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Letter

An improved model for predicting effective Young's modulus of the twisted structure under cyclic loading: taking into account the untwisting effect

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HIGHLIGHTS

- Effective Young's modulus of the twist structure under cyclic loading has been experimentally obtained.
- An improved model based on the classical Costello's theory taking into account the untwisting effect has been presented.
- In comparison with the Costello's model, the present model takes good agreements with the experimental results.

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ABSTRACT

Twist structures have diverse applications, ranging from dragline, electrical cable, and intelligent structure. Among these applications, tension deformation can't be avoided during the fabrication and working processes, which often leads to the twist structure rotation (called untwisting effect) and twist pitch increasing. As a consequence, this untwisting behavior has a large effect on the effective Young's modulus. In this paper, we present an improved model based on the classical Costello's theory to predict the effective Young's modulus of the basic structure, twisted by three same copper strands under cyclic loading. Series of experiments were carried out to verify the present model taking into account the untwisting effect. The experimental results have better agreements with the presented model than the common Costello's model.

Many years ago, people in China use the twisted hemp to build suspension bridges and miscellaneous household items, which have been maintained till now. Today, the twist structures have diverse applications, ranging from dragline, electrical cable, cable in conduit conductor (CICC), and intelligent structure, etc. Recently, Haines et al. [1] proposed a new kind of intelligent muscles based on the twist structure. Comparing with the traditional artificial muscles, e.g., electrothermally driven shape-memory metal, thermally powered shape-memory polymers, hybrid carbon nanotube (CNT) muscles, and electric-field driven electrostrictive polymers, this new kind of artificial muscles has many merits such as fast, scalable, nonhysteretic, long-life, and inexpensive (see Ref. [1] and references therein). Therefore, this kind of artificial muscle shows wide applications including intelligent robots, prosthetic limbs and actuators. During these applications, the stretch deformation does not be avoided, which often leads to the twist structure rotation with the increase in twist pitch. As a result, the cable stiffness will decrease and its Young's modulus will vary. On the other hand, this untwisting behavior is often observed during some twist structures fabrication process. The CICC is usually used to construct magnet generating high magnetic field by carrying high current [2, 3]. In order to counter the coupling loss, the cable is made of multistage twists, and totally inserted into a jacket to bear electromagnetic force. During this insertion, several tons of tension is used to balance friction between the cable and the jacket, serious stretching and untwisting take place in the cable and cause

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an increase in twist pitch in the last stage of cabling [4-7], as same as stretch process on common twist structures, the cable's axial stiffness decreases, and its effective Young's modulus varies. Generally, the cable's effective Young's modulus is one of the key mechanical parameters that related to the engineering design and safety assessment. Zhai and Bird [8] and Li et al. [9] analyzed the spring model which can only calculate the deformations of bending and distortion on the twisted strands when axial stretched, and provided a lower predication of the effective Young's modulus. For evaluating the effective Young's modulus of twist structure without gap, the classic Costello [10] model can be used, in the case of twist structure with gap, a new theory model presented by Yue et al. [11] can be applied, however, All of these models did not consider the untwisting behavior, this implies that the predicted results can cause failure in fitting in with the experimental results. In this paper, an improved theory based on the Costello model is presented to predict the effective Young's modulus of the twist structure by taking consideration of the untwisting behavior. The calculated results agree well with experimental results.

Figure 1 shows a classical axial tensile force-displacement curve of a used specimen, which is fabricated by twisting three pure Cu strands with different diameters of 0.8, 1.0, 1.2, and 1.5 mm. The experimental method what we conduct is cyclic loading. As shown in this figure, E_1 represents the nominal Young's modulus obtained by initial loading phase, E_2, E_3, E_4, and E_5 are on behalf of the average effective Young's modulus which are calculated by cyclic process. The corresponding value of each Young's modulus is the slope of the calculated stress–strain curve at a given cyclic strain, respectively. In general, the nominal Young's modulus E_1 is often lower than the effective Young's modulus because of the gap among the twisted cooper strands and pre-stress during the fabrication process. After several cyclic processes, the gap among the cooper strands will be disappeared, and the pre-stress will be released gradually. Therefore, the values of E_2, E_3, E_4, and E_5 come into being convergent, as verified by the experimental process. The theoretic model for nominal Young's modulus E_1 has been presented by Yue et al.

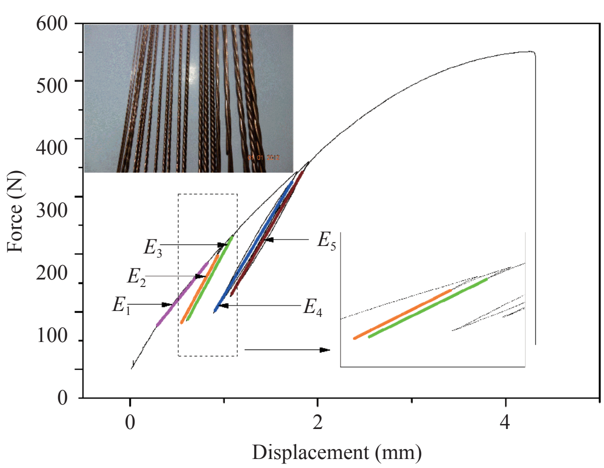

Fig. 1. Axial tensile force-displacement curve (black line) of a used sample. One of insets shows the used samples with different twisted pitch. The other shows the local zoom-in of the cyclic loading process and the definition of the Young's modulus, where the lines with pink, red, green, blue, and brown color are fitted by linear law.

[11]. In this paper, we focus on the theoretic and experimental investigations on the Young's modulus E_2, E_3, E_4, and E_5 after cyclic loading.

In the present model, twist structure's stretching can be divided into two processes: untwisting and elastic deformation, as displayed Fig. 2. In which, two symbols ε_1 and ε_2 denote the axial strain caused by untwisting and the elastic deformation, respectively. For the untwisting process, if this structure's elongation and back rotation are raised at the same time, its tension force in axial direction can be regarded as 0. This implied that the twist structure is free to back rotation caused by residual stress, as a result, the triplet's twisted angle β_1 changes, The untwisting process of the triplet during the tension is schematically showed in Fig. 3(a). One can see that with the triplet stretch, its

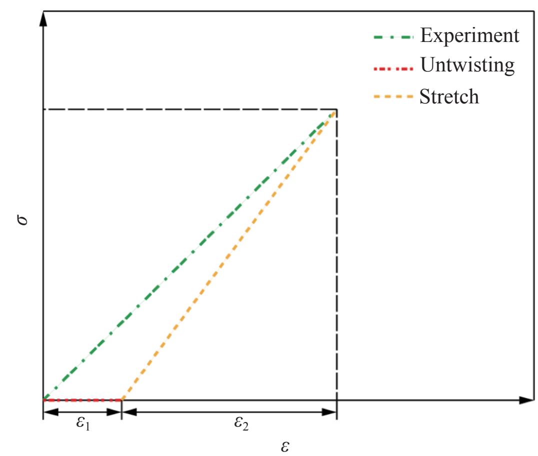

Fig. 2. Schematic diagram of the total axial strain of twist structure in the process of axial tension. The total axial strain can be divided into two components: the axial strain ε_1 caused by untwisting and ε_2 related to elastic deformation.

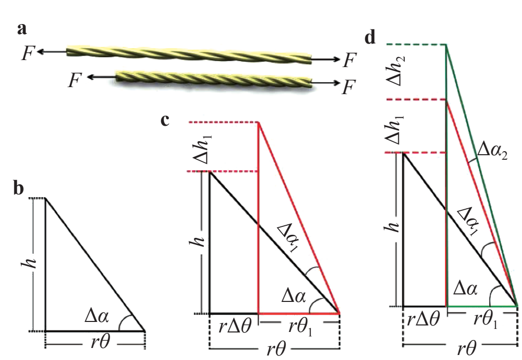

Fig. 3. Schematic diagram of the tension process for the triplet. **a** Both untwisting and stretching of the triplet with increase in twist pitch when triplet is under the tension, **b** initial state of triplet. θ is initial angle, and α is initial helix angle. **c** The state of triplet after untwisting which is denoted by the red triangle. $\Delta\theta$ represents untwisting angle, $\Delta\alpha_1$ is variation of helix angle produced by untwisting, and Δh_1 is stretch deformation of triplet produced by untwisting. **d** The state of triplet after untwisting and stretching, showed by the green triangle. $\Delta\alpha_2$ is variation of helix angle produced by stretching, Δh_2 is stretch deformation of triplet produced by stretching.