Bending and Torsion of Twisted Cable Strands Accounting for the Effect of Friction

Muhannad Hawwash[1], **Vanessa Dörlich**[1], **Joachim Linn**[1]

[1] Mathematics for the Digital Factory
Fraunhofer Institute for Industrial Mathematics (ITWM)
Fraunhofer-Platz 1, 67663 Kaiserslautern, Germany
[muhannad.hawwash, vanessa.doerlich, joachim.linn]@itwm.fraunhofer.de

ABSTRACT

This work contains the investigation of the influence mesoscopic effects on the deformation behavior of unshielded twisted pair (UTP) cables by means of bending and torsion experiments and corresponding finite element simulations. We utilize a previously presented modeling approach using finite beam elements with quadratic shape functions accounting for frictional contact to simulate bending and torsion on UTPs. The model is adapted to UTPs with different pitch lengths and different materials. Comparison of experimental and simulation results show good agreement under bending for UTPs with a comparatively small pitch length as here the dominant effects are friction and geometrical restraints. For torsion, however, only the load path of the experiment can be replicated with acceptable agreement as irreversible effects occur in the experiment which cannot be captured in the simulation. The presented results show the versatile applicability of the approach to technically relevant structures

Keywords: Bending, Torsion, Twisted pair cable, Finite beam element, Frictional contact.

1 INTRODUCTION

Flexible components such as cables and hoses are commonly used in automobiles for various purposes such as transmitting electric signals, fluids or gases. For instance, brake hoses and sensor cables are crucial components that enable the proper functioning of a car. However, these cables and hoses are typically bundled together in the wiring harness of a car resulting in several hundred cable bundle segments with different cross sections. Parts of the wiring harness are subjected to repeated multi-axial loads during the lifetime of the vehicle. Therefore, it is essential to understand their mechanical responses to ensure their durability and reliability.

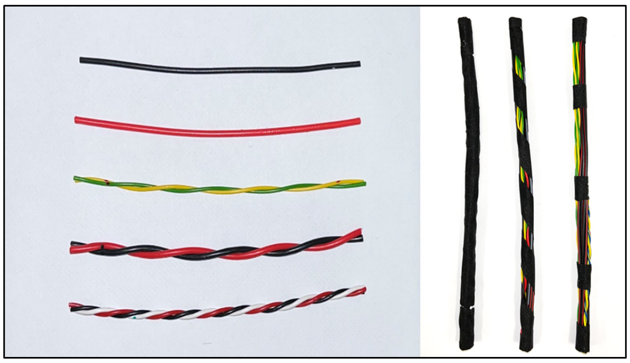

Figure 1. Examples of different types of cables, unshielded twisted pairs and triples (from top to bottom on the left) and cable bundle specimens with different taping patterns (right).

To achieve this, the authors utilize the approach presented in [1, 2] based on the commercial finite element (FE) tool ANSYS to simulate the most simple cable bundle consisting of two twisted cables, unshielded twisted pairs (UTP), see Figure 1, in this work. The model uses finite beam elements with second-order shape functions and takes frictional contact into account. Simulations under bending and torsion are executed and compared with experiments.

Since cables themselves consist of several components, effects on the mesoscale, i.e. interactions between wires or wires and the insulation, influence the behavior of the cable. Cable bundles add the next layer of complexity, as several cables are usually bundled together using tape or cable ties for fixation. These mesoscopic effects in cables and cable bundles can significantly affect the performance of the system, e.g. in the form of mechanical damage or cross-talk between adjacent wires in a cable bundle due to their proximity, which can cause coupling between different pairs of wires in the cable bundle. This coupling can lead to signal distortion and interference [3]. Therefore, considering mesoscopic effects can improve the reliability and performance of cable systems and it is important to take them into account during design. The varying structure and material of cable systems cause non-linear and inelastic mechanical behavior under load. The effective mechanical behavior of cables under large deformations have been investigated using experiments aiming at a better understanding of relevant effects. For example, Dörlich et al. [4, 5] presented experimental results for simple cable specimens under pure bending and torsion showing non-linear inelastic behavior, see Figure 2.

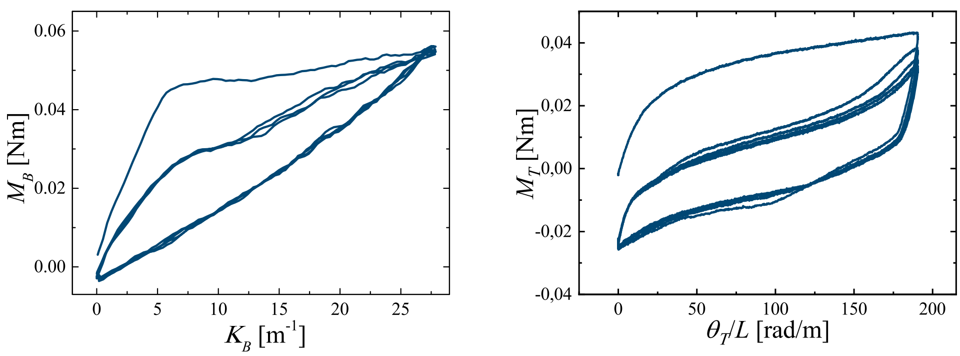

Figure 2. Typical experimental results on cable specimens under large deformations. Left: Pure bending on a simple cable specimen given as bending moment M_B vs. bending curvature K_B diagram [4]. Right: Torsion on a coaxial cable given as torsion moment M_T vs. twist θ_T/L, results originally published in [5].

The literature proposes analytical models for unshielded wire strands and their impact on the strand's stiffness. Costello [6] used a mathematical approach to describe the bending moment related to curvature in single-layered wire strands consisting of one straight core wire and six helical wires. However, the model made significant simplifications, such as neglecting the contact between adjacent wires on the same layer to minimize contact influence, and assuming that the strand's cross-section remains plane after bending. Thus, numerical studies are necessary to capture mesoscopic effects in order to better understand the mechanical behavior of cables. FE methods can be used to simulate the behavior of flexible multibody systems [7, 8]. Zhou and Tian [9] used beam elements to model a single-layered strand and considered wire contact interactions through coupling equations between corresponding nodes. This model was applied to analyze strands under bending loads. Lalonde et al. [11] present a FE modeling strategy for multilayered strands under multi-axial loads using beam elements. The analysis shows that friction forces control the hysteresis and the bending stiffness. Saadat and Durville [10] presented a computational homogenization approach to capture the hysteretic bending behavior which occurs when spiral strands are axially loaded.

The authors have presented an FE approach using the commercial tool ANSYS [12] to model strands of stress-free helices in previous work [1]. Finite beam elements with quadratic shape functions and a beam-to-beam contact algorithm based on the Coulomb model available in ANSYS were used. The results obtained from the simulation showed good agreement with the elasticity theory of Costello. The authors took first steps to compare the simulation results for multi-wire strands with results obtained from bending and torsion experiments. For this purpose, a specimen consisting of three parallel elastic wires, i.e. spring steel rods, was used [2]. While the resulting forces and moments showed qualitatively a good agreement, the hysteresis observed in the experiments could not be replicated in the simulation due to a lack of relative displacement between adjacent wires. Thus, frictional contact did not have an influence on the strand's response in the simulation.

In this work, the presented approach is utilized to model unshielded twisted pairs (UTPs), i.e. simple cable bundles relevant for automotive applications. The UTP consists of two separate intertwined wires, designed to reduce electromagnetic radiation and improve compatibility while being easy to install. The geometric parameters and further details of the FE model are explained in section 2.1. Bending and torsion experiments on UTPs are performed, see sections 2.2 and 2.3. We investigate the influence of material and geometrical parameters in experiments and simulations for UTP specimens by using different manufacturers resulting in different effective material properties and varying pitch lengths, i.e. different specimen geometry. The results from experiment and simulation are summarized and discussed in section 3.

2 NUMERICAL AND EXPERIMENTAL METHODS

Three different UTP specimens are investigated in experiments and modeled using FE simulations. All UTP consist of two wires with a diameter of $d_w = 1.3$ mm, resulting in a total diameter of $d_{UTP} = 2.6$ mm. Model variants with different pitch lengths to investigate the influence of the geometric parameter are used, see Figure 3. Furthermore, UTPs 2 and 3 have material properties different from those of UTP 1, as the manufacturers are different, see Table 1.

2.1 Finite element models for UTP

The wires of the UTP are modeled as stress-free helices following the expression given in [13], which is a good approximation of the pre-curved center line of each wire. To avoid a superposition of material and structural inelasticity, we assume that the material is linear elastic and incompressible with a Poisson ratio $\nu = 0.5$. Since cables show anisotropic behavior, their Young's moduli derived from bending and torsion typically differ, see [4], chapter 2.4 for reference. Thus, choosing the correct parameter for simulation of bending and torsion is not straight-forward. Here, we derive the Young's modulus from the geometrically non-linear bending experiment of a cable E_B and use it as material parameter for the single cables in the bending simulation. Analogously, the Young's modulus E_T can be derived from a torsion experiment on the cable and is used in the simulation of the torsion experiment. The parameters for UTP models are summarized in Table 1.

Table 1. The parameters for three different UTP models. The lengths are given in mm and Young's modulus in MPa.

	pitch length	free length	E_B	E_T
UTP1	20	100	1050	1870
UTP2	30	105	638	568
UTP3	15	105	638	568

For this numerical study, the centerline of each wire is discretized using beam elements. Specif-

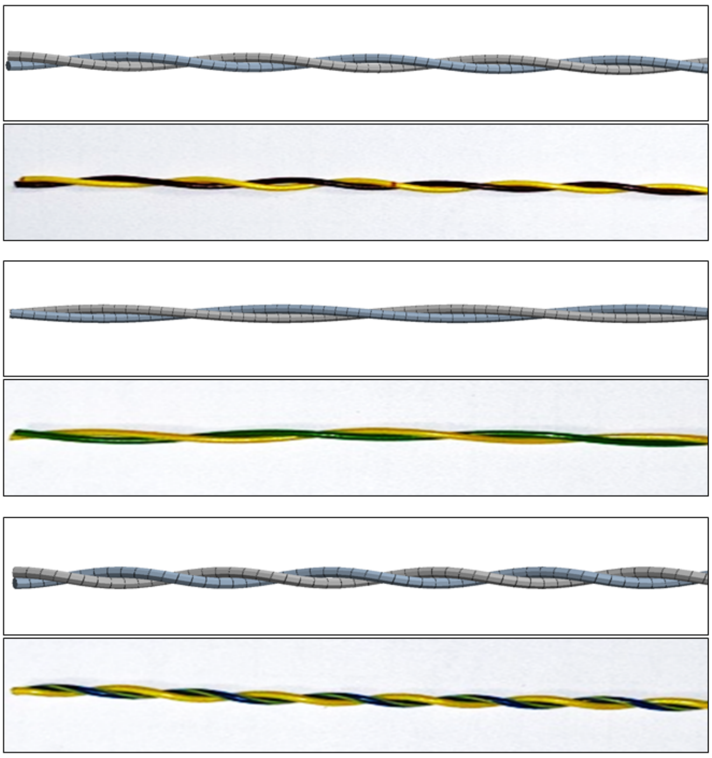

Figure 3. The three different UTPs under investigation. From top to bottom UTP 1, UTP 2 and UTP 3 are shown with their FE model and a picture of the specimen.

ically, the element BEAM189 in ANSYS is used, which consists of three nodes with 6 degrees of freedom (DOF) and second-order shape functions. To model contact between the beams, we have utilized a beam-to-beam contact model with pure penalty formulation and friction following Coulomb's law. The friction coefficient used in this model is $\mu = 0.2$, and contact conditions (slide or stick) are determined at each contact node. We assume that the wires begin to slide relative to each other when the tangential inter-wire contact force equals the normal inter-wire contact force. If this condition is not met, the wires remain in a stick condition and no relative tangential displacement is allowed at the contact interface.

2.2 Geometrically non-linear bending experiment

Since cable systems are typically subjected to large bending deformations, we follow our approach presented in [2] and perform a geometrically non-linear bending experiment on UTPs. This experiment allows for large deformations of the specimen with boundary conditions which are easy to implement, as depicted in Figure 4. Both ends of the specimen are simply supported, with the left end allowing only rotation about the y-axis and the right end allowing axial displacement along the z-axis. For initially straight specimens, it is necessary to take into account buckling phenomena under these load conditions to achieve a reproducible experimental procedure [14]. In [2], we explained the experimental and numerical steps to avoid buckling for three initially straight parallel rods. A UTP, however, consists of two initially curved wires and thus the initial step to avoid buckling is not needed. Instead, we can directly apply a displacement on the undeformed UTP at the right end in a cyclic process with an increment of d_{UTP} until reaching a maximum value of $3 \cdot d_{UTP}$. The experiment is performed quasi-statically, and we measure the reaction force F_z necessary to achieve the displacement w_z on the right end.

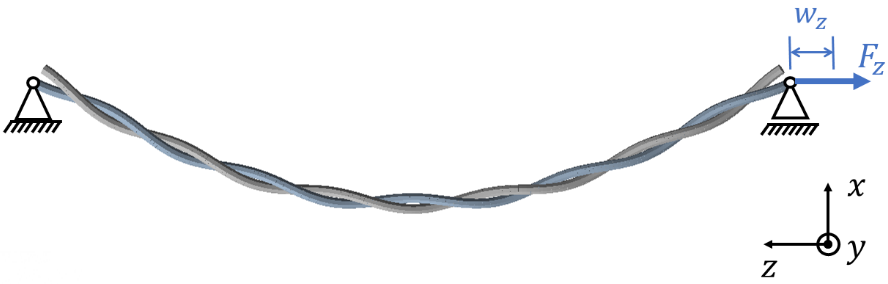

Figure 4. Boundary condition for geometrically non-linear bending of a twisted pair. The reaction force F_z as a function of the displacement w_z is measured during bending.

2.3 Torsion experiment

The standard torsion experiment for slender specimens described in [2] is performed in this work to investigate UTPs under torsion. Consider a clamped specimen of length L which in a first step is subjected to a tensile load F_Z^0 on the right end to ensure contact between wires. In the second step, torsion is applied on the right end by controlling the rotation about $z-$axis, i.e. the angle of twist θ_T. On the right end, displacements in all three directions and rotation about the x- and y-axes are restricted, as depicted in Figure 5. A cyclic process is performed by increasing the angle of twist incrementally from 0° to 12° in steps of 4°. We choose a maximum rotation angle of 12° to ensure that the deformation of the cable remains within the elastic region and plastic deformation does not occur during the loading phase. The relation between the applied angle of twist and measured torsion moment M_T in the z-direction on the left end are plotted.

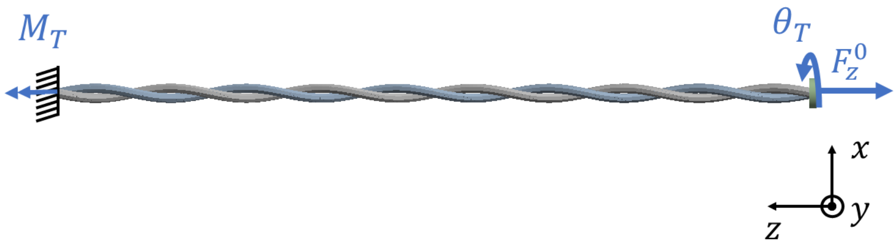

Figure 5. Standard torsion with pre-tension of a twisted pair. The left end of the specimen is clamped. Torsion is applied on the right end by applying a torsion angle θ_T about the z-axis.

3 RESULTS AND DISCUSSION

3.1 Bending of unshielded twisted pairs

The results of the geometrically non-linear bending experiments on UTPs are displayed as plots of the reaction force F_z versus displacement w_z on the right end of the specimen. The results from simulation and experiment for UTP 1 are shown in Figure 6 (left), showing acceptable deviations until approximately $w_z = 5\,\text{mm}$. Afterwards, the behavior observed in the experiment is slightly stiffer than in the simulation. In Figure 6 (right), the results for UTP 3 are displayed. Here, agreement between experiment and simulation is even better, showing minor deviations in the maximum forces. For both UTP 1 and 3, the observed hystereses have similar sizes in experiment and simulation, showing overall an acceptable agreement. Considering that the hysteresis in the FE simulation only stems from friction between the cables and inelastic material effects are not modeled, we conclude that geometry and friction are the dominant effects for these UTPs under bending. While the global spatial displacements of the UTP specimens are large, local material deformations of the two conductors remain small due to their helix shape. Thus, material inelastic effects such as plasticity do not contribute to the inelastic response of these UTPs.

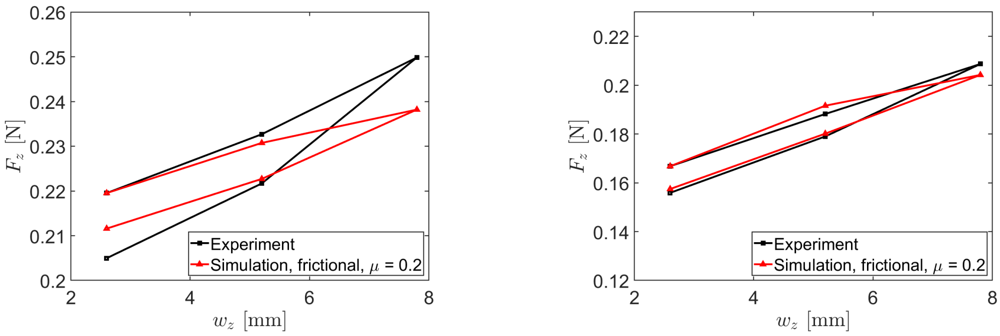

Figure 6. Comparison of experimental and simulation results for bending of UTP1 with pitch length 20 mm (left), for bending of UTP3 with pitch length 15 mm (right).

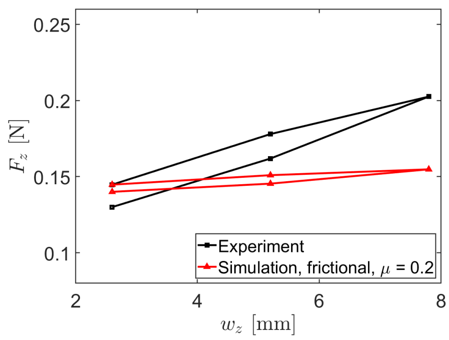

Figure 7. Comparison of experimental and simulation results for bending of UTP 2 with pitch length 30 mm.

Next, we examine the results of UTP 2 in Figure 7, which has a higher pitch length than the other UTPs. Note, that the simulation model for UTP 2 differs from UTP 3 only in the pitch length, as they stem from the same manufacturer and contain the same cables such that the same material parameters were used. It can be observed, that the simulation deviates from the experimental results and shows less stiff behavior. The reaction force in the simulation hardly increases with displacement and only a small hysteresis occurs. Looking at details of the simulation results, one observes here, that the number of elements in contact is significantly lower due to the longer pitch length. Thus, the influence of contact and friction between the wires is smaller. The authors have previously shown in simulation studies on double wire helix models that, depending on the load case and specific structure of the model, contact between the wires has to be enforced to ensure that frictional contact has an influence on the global response of the specimen [1]. Furthermore, the linear elastic material model used for each wire might not be sufficient for this type of UTP.

3.2 Torsion of unshielded twisted pairs

Figure 8 shows the experimental and simulation results for torsion on UTP 1 as plot of the resulting torsion moment M_T versus angle of twist θ_T. Again, we find good agreement between experiment and simulation, especially for the load path. The maximum torsion moments coincide very well. The unloading path of the experiment, however, shows a lower stiffness which results in a smaller hysteresis and a positive remaining torsion moment at $\theta_T = 0°$. This indicates that irreversible deformations, which might be interpreted as damage in the context of bulk materials [15], have occurred in the experiment. In case of the UTP, this damage phenomenon could be a re-ordering of the two wires such that a new stable configuration is found, which cannot be captured in the simulation.

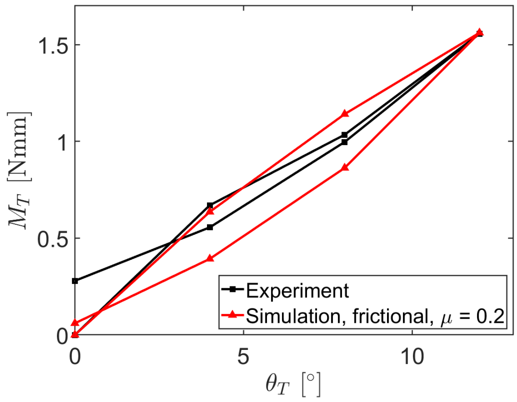

Figure 8. Comparison of experimental and simulation results from torsion experiment on a twisted pair.

4 CONCLUSIONS

In this work, we used a commercial FEM tool to simulate unshielded twisted pair cables and compared the results to experimental reults. The wires were modeled as stress-free helices accounting for different pitch lengths and different material parameters. The model takes frictional contact into account and its influence on the effective behavior of the specimen.

The comparison of experimental and simulation results shows in general good agreement under bending and torsion with one exception. The bending behavior of UTP 2 observed in the experiment could not be replicated using the same material parameters as for UTP 3, which contains the same cables with a lower pitch length. This leads to the conclusion that the FE modeling approach used here can be applied to different multi-wire structures under certain restrictions. The modeling approach using linear elastic material for the wires and frictional inter-wire contact is sufficient in cases where geometrical restraints and resulting contact are the dominant effects which is here the case for UTPs 1 and 3 with the lower pitch lengths.

Future work will be directed towards expanding the FE model to simulate UTP with any pitch length. Additionally, the versatility of the modeling approach will be used for numerical investigations of combined bending and torsion conditions.

ACKNOWLEDGMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 860124. This publication reflects only the author's view and the Research Executive Agency is not responsible for any use that may be made of the information it contains.

REFERENCES

[1] Hawwash, M., Dörlich, V., Linn, J., Müller, R. and Keller, R. Effective Inelastic Bending Behavior of Multi-Wire Cables Using Finite Elements Accounting for Wire Contact. In *ECCOMAS Thematic Conference on Multibody Dynamics*, pp. 369 – 379, Budapest, 2021.

[2] Hawwash, M., Dörlich, V., Linn, J., Keller, R. and Müller, R. Modeling the Effective Inelastic Behavior of Multi-Wire Cables Under Mechanical Load Using Finite Elements. In *European Congress on Computational Methods in Applied Sciences and Engineering*, 2022.

[3] Henry W. Ott. *Electromagnetic Compatibility Engineering*. John Wiley & Sons, 2009.

[4] Dörlich, V., Linn, J. and Diebels, S. Flexible Beam-Like Structures - Experimental Investigation and Modeling of Cables. *Advances in Mechanics of Materials and Structural Analysis. Advanced Structured Materials*, vol. 80. Springer, Cham., 2018.

[5] Dörlich, V., Linn, J., Scheffer, T. and Diebels, S. Towards Viscoplastic Constitutive Models for Cosserat Rods. *Arch. Mech. Eng.*, vol. 63, pp. 215 – 230, 2016.

[6] Costello, G. A. *Theory of wire rope*. Springer Science & Business Media, 1997.

[7] Geradin, M., Cardona A. *Flexible Multibody Dynamics: A Finite Element Approach*. John Wiley, 2001.

[8] Sonneville, V., Cardona, A., Brüls, O. Geometrically exact beam finite element formulated on the special Euclidean group SE(3). Computer Methods in Applied Mechanics and Engineering, vol. 268, pp. 451 – 474, 2014.

[9] Zhou, W. and Tian, H.-Q. A novel finite element model for single-layered wire strand. Journal of Central South University; 20:1767 – 71, 2013.

[10] Saadat, M. A., Durville, D. A mixed stress-strain driven computational homogenization of spiral strands. Computers and Structures, vol. 279, pp. 106981, 2023.

[11] Lalonde, S., Guilbault, R., Légeron, F. Modeling multilayered wire strands, a strategy based on 3D finite element beam-to-beam contacts - Part I: Model formulation and validation. International Journal of Mechanical Sciences, vol. 126, pp. 281-296, 2017

[12] ANSYS Mechanical User's Guide, 2021.

[13] Stanova, E., Fedorko, G., and Fabian, M. and Kmet, S. Computer modelling of wire strands and ropes Part I: Theory and computer implementation. *Advances in Engineering Software*, vol. 42(6), pp. 305-315, Elsevier, 2011.

[14] Gross, D., Hauger, W. and Schröder, J. and Wall, W. A. *Technische Mechanik: Band 2: Elastostatik*, Springer, 2007.

[15] Kachanov, L. *Introduction to continuum damage mechanics*, Vol. 10, Springer Science & Business Media, 1986.