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Mechanical Characterisation of Cables in Different Loading Directions

Prateek Sharma[1,*], **André Hildebrandt**[2], **Alexander Düster**[2], and **Stefan Diebels**[1]

[1] Saarland University, Campus A4.2, 66123 Saarbrücken
[2] Hamburg University of Technology , Am Schwarzenberg-Campus 4 C, 21073 Hamburg

The mechanical characterisation of cables can help improving the production and lifetime of various products, for example a robotic arm. Cables however form a class of composite structures, that is highly anisotropic and dissipates energy due to the reorientation of its constituents which is superimposed by the dissipation due to the deformation of the polymer components. Cables also have a degree of randomness in their structure. Moreover, the stiffness in one loading direction is coupled to the stiffness in another loading direction.

In this work, experimental investigations on the mechanical properties of the cables are presented. An experimental setup has been constructed to test the cables in tensile, torsion and the bending directions individually as well as coupled to each other. Free bending tests were conducted where axial forces were compensated during the bending to dissociate the tensile and the bending properties of the cables. To apply larger tensile and torsional loads on cables a commercial testing device was also used. To characterise the influence of bending on torsion, free bending tests were conducted with a combination of torsional load. Thus, a complete mechanical characterisation of a cable is presented.

1 Introduction

Apart from their application as electrical conductors, cables are widely used as structural elements such as in ships and bridges among others. With the advances made in industry 4.0 and the growing popularity of electro-mobility, the use of cables in robots and automobiles is increasing. The mechanical properties of these cables influence not only the lifetime but also the assembly of the product. For example, the laying up of cables during the assembly of a robot arm can define the ability of the arm to move easily in all directions. Similarly, the cable management in an automobile can influence the lifetime of its various components. With known mechanical properties of the cables, robots and automobiles can be cabled in an optimal way.

Due to their complex structures and due to the interaction between their components, the mechanical response of cables in each loading direction is different and is additionally coupled to the other loading directions [1, 2]. For example a pre-torsion typically changes the tensile stiffness [3], or the bending stiffness [4] of the cable. Therefore, for a complete mechanical characterisation of the cable it is necessary to test the sample with not only the classical experiments such as the tensile, torsion and three-point bending tests, but also with combined loading conditions, such as a combination of bending and torsion tests.

To this end, a test bench was conceptualised and developed to load the cable in the tensile, torsion and bending direction independently as well as in combined form. Three independent drives that can be coupled with each other were used to deform the test sample. The forces and the moment during the deformation were recorded using 6-axes-sensors at the ends of the cables. It was observed that the reproducibility of the experimental results, specially for the bending experiments, was not sufficient and a pre-loading was needed to condition the samples before testing.

In the following sections, the construction and the working principle of the test bench is explained, followed by the methods used for the experiments. Finally, the experimental results for tensile, torsion, bending, and coupled torsion-bending tests for a coaxial cable are discussed.

2 Experimental Setup

The cables were tested in tensile, torsion and three-point bending experiments using *Instron-ElectroPuls E10000*, a commercial testing device. A displacement/rotation controlled deformation was applied to the cable and the forces and the moments were recorded using the sensors on the machine. The displacements were recorded using the encoders of the drives causing the deformation. Moreover the deformations were recorded using the digital image correlation (DIC) method[1].

The in-house test bench constructed for the pure bending, pure torsion, as well as the coupled loading experiments consists of a bending motor (B), a torsion motor (F) and two linear motors (C) (Fig. 1). The cable is clamped to the test setup using chuck collets (G), that are mounted on two different arms. While one of the arms stays stationary (D), the other (E) is mounted on top of the bending motor, such that it can rotate around the stationary arm. With the rotation, a bending angle (θ_b) can be applied on the cable. On the stationary arm, the collet chuck is attached to a torsion motor, which can rotate the cable along

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[*] Corresponding author: e-mail prateek.sharma@uni-saarland.de, phone +49 681 302 3648, fax +49 681 302 3992

[1] Due to the long and thin structure of cable specimens, the DIC was not effective for torsion experiments after a certain rotation angle. Even with multiple cameras, the number of pixels along the thickness of the sample was not enough to record the complete deformation.

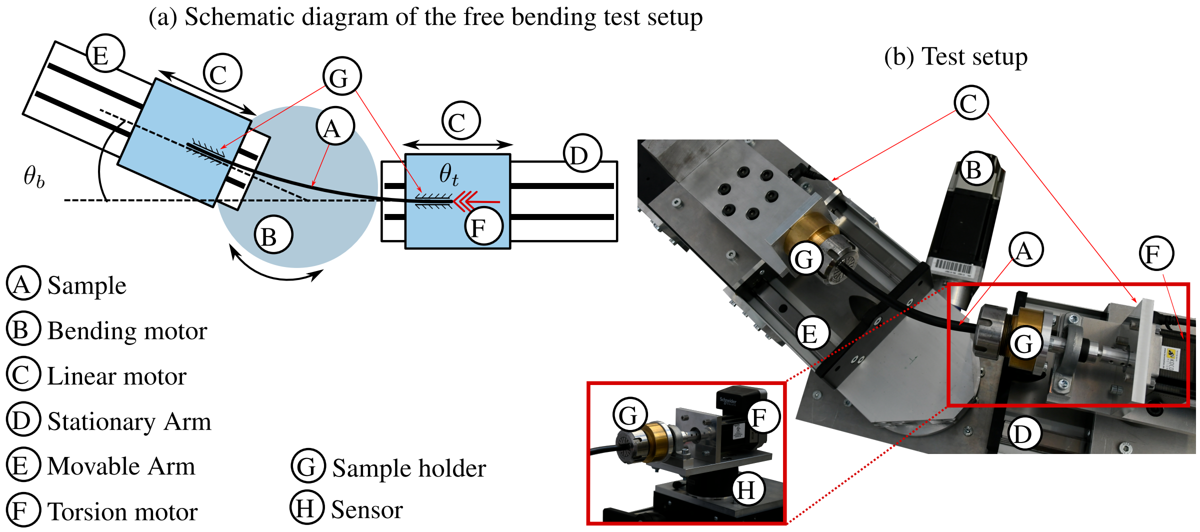


Fig. 1: A schematic representation and the construction of the in-house test bench.

Table 1: The specification for the test setup in various loading directions. The minimum for force/moment gives the least count for the sensors.

	Bending		Torsion		Linear	
	Angle	Moment	Angle	Torque	Displacement	Force
maximum	+90°	1 Nm	No limit	1 Nm	60 cm	300 N
minimum	-90°	0.01 Nm	No limit	0.001 Nm	0 cm	0.01 N

its own axis (θ_t), resulting in a torsion motion. The reaction forces and moments that are generated by the cable during its deformation are recorded by 6-axis sensors (H) that were procured from ME-Meßsysteme GmbH (K6D80), that are mounted on both ends of the cable. They are called 6-axis sensors as they can measure three forces and three moments along the three spatial axes. The sensors are calibrated such that the forces and the moments at the collet chucks are measured and the distance between the sensor and the sample holder do not influence the results. The sensor and the sample holder assembly (including the torsion motor for the stationary arm) are mounted on top of the carriage for the linear motor. By the movement of the carriage, the distance between the two sample holders can be changed, which leads to a stretch of the cable along its axis. Thus, by the movement of the linear motors, a tensile test can also be conducted. The limits for the different loading directions are mentioned in Table 1. Since the three motors (bending, torsion and linear) can be moved independently from each other, it is possible to deform the cable in the three directions independently as well as with superimposed deformations. However an independent movement in the bending or the torsion direction does not guarantee uncoupling from tensile deformation. A normal/axial force is generated when the linear motors are fixed at a position and the cable is bent. Similarly due to the internal structure of the cable, a tensile force is generated during torsion of the specimen. Therefore, to conduct free bending or free torsion test, the linear motors have to be moved to compensate the axial forces.

A control system is implemented to regulate the movement of the linear motors according to the axial forces generated in the cable. The sensor on the moving arm (A) and the sensor on the fixed arm (B) record the forces and moments along the coordinate-axes as shown in Fig. 2. The linear motors move along the x-axis of the respective arms, so that the forces recorded in x-direction is either compensated to zero or to a fixed given value. The axial forces measured by the sensors are directly relayed to the controller and according to the difference between the recorded forces and the input value, the controller sends out signals to move the linear motors. The controller employs a PI (proportional, integral) type control system [5], where the parameters K_p and K_i are the proportionality parameters that control the weights of the proportional error and the integral error respectively. Since both the ends are regulating the same force, there is a coupling between the movement of the two linear motors. With the same parameters K_p and K_i for A and B, the force that is already compensated by A is simultaneously compensated by the movement of B, which results in a force in the opposite direction. Hence, a back and forth motion occurs which could be observed as oscillations in the axial force signal from both sensors. Therefore, the parameters were suppressed for one of the arms, and the force was controlled primarily by the movement of only one arm. The parameters for different types of cables were determined with a trial-and-error method till a satisfactory accuracy in the regulation was achieved, without any back and forth motion. Further improvements in the control system have been implemented, however the results presented in this work were conducted with the above explained control system.

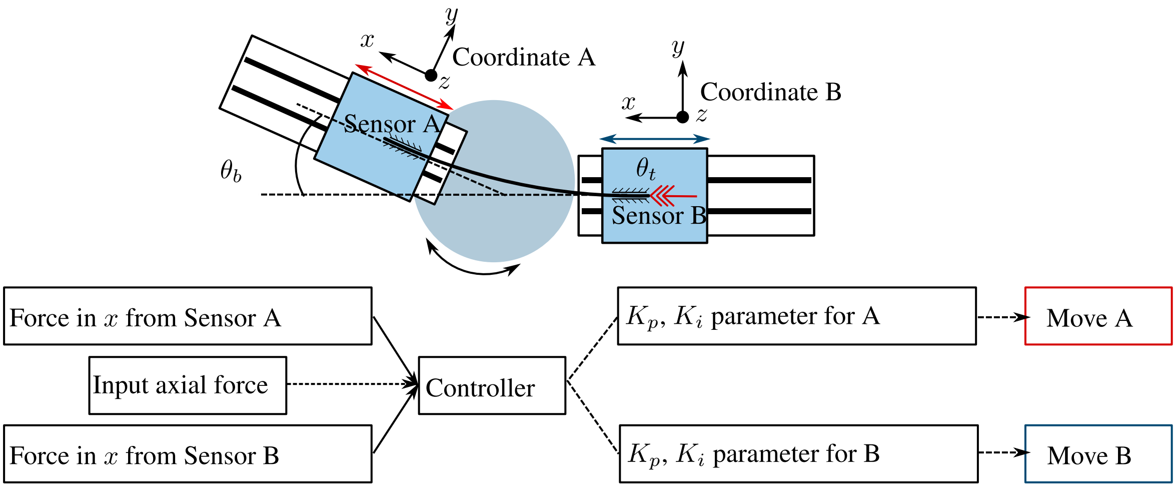


Fig. 2: A representation of the control system for free bending and free torsion.

3 Validation

In order to validate the in-house experimental setup, a comparison was made between the results of the setup and other commercial test benches. In order to ensure that the free bending experiment results in a uniform deformation of the cable along its axis the kinematics of the movement were also validated.

3.1 Kinematics

In order to ensure that during free bending a constant curvature is obtained along the axis of the cable, the deformation of the cable during an experiment was recorded with the help of a camera. The outer coating of the cable was painted black and a white background was prepared, to achieve maximum contrast between the edges of the cable and the background. The recorded images were analysed with the help of NI Vision Assistant, a commercial computer vision software, and the edge of the cable during bending was fit with a circular arc. For a bending angle of θ_b, the theoretical bending radius R_b for a length l_b of the specimen can be calculated by

$$R_b = \frac{180}{\pi}\frac{l_b}{\theta_b}. \tag{1}$$

This gives a theoretical bending radius of $R_b = 190.9$ mm (at the edge of the cable) for a cable of length $l_b = 100$ mm and a bending angle of $\theta_b = 30°$. The circular fit on the edge of the cable, gives a measured bending radius of $R_b = 181.9$ mm (Fig. 3). Thus a deviation of 4 % can be observed between the theoretical and the measured value. The image distortion at the edges of the field of view of the camera can cause such deviations, and the 4 % deviation was considered to be within acceptable limits.

3.2 Measured forces and moments

To validate the forces and moments, tensile tests and torsion tests were conducted on the *Instron ElectroPlus E10000*, and the results were compared with that of the in-house test bench. The results of both the test setups were comparable and the accuracy of the sensors in x-direction was validated. However, to validate the bending moments, the results of free bending were compared with the three-point bending tests. For this purpose, cylindrical rods made out of carbon fibre reinforced polymer (CFRP) with a diameter of 2 mm were used. A linear fit of the results of the three-point bending tests were used to evaluate the bending stiffness of the rod

$$(EI)_b = \frac{Fl^3}{48w} \tag{2}$$

using the Euler-Bernoulli beam theory. Here F represents the bending force recorded by a deflection of w and l is the distance between the two support points. Considering that the three-point bending experiments can result in local deformations and the fit with the Euler-Bernoulli theorem is an approximation, the bending moment measured with the bending stiffness $(EI)_b$ and the moments measured in free bending experiments, fit quite well with each other (Fig. 4).

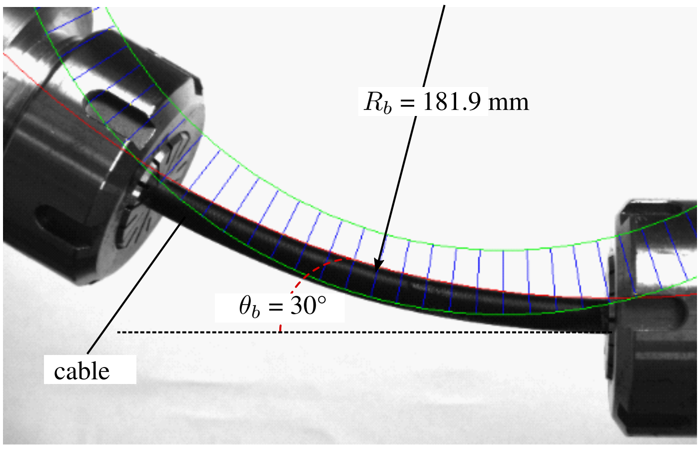


Fig. 3: The bending radius measured through edge detection technique for a cable of length 100 mm. The green lines denote the region of the image in which the edge detection algorithm is executed and the blue lines depict the discretisation that is used for the algorithm.

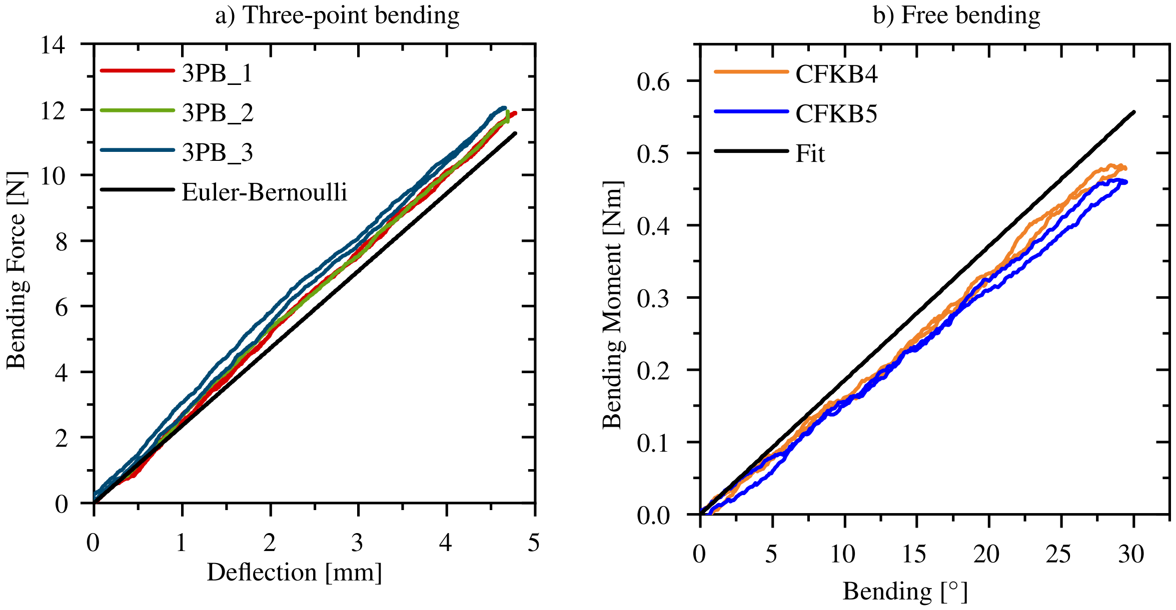


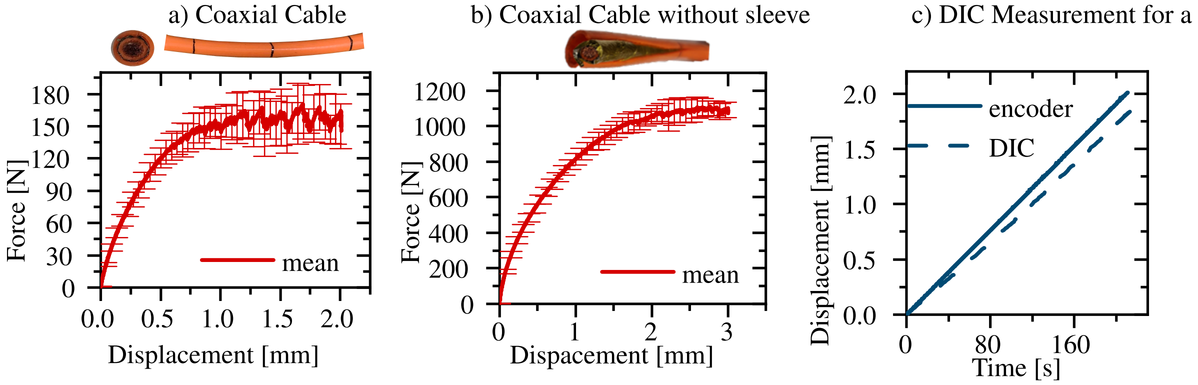
Fig. 4: Comparison of a) the three-point bending test and b) the free bending for a CFRP rod. The linear fit of the three-point bending is used to evaluate the stiffness according to the Euler-Bernoulli beam theory. The same stiffness gives comparable bending moments when compared to the bending moments measured in the free bending tests.

4 Results of Coaxial Cable

The results of tensile test, bending test and the combined loading condition of bending with pre-torsion on a coaxial cable with 8.3 mm diameter are presented here. The length of all the samples was 90 mm. For a more thorough analysis on the experimental investigations and the modelling of the cable, the readers are referred to [4].

4.1 Tensile Test

The tensile tests were conducted on the *Instron ElectroPlus E10000*, where a displacement driven deformation was applied on the cable while the forces were measured. The cables were clamped using pneumatic holders, that insured no slipping between the clamps and cables occurs. However, it was observed that there were huge oscillations in the forces at higher displacements. The displacement measured using DIC, however did not show any oscillations. Due to a suspected slip between the inner layers of the cable, the tensile tests were repeated after removing the outer sleeve of the cable. It was observed that the oscillations in the measurements reduced drastically and a ten times higher force could be achieved for the same displacement. The outer sleeve made of polymer is softer and is deformed when the full cable is tested. However a slip between the outer sleeve and the inner core occurs, and a stick-slip effect can be observed as the oscillation in the force signal.



a) Coaxial Cable

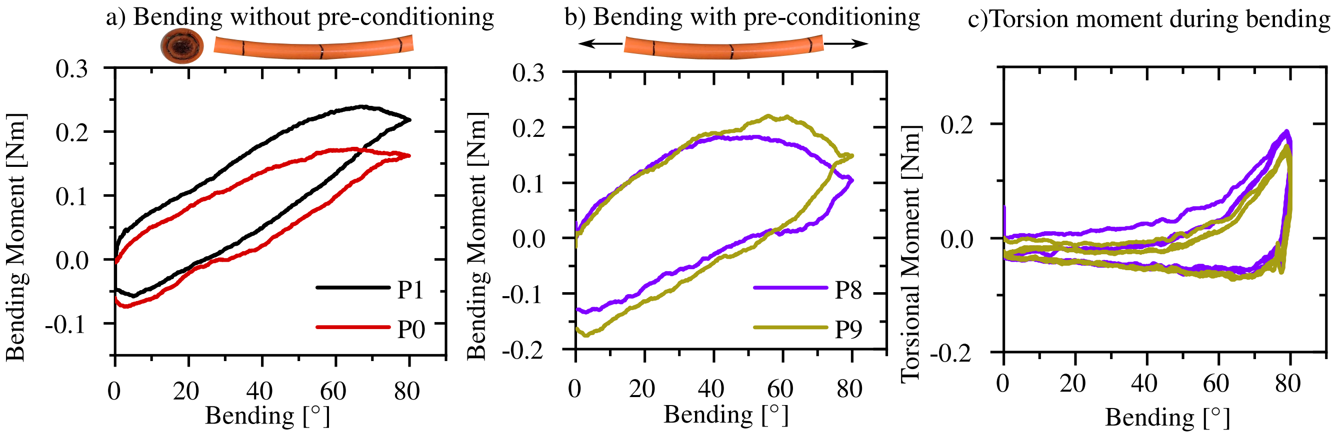
b) Coaxial Cable without sleeve

c) DIC Measurement for a

Fig. 5: The tensile test conducted with the a) full cable and b) after removing the outer sleeve. c) The DIC measurement for dispacements during the tensile test with full cable did not show any oscillations.

4.2 Free Bending Test

The results from the free bending experiment show a deviation between the samples of the same cable as can be seen in Fig. 6a). In order to achieve reproducibility, an initial tensile loading of 50 N was applied on the specimen and then removed. This ensured that the pre-curvature that existed in the cable specimens due to their storage conditions, do not influence the results of the bending experiments. An improvement was observed with this method, however a deviation at higher bending angles was still observed. This is because of the randomness in the internal structure of the cables. Interestingly, during the bending test, as a result of the interaction between the components, an increase in the torsion moment was also observed. This shows a coupling between the bending and the torsion stiffness.



a) Bending without pre-conditioning

b) Bending with pre-conditioning

c)Torsion moment during bending

Fig. 6: The free bending experiment of coaxial cable a) without pre-conditioning, b) with pre-conditioning. c) The coupling between the bending and the torsion moment can be seen with the increase in torsion moment with bending.

4.3 Free Bending with Pre-Torsion

In order to observe the effect of the coupling between the stiffnesses, experiments with coupled loading conditions were carried out. An initial torque of 90° was applied to the cable and with this pre-torsion, a free bending test was conducted. In Fig. 7, due to the applied torque, an increase in the bending moment and hence an increase in the bending stiffness is to be observed. This can be attributed to the increasing friction between the wires inside the cable during pre-torsion. In Fig. 8 the change in the torsion moment during the bending can be observed, which further demonstrates the coupling between the loading directions.

5 Conclusion and Future Work

A test setup was constructed to characterise cables under uncoupled and coupled loading conditions. To achieve this, the normal force occurring during bending or torsion of the cable was balanced out by the movement of the ends of the cables. The ends that are mounted on linear motors, are moved according to the forces that are measured at the two ends of the cables.

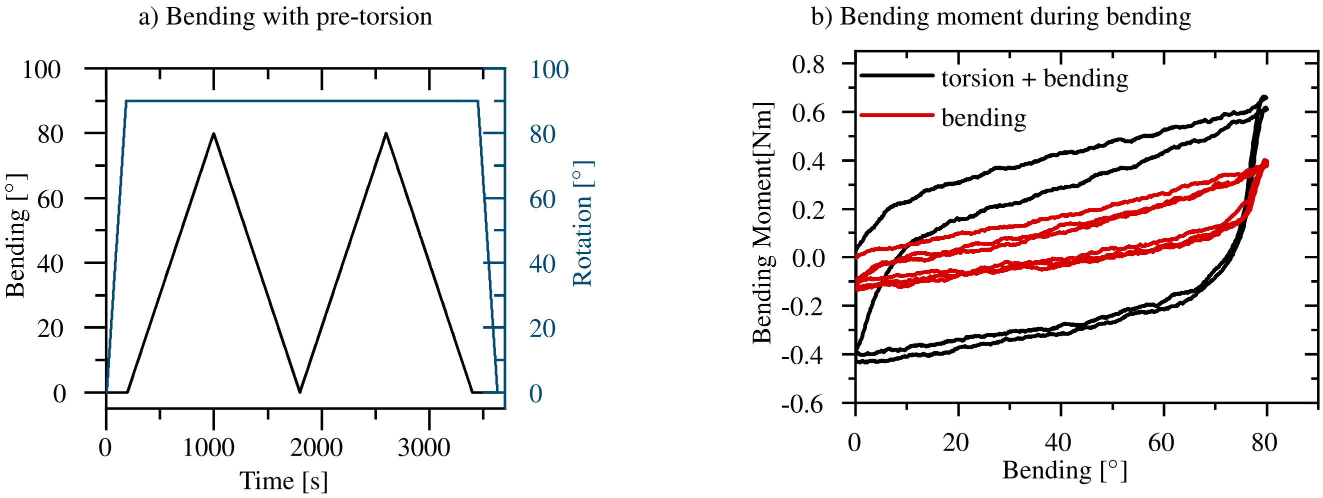


Fig. 7: Coupled bending and torsion experiment. a) The input deformations for the experiments, b) A comparison of the bending moment with and without pre-torsion.

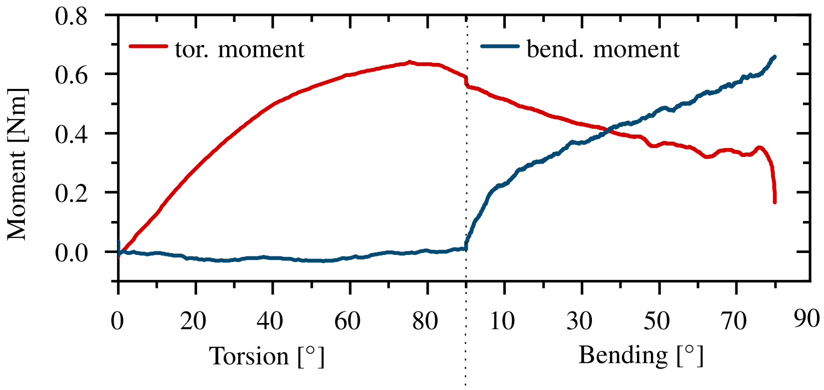


Fig. 8: The change in the bending and torsion moments during the loading of the cable.

A PI-control system is responsible for the movement of the linear motors. Since both the ends are moving to regulate the same force, the movement of one of the arms was suppressed and the regulation was handled by the other arm. With this system, bending and a coupling of bending and torsion was realised on a coaxial cable. The coupled tests show dependency of the bending stiffness on the pre-torsion. Moreover a change in torsion moment during bending could also be observed. To increase the reproducibility of such experiments, a pre-conditioning tensile load in the elastic region was applied and then removed, which reduces the curvature existing due to the storage of the cable.

5.1 Improvement in Control System

The control system as shown in this work, leads to unsymmetrical movement of both ends of the cable in free bending. This can lead to a deviation from the constant curvature along the length of the cable. Therefore, the control system was improved by mirroring the movement of one arm on the other in the opposite direction. With this the PI-controller is active only for one end and the other end is repeating the movement in the opposite direction and a symmetrical movement of both the arms could be achieved.

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