Advances in Engineering Software 73 (2014) 11–21

Contents lists available at ScienceDirect

Advances in Engineering Software

journal homepage: www.elsevier.com/locate/advengsoft

Computer modelling and finite element analysis of spiral triangular strands

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ARTICLE INFO

Article history:
Received 24 May 2013
Received in revised form 31 October 2013
Accepted 25 February 2014
Available online 28 March 2014

Keywords:
Triangular strand
Geometric parametric equations
Computer modelling
Strand model
Finite element behaviour analysis
Stresses
Displacements

ABSTRACT

In this paper a new mathematical geometric model of spiral triangular wire strands with a construction of (3 + 9) and (3 + 9 + 15) wires is proposed and an accurate computational two-layered triangular strand 3D solid modelling, which is used for a finite element analysis, is presented. The present geometric model fully considers the spatial configuration of individual wires in the strand. The three dimensional curve geometry of wires axes in the individual layers of the triangular strand consists of straight linear and helical segments. The derived mathematical representation of this curve is in the form of parametric equations with variable input parameters which facilitate the determination of the centreline of an arbitrary circular wire of the right and left hand lay triangular one and two-layered strands. Derived geometric equations were used for the generation of accurate 3D geometric and computational strand models. The correctness of the derived parametric equations and performance of the generated strand model are controlled by visualizations. The 3D computational model was used for a finite element behaviour analysis of the two-layered triangular strand subjected to tension loadings. Illustrative examples are presented to highlight the benefits of the proposed geometric parametric equations and computational modelling procedures by using the finite element method.

1. Introduction

Spiral strands and ropes are widely used in civil, mechanical and mining engineering applications. These structures are usually subjected to large tension loads which are associated with torsion and bending effects. Triangular strand ropes are characterized by high structural stability, high fill factors and large bearing surfaces. They have a high strength-to-mass ratio and good efficiency of construction, and because of their increased outer-wire surface area, they have good wear properties. The use of these ropes is especially efficient when there is a heavy end load and severe abrasive wear.

The triangular strand shape not only provides better resistance to crushing, but also offers a greater exposed surface area for contact with sheaves, drums or underlying layers of spooled rope. This feature, in connection with the use of Lang lay construction, distributes the abrasive wear over a greater number and length of wires. The smooth surface of the rope also helps minimize wear on drums and sheaves.

Owing to the helical construction of the wires and strands in a triangular-strand rope, a torque is generated when the rope is restrained and tensioned. When a rope is suspended vertically, there is a load differential along its length due to the self weight of the rope. This load differential gives rise to an initial torque differential in the rope. Rebel et al. [1] showed how the results of the tension–torsion tests of triangular steel-wire ropes can be used to predict static in-shaft torsional behaviour. The expected changes in strand lay length in very deep shafts (deeper than 2500 m) were calculated, and the associated problems and effects of severe changes in lay length on rope endurance and safety were discussed. Rebel et al. [2] investigated depth limitations in the use of triangular strand ropes for mine hoisting. The analysis showed that, using current available technology, torsional deformations in triangular strand hoisting ropes can be kept within acceptable limits for winding depths of at least 3200 m.

Numerous works have been devoted to the development of mathematical geometric models of round spiral wire strands and ropes as well as the modelling of their behaviour under static and dynamic loads. The round wire strands and ropes are treated either as a discrete set of concentric orthotropic cylinders, where individual layers of wires are replaced by equivalent cylindrical orthotropic sheets or as a configuration of helically curved rods,

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http://dx.doi.org/10.1016/j.advengsoft.2014.02.004
0965-9978/

with different assumptions about the cable geometry and interwire contacts [3,4]. Utting and Jones' analysis [3,4] based on the classical twisted rod theories for the behaviour of helical laid wires takes the contact deformation and friction effects into account whereas Costello's approaches neglect them [5]. Jiang et al. [6] presented a concise finite element model of a three-layered straight helical wire rope strand under axial loads. For the global behaviour of wire strand, the finite element results showed better agreement with the experimental results of Utting and Jones [7] compared with results obtained by the closed-form analytical strand model of Costello [5].

The orthotropic sheet model was first applied to cable modelling by Hobbs and Raoof [8] and then extended by Raoof and his associates over two decades [9]. Velinsky [10,11] presented the closed-form analysis for elastic deformations of multilayered strands and the design of wire ropes. Lee [12] presented the geometrical analysis applicable to any rope with axisymmetric strands. He derived the Cartesian coordinate equations, which describe the helix geometry of wire within a rope. Through the application of differential geometry and the use of engineering drawing development approaches, problems associated with the three-dimensional helix geometry of wire ropes could be solved. The derived geometric equations were used for an analysis of the geometrical properties of cables. Knapp et al. [13] developed the CableCAD software code for the geometric modelling and finite element analysis of cables. Elata et al. [14] presented a new model for simulating the mechanical response of a wire rope with an independent wire rope core. In contrast with previous models, the present model fully considers the double-helix configuration of individual wires within the wound strand. The double-helix geometry is modelled with parametric equations because of its complex nature. A review of previous studies on the geometric modelling and analysis of steel and synthetic cables can be found in [15–17]. Usabiaga and Pagalday [18] derived the parametric equations of the double helical wires for the undeformed configuration of the rope. Nawrocki and Labrosse [19] presented a finite element model for simple straight wire rope strands, which allows the study of all the possible interwire motions. Labrosse et al. [20] investigated the quantity of energy dissipated through friction due to the motions between wires when a cable is loaded.

Evans et al. [21] investigated wire strain variations in tension–tension fatigue for two six-strand rope constructions under normal and overloaded conditions. It has been found that for ropes in tension, there is a considerable variation in wire strains both on different wires at the same cross-section and to a marginally lesser extent along the length of the same wire. It has also been found that a Lang's lay rope has a wider variation of strains than the identical ordinary lay rope. Bradon et al. [22] presented a theoretical model of the torsional characteristics of parallel multi-part rope systems. In such systems, the ropes may cable, or wrap around each other, depending on the combination of applied torque, rope tension, length and spacing between the rope parts. Paczelt and Beleznai [23] developed the p-extension concept in the finite element method for simple straight two-layered wire rope strand which considers all possible inter-wire motions, contact and dry friction between the wires in case of small displacement and deformation. The structure can be subjected to tension, torsion and bending loading. The linear elastic material properties were assumed for the calculations.

Argatov [24] developed the refined discrete mathematical model of a simple helical wire rope strand. The constitutive equations for a helical wire rope strand, which take into account both the Poisson's ratio effect and the effect of contact deformation, were obtained in a closed form. Erdonmez and Imrak [25] proposed a new methodology of defining and modelling the nested helical structure for wire ropes, and presented an accurate wire rope 3D solid modelling, which can be used for finite element analysis. Both single and nested helical wire parametric equations are presented. Prawoto and Mazlan [26] presented computational, mechanical, and metallurgical properties of wire ropes under tension loading. Wang et al. [27] presented the finite element analysis of a hoisting rope and three-layered strand for the exploration of fretting fatigue parameters and stress distributions of the cross-section. The results showed that different wires in the rope or strand and distinct material models in the analyses both induce different stress distributions and fretting fatigue parameters. Frikha et al. [28] presented the asymptotic expansion method which has been applied to helical structures subjected to axial loads (traction and torsion) at its end sections. The proposed approach has been validated for helical single wire structures and seven-wire strands and compares favourably with reference analytical results or 3D finite element computations.

By contrast with earlier references in which geometric models for round spiral strands were built, the main contribution of this paper is to propose a 3D mathematical geometric model for triangular spiral strands and by means of an implementation of the derived geometric model into a finite element model confirm its applicability. For this purpose an example on a spiral triangular strand subjected to a tension load is presented.

2. Basic assumptions and problem formulation

The cables considered in this paper are spiral triangular strands made of one or two layers of circular wires helically laid over a central circular straight core wires. The right (left) hand lay strand is a strand in which the cover wires are laid in a helix having a right (left) hand pitch. If the rope is made up of six triangular strands, for each strand an equilateral triangle can be described as is shown in Fig. 1. Based on this fact, $3n_1$ wires in the first layer of the strand are assumed. This designation actually means that the number of wires in the first layer must be divisible by three, in order to distribute them on an equilateral triangle ABC (see Fig. 3).

A mathematical expression of axes of the individual wires in the strand facilitates in the creation of a geometric model.

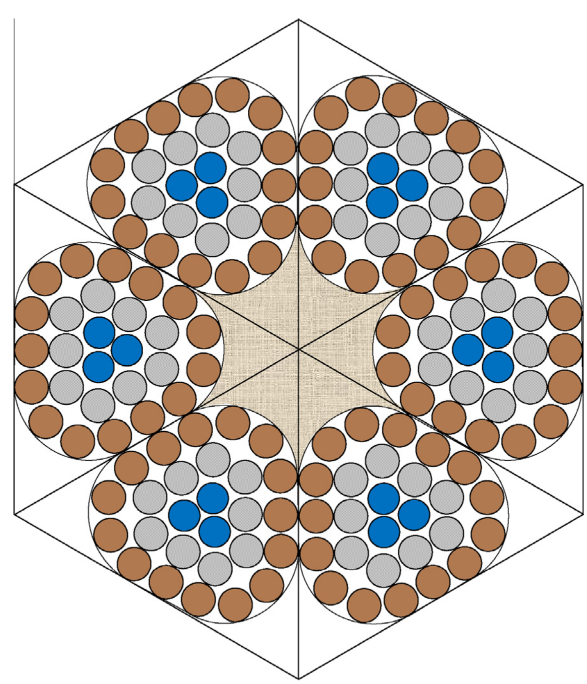

Fig. 1. Layout of a cross-section of the rope made up of six triangular strands.