# MODELING THE EFFECTIVE INELASTIC BEHAVIOR OF MULTI-WIRE CABLES UNDER MECHANICAL LOAD USING FINITE ELEMENTS

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Abstract. In the development and manufacturing process of modern cars, cables and hoses are important system components. In automotive industry, virtual assembly planning and digital validation of system layouts require a fast and physically correct simulation of the mechanical behavior of cables and hoses. The mechanical response of cable systems and hoses under load is typically non-linear and inelastic due to their multi-component structure. However, those effects can hardly be observed and investigated separately in experiments. Thus, the authors recently presented simplified cable models using the commercial finite element tool ANSYS which take wire interactions into account. As cables in automotive applications are often subject to large deformations, finite beam elements with quadratic shape functions were used to discretize the single helix wires. The comparison of simulation results obtained for helix wire strands under bending with analytical results based on wire rope theory showed good agreement for the case of frictionless interactions. Furthermore, the modeling approach serves as a versatile toolbox for the investigation of material and structural inelastic effects which commonly occur when cables are deformed. A significant influence of structural parameters, such as the helix angle of the wires or the choice of friction model parameters, on the mechanical response could be found. In this work, this modeling approach is applied to the simulation of multi-wire strands consisting of parallel elastic wires under bending and torsion. The results of these mesoscopic simulations will be compared to experimental results.

#### **1** INTRODUCTION

The system of cables and hoses in a modern car can be referred to as the nervous system of the vehicle as it is essential for basic features, e.g. brake hoses, as well as advanced functions, e.g. sensor cables. While their main purpose is the transport of electric signals, fluids or gases, their mechanical properties are of relevance in development, assembly and during life-time, if the flexible component is subject to deformations. Thus, virtual assembly planning and digital validation of system layouts in the automotive industry require a fast and physically correct simulation of the mechanical behavior of cables and hoses. In this work, the modeling approach using a finite element (FE) model [1] for simplified cable-like structures as presented in [2] is applied to a wire strand of three parallel elastic fibers. Bending and torsion experiments are performed and implemented in simulations to allow for a validation of the modeling approach.



**Figure 1**: Examples of different types of cables and cable bundles relevant for automotive applications. Left: Coaxial cable with a diameter of 2.8 mm [4]. Right: Different types of simplified bundles using different textile tape patterns: from partly to fully taped (left to right).

Experimental results on simple cable specimens show that the effective mechanical response of cables is usually strongly nonlinear and inelastic. Looking at the choice of cross sections of cables and cable bundles given in Figure 1, the observed behavior is presumably caused by a superposition of inelastic phenomena such as material and structural effects on the level of individual constituents (e.g. contact and friction). Examples are given in Figure 2 for pure bending [3] and torsion [4] of simple cables. Cable models using finite elements on the level of wires provide an approach to investigate such effects and their interplay.



Figure 2: Typical experimental results on cable specimens under large deformations. Left: Pure bending on a simple cable specimen given as bending moment  $M_B$  vs. bending curvature  $K_B$  diagram [3]. Right: Torsion on a coaxial cable given as torsion moment  $M_T$  vs. twist  $\theta_T/L$ , results originally published in [4].

Cables undergo large spatial deformations in applications. Therefore, a modeling approach

utilizing a commercial FE tool [5] to model multi-wire strands using finite beam elements with quadratic shape functions was presented in [2]. Simplified cables were modeled as strands of stress-free helices which approximated the center line of each wire following [6]. The models were validated against the analytical solution for pure bending of a helix wire strand as given by Costello [7]. In addition, contact between wires occurs and is taken into account. In order to investigate the influence of friction on the effective mechanical response of the multi-wire strand, simulations without and with friction were performed. The results led to the conclusion that this modeling approach shows a significant influence of friction on the mechanical response of the strand, under the condition that the load case induces sliding between elements in contact. Furthermore it could be demonstrated that structural parameters such as the helix angles of the wires affect the effective behavior of the strand.

The modeling approach presented in this work serves as a versatile toolbox for detailed investigations of the effective mechanical response of multi-wire cables. In [2], the modeling approach was validated against analytical solutions for frictionless pure bending of strands of elastic helix wires and found good agreement. Since we are interested in the separation of structural and material inelastic effects which presumably contribute to the mechanical response of wire strands, we take first steps to compare our simulation results for multi-wire strands with results obtained in bending and torsion experiments. The modeling approach taken in [2] for multi-wire strands of two helix wires or one straight core wire and six helix wires in the first layer assumed that the helix wires are stress-free, i.e. inelastic effects such as plastic deformations of each wire were not taken into account. Finding such a stress-free specimen consisting of elastic helix wires is especially challenging, since the model parameters of each wire have to be known for a comparison with the FE model. Thus, the multi-wire structure was simplified further for this work by observing a bundle of three parallel and highly elastic rods. Bending and torsion experiments were performed on this specimen and the results were compared to results obtained using the FE model.

In chapter 2, the sample manufacturing and experimental boundary conditions in bending and torsion are described. In the following chapter 3, the model details and implementation of virtual bending and torsion experiments are given. The results are presented and discussed in chapter 4.

## 2 SAMPLE MANUFACTURING AND EXPERIMENTAL PROCEDURE

#### 2.1 Muti-wire strand of elastic rods

The multi-wire strand under investigation consists of three parallel spring steel rods with a diameter of  $d_w = 2 \text{ mm}$ , which yields a strand diameter of  $d_s = 3.7 \text{ mm}$  as the wires are packed closely, and a free specimen length of L = 350 mm. The cross section and a side-view of the specimen are depicted in Figure 3. Spring steel is a highly elastic material with a Young's Modulus of E = 175.6 GPa, which was measured for this purpose using the bending experiment described in section 2.2 on one spring steel rod. In order to ensure a fixed cross section in the plane bending experiment, textile tape is applied in the middle of the specimen. Furthermore, the tape is applied at the ends of the specimen to avoid sliding between the wires and clamps. This tape is used in cable bundle fabrication in the automotive industry and will have to be taken into account at later stages, if bundles such as those shown in Figure 1 shall be simulated.



Figure 3: Strand of three parallel spring steel rods. Left: Cross section of the strand. Right: Side view of half of the specimen including textile tape in the middle of the specimen and at the clamping positions.

## 2.2 Geometrically non-linear bending experiment

A robust planar bending experiment with reproducible and easy to implement boundary conditions, which at the same time allows for large spatial deformations of slender structures, is used, see Figure 4. The boundary conditions are based on the second case of Euler buckling [9] where both ends of the rod are simply supported, the right end on a roller support and the left end on a pinned support. Here, the boundary conditions are implemented for multi-wire strands by clamping the specimen's ends on revolute joints allowing for free rotation around the x-axis. Consequently, the bending plane is the y-z-plane. The bending experiment is performed in two phases to avoid having to deal with the critical Euler buckling load. In the initial phase, a force in negative y-direction is applied in the middle of the specimen at time t = 0 to bend the specimen beyond the critical buckling point. This leads to a displacement of the right end in z-direction which is the starting point  $\Delta w_z^0 \approx 5 \text{ mm}$  of the second phase which is a displacementcontrolled cyclic procedure. The cyclic bending is implemented by applying the displacement  $\Delta w_z$  in z-direction in steps of multiples of the strand diameter  $d_s$  until a maximum displacement of  $\Delta w_z = 3d_s$  is reached. Afterwards, unloading back to the initial position  $\Delta w_z^0$  is performed. These boundary conditions result in a symmetric configuration as shown in Figure 4 where the bending moment in the supports is zero and has its maximum in the middle of the specimen. The experiment is performed quasi-statically and the reaction force  $F_z(t)$  which is caused by the displacement  $\Delta w_z$  is measured, see Figure 5.



**Figure 4**: Bending of a simply supported homogeneous beam. In the initial phase, t = 0, the force  $F_y^0$  is applied for prebending. The reaction force  $F_z(t)$  is measured during bending, t > 0.



Figure 5: Deformed configuration of the strand of three parallel elastic wires under bending. The displacement  $\Delta w_z$  is applied during loading.

#### 2.3 Torsion experiment

A torsion experiment following the standard procedure for a clamped rod specimen is performed [8]. In our case, the left end is clamped and on the right end, torsion is applied by applying a rotation angle  $\theta_T(t)$  about the z-axis. Furthermore, the displacements w in all three directions and rotations  $\theta$  about the x- and y-axes on the right end are prohibited,

$$w_x = w_y = w_z = 0,$$
  
$$\theta_x = \theta_y = 0.$$

The torsion moment  $M_T(t)$  is measured as reaction moment in z-direction on the left end, see Figure 6 for one homogeneous beam. The experiment is again performed in a cyclic rotationcontrolled procedure where torsion is applied during loading up to  $\theta_{T,max} = 12^{\circ}$  followed by unloading to the original position  $\theta_T = 0^{\circ}$  in incremental steps of  $4^{\circ}$ .



Figure 6: Torsion of a homogeneous beam. The left end of the beam is clamped. Torsion is applied on the right end by applying a rotation angle  $\theta_T(t)$  about the z-axis. The torsion moment  $M_T(t)$  is measured as reaction moment in z-direction.

#### **3 STRAND MODEL USING FINITE ELEMENTS**

As presented in [2], we use the commercial FE tool ANSYS and its built-in functionalities to model the multi-wire strand.

## 3.1 Elastic wires

The spring steel rods are modeled as straight lines and discretized using beam elements with quadratic shape functions (i.e. Beam 189) using a constant element length of 2 mm but a

refined mesh with an element length of 0.5 mm in the range of the textile tape. Wire-to-wire contact is modeled using the Coulomb friction model and the pure penalty formulation provided in ANSYS. The results from virtual experiments using frictionless and frictional contact will be compared, however, a friction coefficient of  $\mu = 0.4$  is used to increase the effect of frictional contact. Accounting for the highly elastic material behavior of spring steel, a linear elastic material model with Young's modulus  $E_w = 175.6$  GPa and Poisson ratio  $\nu_w = 0.3$  is applied.

#### 3.2 Textile tape

In the virtual experiment, the textile tape is only modeled in the middle of the specimen as this is essential for keeping a fixed cross section of the strand in bending. The textile tape used to clamp the specimen's ends is not modeled, but taken into account when modeling the boundary conditions using a remote control point. The geometry of the textile tape is shown in Figure 7 (right) as a cross section view. The textile tape has a width of  $w_t = 15$  mm, a thickness of  $d_t = 0.2$  mm and is discretized with shell elements (Shell 281 [5]). Eight elements are used along the width of the tape and one element over the thickness. As the purpose of the textile tape is to keep the cross section fixed, we do not expect large deformations of the tape under load. Thus, a linear elastic material model using the parameters of light density polyethylene given in literature [10] with a Young's modulus of  $E_t = 417$  MPa and a Poisson ratio  $\nu_t = 0.48$  (i.e. nearly incompressible) is sufficient. The interactions between shell and beam elements are modeled using bonded contact to simulate the adhesive textile tape.



**Figure 7**: Finite element model of the three wire strand. Left: Mesh of three parallel wires discretized using beam elements with quadratic shape functions. Right: View on cross section of three wire strand with tape geometry.

#### 3.3 Virtual bending experiment

The boundary conditions of the bending experiment are implemented in the virtual bending experiment as presented in section 2.2, i.e. a pinned support on the left end and a roller support on the right end. In the first phase, the force  $F_y^0$  is applied on the respective middle nodes of the three discretized wires to achieve the pre-bend configuration. The cyclic procedure is then implemented using a remote point on the right end which controls the displacements in z-direction of the respective end nodes of the three wires. The z-displacement and reaction force on the remote point are used as measured quantities for the comparison with the experimental results.

#### 3.4 Virtual torsion experiment

The boundary and loading conditions of the torsion experiment are implemented as described in section 2.3. The rotational loading is applied as a rotation angle  $\theta_T$  using a remote point located on the z-axis on the right end which controls the displacements of the end nodes of the three wires. In order to compare the simulation results with experimental ones, the reaction moment  $M_T$  about the z-axis on the left end is used.

## 4 RESULTS AND DISCUSSION

A comparison of the experimental and simulation results of bending of the three wire strand is shown in Figure 8 as a plot of the reaction force  $F_z$  versus the displacement  $\Delta w_z$  in increments of the strand diameter  $d_s$ . In the diagram on the left, a good agreement between the measured and simulated reaction forces can be found. However, zooming into the plot allows for a more detailed discussion of the results, see Figure 8 (right). The experiment yields a visible hysteresis while the simulation results' loading and unloading paths almost perfectly coincide for both frictionless and frictional contact. Taking a look at the contact status of the elements, it can be observed that hardly any sliding occurs during the bending simulation. As a consequence, the choice of frictional contact cannot influence the results and wire-to-wire friction does not explain the observed hysteresis.



**Figure 8**: Comparison of experimental and simulation results from bending of three parallel spring steel wires. Left: Absolute force and displacement scales. Right: Zoom into relevant force and displacement ranges.

The experimental and simulation results from torsion experiments are given as plots of the reaction moment  $M_T$  over the twist  $\theta_T/L$ , i.e. rotational angle divided by the free length, in Figure 9. Similar to the bending results, good agreement between the torsional moment from real and virtual experiments can be found. However, the experimental results show again a hysteresis which cannot be simulated in the frictionless nor frictional simulation model. The status of elements in contact during the torsion simulation yields again that almost no sliding occurs and consequently using a frictional contact model will not change the result notably.

It has to be noted, that the observed hysteresis for the parallel wire strand is still small



Figure 9: Comparison of experimental and simulation results from torsion experiment on a strand of three parallel spring steel rods.

compared to the hysteresis observed in bending and torsion of real composite cables. Since spring steel rods with a high elastic limit were used, plastic effects cannot serve as explanation for the hysteresis observed in both types of experiments. Thus, it is most likely caused by imperfections in the clamping, e.g. imperfect contact between the clamps and tape or tape and the wires.

#### 5 CONCLUSIONS

In this work, we use the modeling approach presented in [2] and apply it to the simulation of wire strands consisting of three parallel elastic wires. The choice of this specimen allows for a first comparison of the simulation results with results obtained in bending and torsion experiments. While good agreement between measured and simulated forces and moments can be found in the respective experiment type, deviations between simulation and experiment can be observed. In both experiments, a comparatively small hysteresis occurs which cannot be simulated in the virtual experiments using frictional contact. Thus, the influence of friction on the mechanical response can be neglected for the investigated load cases. However, aiming at an application of this modeling approach to cable bundle structures it has to be considered that the observed hysteresis is comparatively small and the stiffness of the single wires relatively high. As cables usually behave inelastically themselves and have a lower stiffness, frictional effects might have a bigger influence on the mechanical response of cable bundles.



Figure 10: Example of a twisted pair of two conductors. Top: Photograph. Bottom: FE mesh using two helices discretized with beam elements to implement the double wire strand.

Future work will make use of the double helix models as presented in [2] to simulate unshielded twisted pairs [11] as shown in Figure 10. Twisted pairs consist of two intertwined conductors which reduces electromagnetic radiation and cross talk between pairs. As twisted pairs are inexpensive and can easily be installed, their applications range from ethernet networks to wiring harnesses of automotive onboard electronics. However, their beneficial electrical properties can be disturbed by mechanical deformation, i.e. by torsion, tensile strain or locally small bending radii [12]. We thus aim at the simulation of bending and torsion of twisted pairs with effective mechanical and geometrical parameters of the two cables and a comparison with real experiments on twisted pairs.

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