



Elasto-plastic behavior of a Warrington-Seale rope: Experimental analysis and finite element modeling



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ABSTRACT

The mechanical behavior of Warrington-Seale (WS) strands as well as of a Warrington Seale rope with a polymeric fiber core is investigated. Specifically, the elasto-plastic response under axial loading conditions beyond the elastic limit is studied. Tensile tests were carried out on both WS strands and ropes. The strain–stress curves of single wires with different diameters were determined and used as input of a fully parametric Finite Element (FE) study aimed at investigating the stress and strain evolution in the rope in the elastic as well as in the elasto-plastic regime. The numerical simulations, validated on the basis of the experimental results, are useful to shed light on the way the load is distributed among the wires. The different damage evolution and the most likely failure mechanisms of strands and of ropes were identified. Helpful remarks are drawn about the structural response of these components under heavy loading conditions.

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1. Introduction

The ability to withstand high axial loads coupled with high flexibility, compactness and high strength to weight ratio have determined the success of ropes as structural elements for many applications. For this reason, a great effort has been devoted in the past century to develop theoretical models for the structural analysis and to build up experimental data bases necessary for explaining their mechanical behaviors. The structural complexity and the expensive experimental investigation together with the non-linear nature of the problem render the analysis particularly difficult, thus hindering the formulation and closed-form solution of the equilibrium equations of each wire. The knowledge of the state of internal stress could play a crucial role since it could allow not only to properly design the rope in relation to the external loads, but also to prevent some of the damage phenomena, such as the wear of the wires, which might be very detrimental to its functionality. In this context, some aspects of their mechanical response such as for example the way the plastic deformation spreads across the strand cross section beyond the elastic limit, so as to establish the damage evolution and predict rope's failure, have not been fully clarified yet. In the literature, several analytical

models have been published, the books of Costello [1] and Feyrer [2] summarize the theoretical foundations and also report a comprehensive database of experimental results. Theoretical models, based on a set of simplifying assumptions, provide an estimate of the stress state induced by external loads into the cross section of a single strand. As pointed out by Elata et al. [3] these analytical models can be grouped into two main categories: fiber-based approaches and rod-based approaches. The first ones consider the wires as fibers having axial stiffness without bending and torsion capabilities (e.g. Lanteigne [4], Cardoux and Jolicoeur [5]), the latter ones assume that wires behave like beams thus possessing not negligible flexural and torsional stiffness (e.g. Velinsky et al. [6], Costello and Miller [7], Costello [1]). Jolicoeur and Cardoux [8] compared theoretical predictions of different models with the results of experimental tensile tests showing that fiber-based models may provide a sufficiently correct representation for single strand. Of considerable interest for the development of a design methodology of multilay wire strands is the approach proposed by Velinsky [9] based on the formulation of a set of dimensionless parameters, allowing the study of a wide variety of strand configurations. For multistrand ropes the theoretical analysis is more complex Velinsky et al. [6], Costello [1], Velinsky [10], adopted some simplifying assumptions to treat the wound strands starting from the formulation of the single multilay straight strand by incorporating the strands into the ropes in the same way as the single wire is incorporated into the single strand, thus predicting

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with satisfying approximation the rope's response. Utting and Jones [11,12] included in the analysis also contact deformation and friction effects among wires. Velinsky [13] extended the design approach proposed in [9] to wire ropes with three types of cores, independent wire rope core, fiber core, wire strand core. For its versatility, this methodology showed to be effective for carrying out an optimization analysis in the strand design. Velinsky [14] showed the usefulness of this approach by carrying out an optimum design analysis formulated for rope's minimum weight. Raoff and Kraincanic [15] proposed an extension to multi-strand wire ropes of the orthotropic sheet theory initially developed for multilayer strands, thus allowing to estimate with fairly simple formulas wire ropes stiffness coefficients. In order to take into account the double helical geometry of the wound strands Wang and McKewan [16] proposed a geometrical modeling approach of strand's double helix configuration, necessary for a complete description of the load distribution among wires. An interesting application of this representation for multi strand constructions was proposed by Elata et al. [3]. By considering the double-helix configuration of single wires (treated as fibers) within the wound strand they were able to relate the wire level of stress to the load applied to the rope, thus finding a good agreement between theoretical predictions and experimental results.

If, on the one hand, analytical models can be used to explain the behavior of single wires and, in some instances, to qualitatively predict the mutual contact actions exchanged by the wires, they are unable to fully describe the mechanical response of the generic strand because of the various phenomena occurring simultaneously during in service loading, such as nonlinear contact condition, friction, plasticity and large displacements (full-slip regime vs. sticking conditions), which will inevitably affect the mechanical response. Some approaches based on the Finite Element analysis (FE) have been proposed to study these aspects in the last two decades. Chiang [17], Jiang et al. [18], Nawrocki and Labrosse [19] used the FE analysis to simulate a simple strand made up of seven wires in order to investigate different aspects of the mechanical behavior such as for example the inter-wire motion, contact stresses and possible local plastic yielding. Jiang et al. [20] extended their analysis to a three layered straight wire strand by modeling a basic sector of the wire strand accounting for the helical symmetry. More recently, Fontanari et al. [21] presented a FE modeling and an experimental analysis of a full-locked rope undergoing a heavy thermal loading simulating a fire scenario. Imrak and Erdonmez [22] presented an interesting FE modeling of an independent wire rope core (IWRC) made up of six strands wound around a straight core strand. Stanova et al. [23,24] published a comprehensive work on the computer modeling of wire strands. They focused firstly on the development of a mathematical model able to generate any rope geometry and then carried out a FE analysis of a multi-layered strand. Moradi et al. [25] performed a finite element modeling of an independent core wire rope, made up of Warrington Seale strands, bent over a sheave, obtaining useful information for the failure analysis of the rope. Kmet et al. [26] used the approach proposed by Stanova et al. [24] to study the mechanical behavior of a four layered spiral strands bent over a curved support. They found very interesting information about the load sharing among wires.

Although these numerical models are computationally heavy, they provide results closer to the experimental evidences in estimating normal, torsional and flexural stiffness, if compared with predictions of analytical models and undoubtedly they could have an ever increasing impact on the study of these structural components.

Within this framework, the present work aims to develop a parametric numerical approach able to provide a complete and reliable description of the mechanical response beyond the elastic limit of wire strands and fiber-core wire ropes. The attention is

firstly focused on the strand as this is the key component of strand ropes and then extended to the multi-strand fiber core rope. The capability of predicting the strand behavior establishes the basis for the study of the structural response of the rope. Although, to date, various different types of strands have been developed and used in structural application, the Warrington-Seale constitutes by far the most widespread solution. This solution represents an optimal compromise between the high wear resistance of Seale's configuration and the ability to withstand high loads together with high flexibility of the Warrington geometry.

The proposed FE parametric analysis has been developed with reference to this constructive solution, even if the FE model has been designed to be adapted to any strand's geometry. Experimental tensile tests were carried out on single wires to determine the material true stress and strain curve to be used in the FE model for predicting the strand behavior. The FE model was set up on the basis of a sensitivity analysis and validated by comparing the predicted load vs. elongation curve with results of experimental tensile tests carried out on a 31-wires Warrington Seale strand and a six-stranded 186 wires rope with polymeric core. The numerical model was then used to evaluate the distribution of the load among wires at different steps of the test. In this way, the yielding mechanism and the plastic strain evolution responsible for the final failure both for the single strand and for the rope can be predicted.

2. Geometry of the warrington seale strand and of the fiber core rope

The Warrington-Seale strand configuration and the corresponding standard wire's layers definition is represented in Fig. 1a. This solution consists of three concentric wire layers helically wound around the core wire, comprising a total of 31 wires having different cross section, aligned in a parallel configuration (the standard sequence labeling $12 + 6/6 + 6 + 1$ reports the number of wires from the external layer to the inner core). This geometry is typically adopted for producing ropes to be used for ropeways and similar applications. The strand nominal cross-section amounts to nearly 143 mm^2 thus reaching an allowable breaking load around 240 kN.

The fiber core WS wire rope is made up of a polymeric core and 186 wires, subdivided into six $12 + 6/6 + 6 + 1$ WS strand helically wound around the core. The geometry of the rope is represented in Fig. 1b. Table 1 lists the main geometric-constructive features of the strand and of the rope.

3. Experimental characterization

The wires were produced by cold drawing starting from high carbon steel C80 bars characterized by a pearlitic microstructure typical of nearly eutectoid steels. The nominal chemical composition is reported in Table 2.

3.1. Tensile properties of the different wires

The wires constituting the WS strand are characterized by different cross sections (Table 1). The mechanical behavior of the wires are closely related to their degree of drawing (Fontanari et al. [27], Panteghini and Genna [28], Phelippeau et al. [29]). In order to account for this size effect, twelve specimens having length of 200 mm were prepared for each wire diameter. Tensile tests were carried out on an universal servo-hydraulic machine (Instron 8506 – 100 kN), measuring elongation with an extensometer having a gauge length equal to 12.5 mm and an excursion of 2.5 mm with accuracy of 0.001 mm. Tests were carried out in position control with a crosshead speed of 1 mm/min at room

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