concentric layers of intertwined wires, shields and the outer jacket, inelastic deformation behaviour has to be expected. In this work, we model simplified cables as strands of helix wires discretised with quadratic beam elements to investigate the influence of geometric parameters such as the helix angle of the wires and the interactions of the wires by means of frictionless or frictional contact models. Starting at low model complexity, we use double wire and seven wire models to simulate pure bending of intertwined strands omitting material inelasticity to avoid superposition of structural and material effects. Different variations of contact states in the undeformed configuration of the seven wire strand are taken into account allowing for the direct observation of the influence of active contacts on the strand's bending response. First steps towards modelling the interactions between wires and objects relevant in cable bundle assembly, e.g. cable ties or clips, are presented for the double wire model. The presented models yield a valuable toolbox for the investigation of specific structural parameters affecting the deformation behaviour of cables.

Keywords: Cable simulation, nonlinear beam, frictional wire contact, multi-wire strand, bending experiment.

1 INTRODUCTION

In the development and manufacturing process of modern cars, cables and hoses are important system components, see Fig. 1 left. In automotive industry, virtual assembly planning and digital validation of system layouts require fast and physically correct simulations of the mechanical behaviour of cables and hoses. Section 6 of [1] and section 4 of [2] summarise application examples from vehicle industry and [3] describes virtual product realisation processes using one-dimensional deformable objects from the design phase to production and assembly planning.

In this work, we present a modelling approach using a detailed finite element (FE) model [4] for composite cables which can be used to investigate the effective inelastic constitutive behavior of abstract cables resulting from structural effects. We follow approaches for detailed wire strand models using finite element models as described in [5, 6, 7, 8, 9, 10] for the investigation of wire

strands under load. However, while these contributions use finite volume elements, we use finite beam elements to model the individual wires. Following the method given in [11], we approximate the centreline of each wire with a helix and discretise it with quadratic shape functions. This allows for a comparatively easy implementation of the boundary and loading conditions as well as relatively short computation times.

Figure 1. Left: Overview of the system of cables and hoses in a car. *Courtesy of Volvo Cars and Fraunhofer-Chalmers Research Centre, Gothenburg.* Right: Experimental result of the pure bending of a cable specimen given as bending moment M_B vs. bending curvature K_B diagram [12].

Cyclic pure bending experiments on a simple cable specimen show that the effective mechanical response of cables is usually strongly nonlinear and inelastic [12, 13], see Fig. 1 right. Presumably, material plasticity, damage and structural effects on the level of individual constituents such as contact and friction between wires occur in such experiments due to the structural complexity of cables. In real experiments, material and structural effects can hardly be investigated separately with acceptable experimental effort. Previous work of the authors focused on modelling the inelastic bending behaviour of a simple cable using standard constitutive laws for elasto-plasticity and damage in the framework of geometrically exact rod models [14]. While it was possible to simulate the bending response of the cable on the level of the sectional quantities of the geometrically exact rod, this approach only yields an inelastic model for one class of cables and the modelling parameters for one specific cable type. It does not allow for the investigation of the underlying inelastic effects which is necessary to enable a more universal estimation of the deformation behaviour of any cable based on its structure in the future.

We therefore investigate these effects and their interplay separately with cable models using finite elements on the level of wires in this work. A commercial FEM tool [15] is used to model the pure bending of a cable. We model the cable as an abstract strand of intertwined wires starting at low model complexity. In this first step, the wires are modelled as materially elastic in order to avoid a superposition of material and structural inelasticity.

This modelling approach can furthermore be used to investigate the influence of different helix angles of the wires on the effective behaviour of the abstract cable model. Therefore, the pure bending simulation is performed using models with different wire helix angles as initial stress-free configuration. The modelling approach presented in this work allows for versatile and detailed investigations of the effective mechanical response of wire strands as abstract cable models. We will show that it is useful for specific simulation experiments on cable-like structures to get a better understanding of the different material and structural inelastic effects which occur in real experiments performed on cables. While it is not simply possible to switch friction on and off in real experiments and measure the influence of friction on the effective behaviour, we can perform such investigations using the presented model.

2 Cable model using finite elements

Cables undergo large spatial deformations in applications. Therefore, we discretise the wires in our abstract cable model using finite beam elements with quadratic shape functions [4]. The beam element is a one-dimensional line element in space and is defined by three nodes having six degrees of freedom per node: translations in x , y and z directions and rotations about the x , y and z axes [15]. In order to avoid superposition of structural and material inelastic effects, we model the wires using a linear elastic material model with standard parameters for a copper alloy ($E = 1.1 \cdot 10^5$ MPa, $\nu = 0.34$). We thereby deliberately omit material inelasticity which certainly occurs during the deformation of the wires in real experiments.

2.1 Wire strand geometry

Figure 2. 3D FE model of the double wire strand with a wire helix angle of $\alpha_c = 36^\circ$.

Figure 3. 3D FE model of the seven wire strand with a wire helix angle of $\alpha_c = 36^\circ$.

The first model we investigate is a double wire strand consisting of two intertwined helices, see Fig. 2. The second simplified cable is modelled using seven wires with one straight wire as core and six helices in the outer layer, see Fig. 3. The intertwined wires are modelled as stress-free helices [11], one helix resembling one metallic wire. While the definition of the geometric parameters of the double wire strand is straightforward, the choice of the geometric parameters of the stress-free configuration of the seven wire strand determines the contact state in the undeformed cross section. The necessary parameters for the double helix structure are the helix radius r and the wire radius, where both wires have the same radius R . In the seven wire strand, the outer wires' cross sections have an elliptic shape in the plane orthogonal to the z -axis of the structure. The radius of the ellipse depends on the helix angle α of the wire and essentially determines if neighbouring wires are in contact, see Fig. 4. Here, the core wire radius R_c and outer wire radius R_w can differ resulting in different contact states in the undeformed cross sections. We distinguish three cases [11, 16]. In the first case, the outer wires and the core wire have the same radius resulting in a cross section where the outer wires are only in contact with their neighbouring wires in the outer layer, see Fig. 5 left. The condition

$$R \sqrt{1 + \frac{\tan^2(\frac{\pi}{2} - \frac{\pi}{m})}{\sin^2 \alpha}} = r, \quad (1)$$

with the number of outer wires m , has to be fulfilled. In the second case, core and outer wire radii are different and fulfil the condition

$$R_w \sqrt{1 + \frac{\tan^2(\frac{\pi}{2} - \frac{\pi}{m})}{\sin^2 \alpha}} < R_c + R_w. \quad (2)$$

This results in a cross section as shown in Fig. 5 middle, where the outer wires are only in contact with the core wire in the undeformed configuration. In order to generate a cross section, where

Figure 4. Definition of the parameters of a seven wire strand according to [16].

all neighbouring wires are in contact in the initial configuration, see Fig. 5 right, the radii have to fulfil

$$R_w \sqrt{1 + \frac{\tan^2(\frac{\pi}{2} - \frac{\pi}{m})}{\sin^2 \alpha}} = R_c + R_w. \quad (3)$$

To ensure comparable results and boundary conditions in the virtual experiments, we aimed at a resulting strand radius of approximately 8 mm and a specimen length of 220 mm for all models. For all seven wire strand models, a helix radius $r = R_c + R_w = 5.33$ mm was used. Model variants with different helix angles were set up for the double helix and the seven wire model to investigate the influence of this geometric parameter. The parameters for the seven wire strand models are summarised in table 1.

Table 1. Geometric modelling parameters for the seven wire strand models. Wire radii are given in mm.

contact case	$\alpha_a = 9^\circ$	$\alpha_b = 18^\circ$	$\alpha_c = 36^\circ$
<i>I</i>	$R_c = R_w = 2.642$	$R_c = R_w = 2.567$	$R_c = R_w = 2.257$
<i>II</i>	$R_c = 3.233, R_w = 2.1$		
<i>III</i>	$R_c = 2.691, R_w = 2.642$	$R_c = 2.766, R_w = 2.567$	$R_c = 3.076, R_w = 2.257$

Figure 5. Cross sections of seven wire strand models with different wire radii in undeformed state. Left: Only outer wires are in contact, with $R_c = R_w$. Middle: Outer wires are only in contact with core wire, $R_c \neq R_w$. Right: Each wire is in contact with its neighbours, $R_c \neq R_w$.

2.2 Contact modelling

During mechanical loading, contact between wires occurs and must be taken into account. We use the Coulomb friction model provided in ANSYS to model contact between wires [15]. The

pure penalty contact formulation was chosen to model wire-to-wire contact in this work. In order to investigate the influence of friction on the effective bending response of the cable, simulations without and with friction have been performed. A Coulomb friction model with varying isotropic friction coefficients was used for that purpose.

The presented wire strand models were further enhanced in order to investigate the influence of additional objects on the wire interactions, especially the friction behaviour. Those first steps include the introduction of rings resembling objects such as cable ties, clamps or clips, see Fig 6. We investigated double wire strand models with one central ring and two equally distanced rings with an inner diameter of $D_i = 16.5$ mm, outer diameter $D_o = 17$ mm and the width $w = 5$ mm. The bonded contact formulation, which connects the degrees of freedom of both contact objects in the relevant region, was used to model the interaction between the rings and the wires in order to emulate clamping or tight rings.

Figure 6. Double helix models with helix angle α_a and additional rings modelled as rigid bodies.

3 Virtual pure bending experiments

3.1 Boundary conditions

The boundary conditions of a planar pure bending experiment yield a deformation state where a constant bending moment acts on the specimen. In an ideal setup, neither lateral or normal forces nor torsional moments occur. Thus, a homogeneous specimen will reach a configuration in the static equilibrium with a constant bending curvature along the specimen. In this work, the pure bending boundary conditions were defined using a homogeneous beam model and later applied to the composite structures described in the previous section. Fig. 7 shows the implementation of the boundary conditions using a hinged support on the left, and a simple movable support on the right end. Bending was induced by applying the bending angle θ_B on both ends up to a maximum of 90° . In all virtual experiments, one full load cycle including loading and unloading to $\theta_B = 0^\circ$ was simulated.

Figure 7. Boundary conditions for pure bending of a homogeneous beam.

The boundary conditions were applied to the composite wire strand structures using remote points which control the degrees of freedom of the nodes in the cross sections on the strand ends. Fig. 8 shows the deformed configurations of the double and seven wire strand models at $\theta_B = 90^\circ$ with a constant global curvature of the structure, resulting in a semi-circular shape of the specimen.

Figure 8. Deformed configurations of FE models of the composite structures. Left: Double wire strand with a helix angle of $\alpha_c = 36^\circ$. Right: Seven wire strand with a helix angle of $\alpha_c = 36^\circ$.

3.2 Analytical solution for pure bending of a wire strand

The results of the simulation experiments will be examined by analysing the bending moment M_B as a function of the bending curvature k . Costello derives in [16] an analytical expression for the bending moment of an m wire strand consisting of one core wire and m_2 outer wires with helix angle α under bending,

$$M_B = \frac{\pi E}{4} \left[\frac{2m_2 \sin \alpha}{(2 + \nu \cos^2 \alpha)} R_w^4 + R_c^4 \right] \frac{1}{\rho}, \quad (4)$$

with the wires' Young's modulus E , their Poisson ratio ν and the bending radius ρ of the strand, i.e. the inverse of the bending curvature,

$$k = \frac{1}{\rho}. \quad (5)$$

This expression has been derived neglecting friction and under the assumption that the outer wires are only in contact with the core wire, but not their neighbouring outer wires to minimise wire interactions. Thus, the analytical solution for $m_2 = 6$ is comparable to our virtual simulations using the seven wire model with contact case *II* given by equation (2).

3.3 Results

The following section summarises a choice of simulation results using the presented FE models to demonstrate their capabilities.

We compare our numerical results derived with a seven wire strand model with contact case *II*, see eq. (2), with the analytical solution introduced in the previous section. Fig. 9 shows the analytical and numerical results for the three investigated helix angles α . The analytical and numerical results show good agreement for all helix angles and thus validate our FE model. A minor deviation can be observed for the largest helix angle α_c , where the FE solution exceeds the analytical solution at higher curvatures. Here, contact between the outer wires occurs in the FE model, which is not considered in the analytical solution, resulting in stiffer behaviour.

Fig. 10 shows the influence of the helix angle on the effective bending behaviour for the double (left) and seven wire strand models (right). Both figures show that the strand's stiffness decreases with an increasing helix angle. The analytical solution shown in Fig. 9 gives the same tendency. This result is caused by the fact that the bending behaviour of helix wires with a smaller helix angle tends towards the behaviour of straight wires, resulting in higher local material strain. The behaviour of wires with a higher helix angle, however, resembles the behaviour of a spring with smaller local strains in bending.

The presented model takes into account different contact states in the cross section, as defined in section 2.1. Fig. 11 allows for the comparison of the bending behaviour of the different models

Figure 9. Comparison of analytical results derived using Costello's solution [16] with numerical results for seven wire strands with contact case II and helix angles $\alpha_a = 9^\circ$, $\alpha_b = 18^\circ$ and $\alpha_c = 36^\circ$.

Figure 10. Influence of the helix angle used to model the wire strands on the effective bending behaviour. Left: Double helix model. Right: Seven wire strand models with contact cases I and III.

with helix angle $\alpha_b = 18^\circ$. The results show that contact cases *I* and *III* yield similar results while contact case *II* shows significantly less stiff behaviour. In case *II*, the core wire is only in contact with the outer wires. In case *I*, the outer wires are in contact with each other and in case *III*, the outer wires are additionally in contact with the core wire. This means that for models with helix angle $\alpha_b = 18^\circ$, the contacts between core and outer wires contribute less to the composite stiffness than contacts between outer wires. Similar behaviour can be observed for the smaller helix angle $\alpha_a = 9^\circ$. For models with a higher helix angle $\alpha_c = 36^\circ$, however, the model with contact state *I* shows the least stiff behaviour, see Fig. 12 while contact states *II* and *III* yield bending moments in a similar range. This implies that for this higher helix angle, the contacts between neighbouring outer wires contribute less to the effective stiffness of the composite structure.

Figures 11 and 12 additionally show the results for each model with frictional contact. For both helix angles, using frictional instead of frictionless contact results in hysteresis cycles. The smallest hysteresis cycle occurs for the model with contact state *II* and α_b and the largest for contact state *III* and α_c . This coincides with the number of elements in contact in the respective models, which is lowest for contact state *II* and α_b and highest for contact state *III* and α_c . The result for contact case *I* in Fig. 12 allows for the study of the curvature dependence of the frictional effects. Here, the hysteresis loop only opens after a curvature of approximately 8 m^{-1} has been reached. The observation of the beam elements in contact yielded that this curvature marks the

Figure 11. Simulation results for pure bending of seven wire models with helix angle α_b and different contact states *I*, *II* and *III*. For each model, results of frictionless and frictional contact are given.

Figure 12. Simulation results for pure bending of seven wire models with helix angle α_c and different contact states *I*, *II* and *III*. For each model, results of frictionless and frictional contact are given.

onset of sliding between elements in contact leading to frictional behaviour. Below this curvature, the beam elements do not slide on each other and the frictional model does not contribute to the bending moment.

We will now take a closer look at simulation results obtained with double wire strand models. Fig. 13 shows the pure bending results using a frictionless and frictional contact model for the strand model with helix angle α_a . It shows that the use of frictional contact has no influence on the bending moment of the double wire strand. Closer investigations showed, that almost no sliding between beam elements occurs in this structural model under pure bending. Consequently, the choice of frictional contact cannot influence the response of the composite model. This is also the case for larger helix angles.

In order to enforce sliding between the beam elements in the double wire strand, additional restrictions on the wire movement were introduced by adding rigid body rings with bonded contact, as described in section 2.2. Fig. 14 shows the resulting bending moments for frictionless and frictional contact for these models. One additional rigid body ring in the middle of the strand increases the stiffness of the composite model more than two rings. Furthermore, the hysteresis opens at a smaller bending curvature and the hysteresis cycle is bigger. This coincides with the fact that a

Figure 13. Influence of friction on the double wire strand model with helix angle α_a .

Figure 14. Influence of friction on the double wire models with helix angle α_a with one (black) or two (red) additional rigid body rings.

higher number of elements is in sliding contact during loading for the model with one ring, even though the percentage of elements in contact is higher in the original model without any rings.

4 CONCLUSIONS

In this work, we presented an approach to model the effective mechanical response of helix wire strands for the investigation of cable behaviour under mechanical load. A commercial finite element tool was used to generate structural models for double and seven wire strands. The wires were modelled as stress-free helices in the straight initial configuration accounting for different helix angles in different models. Frictionless and frictional contact models were used to investigate the influence of friction on the effective behaviour of the presented composite structures. The wires were modelled as materially linear elastic in order to avoid a superposition of material and structural inelastic effects. The FE models of the wire strands were used for virtual pure bending experiments.

We have shown that the presented modelling approach is useful to improve the understanding of the influence of structural effects on the composite behaviour. The results show that structural parameters such as the helix angle of the wires, already has an influence on the resulting behaviour, even for frictionless contact. Furthermore, the results showed that special attention has to be paid to correct modelling of the cross section and definition of the contacts within the cross section of the composite structure as the number of contacts strongly affects the deformation behaviour. The

influence of friction on the results depends on the specific structural model and can be impacted by objects in the environment. In this work we took first steps to simulate objects relevant for cable bundle assembly by adding rigid body rings to the double helix structure.

While this work shows the capabilities and usefulness of the FE wire strand models for the investigation of structural effects occurring under bending load, the model does not suffice to represent the complex inelastic behaviour of a real cable as shown in Fig. 1 right. Thus, a comparison of simulation results with experimental results is not possible, yet. In order to approach the inelastic behaviour of a real cable specimen, the material model of the wires has to be extended to an elastoplastic model and the viscoplastic polymer jacket has to be added. It has been shown in previous work [14], that the qualitatively different behaviour in the first and following cycles is a result of initial damage during the first load cycle, e.g. detachment of the jacket from wires. Consequently, a proper approach to model the interactions between wires and the polymer layer has to be used. Another option is the generation of experimental data for simplified cable strands using elastic wires to approach the wire strand models presented here.

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