New Approaches for Model Generation and Analysis for Wire Rope

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Abstract. Independent wire rope cores are composed by helically wrapping a wire strand over a straight wire strand. Outer strand of the wire rope is composed with nested helical geometry which is difficult to model for analysis. In this paper a wire by wire based, a more realistic analysis model determination of an independent wire rope core is defined with the parametric equations of the nested helical geometry. The locations of the single and nested helical wires are created and the meshed model of each wire is constructed separately. Wire rope is assembled and the axial loading model is constructed and analyzed using finite element analysis. The obtained numerical results are compared with the theoretical results. The results have in good agreement and the wire by wire analysis gives insight about the wire loads acting within an independent wire rope core.

Keywords: Wire strand, wire rope, independent wire rope core, wire rope modeling.

1 Introduction

Wire rope analysis mostly relies on the classical treatise on the mathematical theory of elasticity of Love [1]. Nonlinear equilibrium equations are solved analytically by a number of researchers and theoretical models are developed in different aspects [2]-[9].

While solving the equilibrium equations of a simple straight strand using the theory of Love, frictionless theory is mostly used due to the difficulties of the equilibrium equations and geometric considerations of the helical structure. Costello has brought together his comprehensive studies over wire rope theory in his reference book [3]. Theoretical investigations of wire rope theory based on the analysis of a simple straight strand. Static behavior of a simple straight strand is investigated in [2]. For more complex geometries such as wire ropes, theoretical models are applied using some homogenization hypothesis.

To predict the axial static response, a Seale IWRC is analyzed in [7]-[8]. A design methodology for multi-lay wire strands is investigated in [9]. Among them the analysis of IWRC in [4] is remarkable which represents excellent correlation with the available experimental results in the literature.

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In finite element models given in the literature, a basic sector of a simple straight strand is studied at first in [10]. Then it is developed to a three-layered straight helical wire strand in [11]. A new theoretical model simulating the mechanical response of a wire rope with an IWRC which fully consider the double-helical configuration of individual wires is investigated in [12]. Also the advantage of wire-by-wire modeling approach based on the general rod theory is introduced and compared with the fiber models in [13].

Lately modeling difficulties of double helical wires is investigated in [14]. Some of the encountered modeling problems are solved by the referred modeling scheme by Erdönmez and İmrak. Analysis of an IWRC including plastic deformations is investigated in [15]. The robustness of the generated solid model is mentioned.

Independent wire rope core (IWRC) is a special type of wire rope. It is composed by using a straight wire strand as a core, wrapped by six outer strands as shown in Fig. 1. The core strand of the IWRC is composed by (1+6) wires. The core wire of the core strand is a straight wire and the outer 6 wires are single helical wires. In the composition of the outer strand core wire of the outer strand is a single helical shape while the outer wires of the outer strand is in nested helical form as shown in Fig. 1. IWRC has been used in a variety of applications and also become a core strand for some of the wire ropes, such as Seale IWRC and Warrington IWRC. Large tensile force strength of the wire ropes is very important in application areas where as the small bending and torsional stiffness.

In this paper first of all a nested helical geometry definition is described. Then modeling of an IWRC with using the nested helical geometry is presented. Using the proposed geometrical model a numerical solution of the IWRC is presented and compared with the theoretical results.

2 New Approach for Wire Rope Geometry

2.1 Definition of the Nested Helical Geometry

An IWRC is composed by a core strand wrapped by six outer strands as shown in Fig. 1. Due to the complexity of the outer wires of the outer strand of the IWRC, it is difficult to model in 3-D form the outside nested helical geometries via using the computer aided design software. Even the generated models via CAD softwares have problematic surfaces and it is not coherent to analyze such problematic body using finite element analysis FEA codes such as Abaqus™. To overcome this, a new procedure for modeling wire rope is proposed using the mathematical definition of the nested helical structure. In this paper first of all a single helical wire composition will be described and then IWRC definition will be given.

The general construction of a simple straight strand and an IWRC is shown in Fig. 1 and Fig. 2. Straight core strand is composed by a straight center wire of radius R_1 surrounded by six single helical wires of radius R_2 around it. Center wire raius of the outer strand is given by R_3 and the nested helical wire radius is given by R_4 as shown in Fig. 2. The relation of the helix angle and the pitch length can be given with,

$$\alpha_i = \arctan\left(p_i / \left(2\pi r_i\right)\right), \tag{1}$$

where p_i is the pitch length of the helical wire and r_i is the helix radius for the i'th wire. To define the location of a single helix centerline, Cartesian coordinate system (X,Y,Z) is used with the Cartesian frame $\{e_X, e_Y, e_Z\}$ and the location along the centerline of a single helix is defined as,

$$\begin{aligned} X_s &= r_s \cos(\theta_s), \\ Y_s &= r_s \sin(\theta_s), \\ Z_s &= r_s \tan(\alpha_s)\theta_s, \end{aligned} \tag{2}$$

where e_Z is the rope axis, r_s is the radius of the single helix, α_s is the single helix laying angle and $\theta_s = \theta_0 + \theta$. Free angle θ is used to define the location of the wire around the rope axis e_Z, relative to e_X. Single helix phase angle is defined by $\theta_0 = \theta_{(z=0)}$. The outer double helical wires are wound around a single helical wire by using the location along the centerline of a single helix given in equation (2) and the location of the nested helices can be defined as [12],

$$\begin{aligned} X_d &= X_s(\theta_s) + r_d \cos(\theta_d)\cos(\theta_s) - r_d \sin(\theta_d)\sin(\theta_s)\sin(\alpha_s), \\ Y_d &= Y_s(\theta_s) + r_d \cos(\theta_d)\sin(\theta_s) + r_d \sin(\theta_d)\cos(\theta_s)\sin(\alpha_s), \\ Z_d &= Z_s - r_d \sin(\theta_d)\cos(\alpha_s), \end{aligned} \tag{3}$$

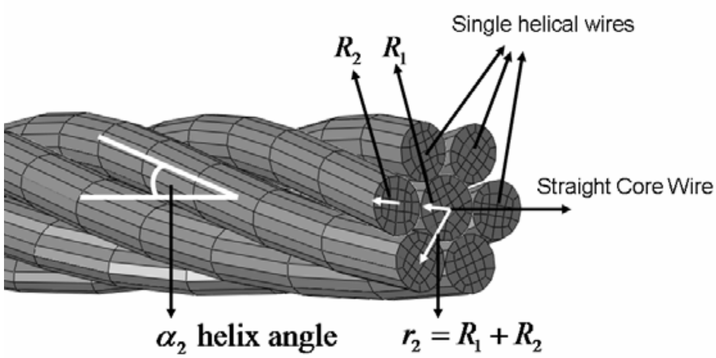

Fig. 1. A simple straight strand geometry

where $\theta_d = m\theta_s + \theta_{d0}$ and r_d is the distance along the nested helix wire centerline and single helix strand centerline shown in Fig. 2. The construction parameter m is a constant value that can be estimated by $m = h_s / \left(h_w \cos\alpha_s\right)$, where h_s and h_w are the lay lengths of the outer strands and outer wires of the outer strands respectively [13] and θ_{d0} is the wire phase angle. According to (1)-(3) a right lang lay wire rope structure can be constructed and to construct a left lang lay wire rope, it is enough to negate one of the coordinate values of X_d, Y_d or Z_d given in equation (3).

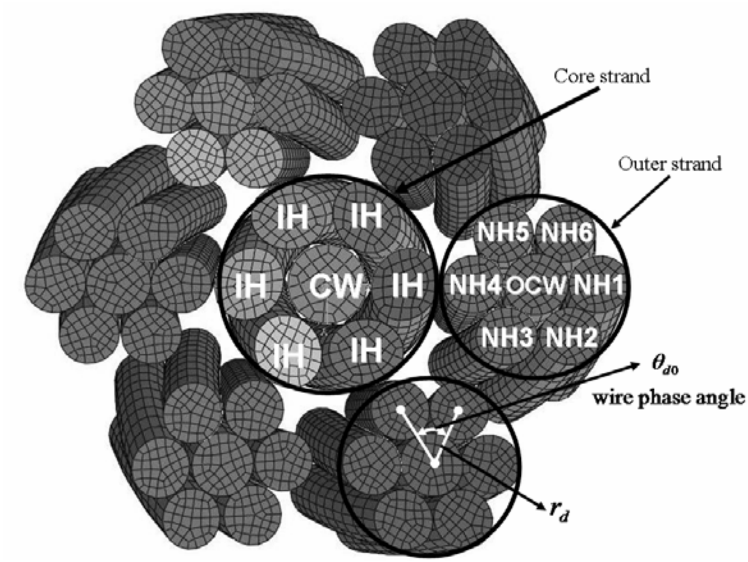

Fig. 2. Geometry and wires within an IWRC

2.2 Wire Rope Generation and Modeling

Due to the complex wire geometry, nested helical wires over the outer strand of the IWRC is not in the scope of the commercial solid modeling softwares for the moment to model a nested helical wire. To model a nested helical wire a code was developed by the authors in Matlab™. Using this code each wire centerline is created using the control nodes. Control nodes are generated by using the parametric equations of the both single and nested helical structures. To compose the simple straight strand, a straight center wire and a single helical wire is enough. The single helical wire will be wrapped by the six single helical wires which are identical. This procedure completes the construction issue of the simple straight strand.

IWRC geometry is composed by a straight strand and with six identical outer strands. In Fig. 2 the combination of the wires are shown. The core strand has two titles as CW for core wire and IH for six identical inner helical wires. For the outer strand each wire has been titled with different code. OCW stands for outer center wire which is a single helical shape while the other six different nested helical wires are titled as NH1-NH6.

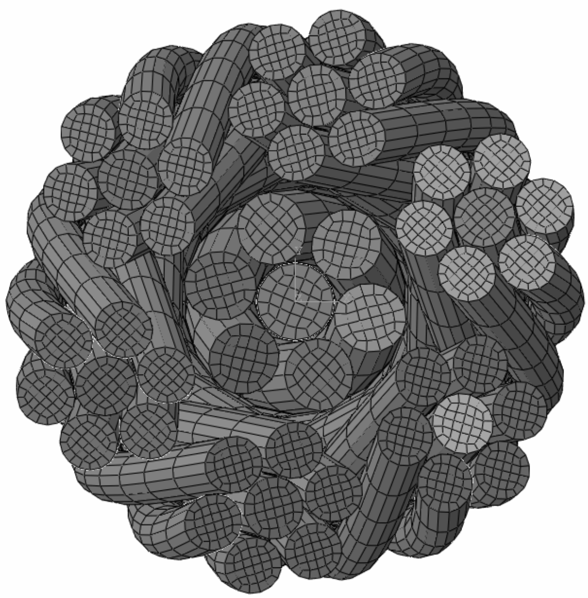

Fig. 3. Meshed form of a Right Regular Lay (RRL) IWRC

Each of the nested helical wire has to be generated separately to compose the outer strand of the IWRC. Once these wires are constructed, all of the wires are imported in Abaqus/CAE^{TM} and assembled to complete the IWRC.

In the generated Matlab^{TM} code each nested helical wire control nodes are created separately. After wire control nodes are imported in a modeling and meshing software HyperMesh^{TM}. Using HyperMesh^{TM} each wire is constructed with the meshed form and exported to the analysis software Abaqus/CAE^{TM}.

Each wire is assembled and the complete meshed form of the IWRC is generated in Abaqus/CAE^{TM}. There are two benefits of this procedure. First one, the geometry is ready to analyze, no need to further meshing of the geometry and the geometry is error free. Second one is that the proposed method has no length limit.

It is possible to produce longer parts using this procedure. Using the generated wire rope geometry it is possible to analyze the model and find out the wire by wire behavior of the IWRC easily. A meshed form of a right regular lay IWRC is presented in Fig.3 by using Eqn. 3. It can be analyzed by applying the necessary boundary conditions.

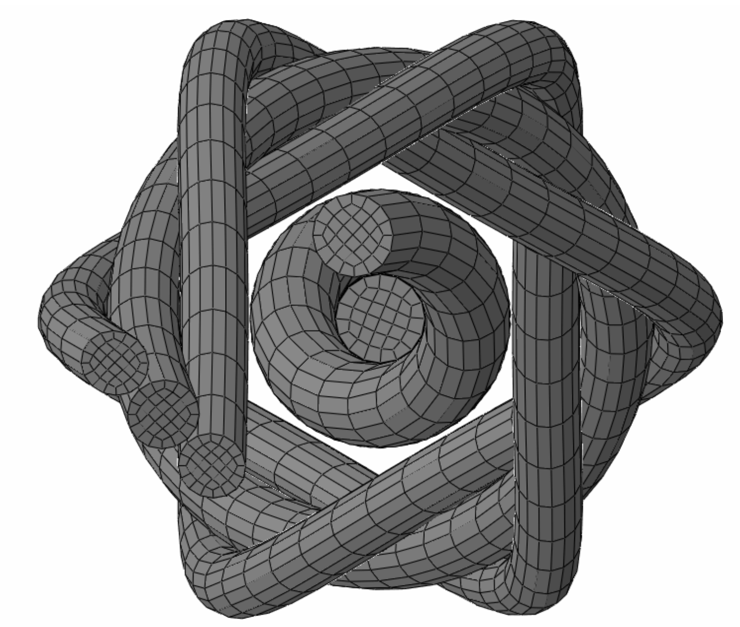

Fig. 4. Indentations over the double helical wires are presented for a Right Regular Lay (RRL) IWRC

2.3 Wire by Wire Analysis of the IWRC

The constructed IWRC is analyzed under the axial loading conditions using the commercial analysis code Abaqus™. The geometrical parameters of the wire rope are given in Table 1 [13].

Table 1. Geometric Parameters of IWRC

Parameter	Description	Value
d	IWRC diameter	29.80mm
R_1	Core strand center wire diameter	3.94mm
R_2	Core strand outer wire diameter	3.73mm
R_3	Outer strand center wire diameter	3.20mm
R_4	Outer strand double helical wire diameter	3.00mm
h	IWRC length used in the model	18mm
p_2	Pitch length of the inner helix	70mm
p_3	Pitch length of the outer center single helical wire	193mm
p_4	Pitch length of the outer nested helical wire	70mm
α_2	Helix angle	71.01^o
α_3	Helix angle	74.45^o
α_4	Helix angle	71.46^o

One side of the model is constraint with encastre boundary condition and the other end is constraint to be non rotating as $\Theta = 0$. Material properties are defined as follows; Young's modulus of 188000 N/mm^2, plastic modulus of 24600 N/mm^2, yield stress of 1540 N/mm^2, limit stress of 1800 N/mm^2, Poisson's ratio of 0.3, friction of 0.115.

Surface to surface contact controls defined for the interactions of the each wire with the neighbor wires. The analytical results obtained by the theory of Costello and finite element results are presented and compared in Table 2.

From the results it can be seen that the analysis results shows good agreement with the theory for the frictionless case. In frictional case the plastic behavior of the wire rope has been seen.

In Table 3, wire by wire forces of the IWRC have been presented. From the results, it can be concluded that core strand carries the maximum load within the strands. Within the outer wires of the outer strand NH4 in average carries the maximum load and NH5 and NH3 follows it.

From Fig. 2 the location of the NH4 can be seen and it shows that the wires close to the center strand carry more loads that the other wires in the outer strand. This information may help while optimization processes of the wire rope production.

Table 2. IWRC Force Results [N]

Strain 10^{-3} (mm)	Theory of Costello	Frictionless FEA	Frictional FEA
1	53852.46	53733	53549
2	107704.92	107392	107002
3	161557.38	160977	160360
4	215409.83	214487	213623
5	269262.29	267924	266792
6	323114.75	321285	319863
7	376967.21	374572	372579
8	430819.67	427784	423340
9	484672.13	480922	466319
10	538524.59	533984	494556
11	592377.04	586971	512383
12	646229.50	639882	525727
13	700081.96	692776	536805
14	753934.42	745551	546611
15	807786.88	798252	555685

Table 3. Wire by Wire Forces of the IWRC [N]

Strain 10^{-3} (mm)	CW	IH	OCW	NH1	NH2	NH3	NH4	NH5	NH6
0.8	1761	1202	952	712	742	826	882	845	760
1.5	3519	2402	1903	1423	1483	1650	1762	1689	1518
3.0	7030	4801	3803	2845	2965	3297	3522	3376	3035
4.5	10523	7189	5694	4260	4439	4937	5272	5054	4545
6.0	13998	9566	7576	5671	5907	6568	7014	6725	6049
7.5	17486	11829	9470	7089	7382	8208	8766	8405	7562
9.0	19182	13432	11177	8391	8682	9591	10381	9973	8966
10.5	19754	14406	12104	9336	9534	10306	10943	10776	9929
12.0	20291	15072	12560	9919	10042	10683	11205	11173	10488
13.5	20819	15585	12884	10328	10404	10959	11458	11464	10876
15.0	21335	16020	13172	10654	10701	11207	11708	11726	11185

3 Conclusion

Due to its complex geometry nested helical wires in an IWRC needs special handling while solid modeling. In this paper an IWRC is modeled taking into account the complex nature of the outer nested helical wires within the outer strand of the IWRC. This issue enables one to obtain results on wire by wire bases. A wire by wire analysis of an IWRC has been modeled and analyzed. First of all wire by wire modeling procedure using the nested helical structure of the IWRC has been described. Then the finite element analysis is constructed with the given boundary conditions. An example of the axial loading of an IWRC has been analyzed. Both theoretical and finite element analysis shows good agreement. Using the wire by wire analysis results, loads acting on each wire of the IWRC has been reported. Results show that the center wire of the core strand has been loaded with the maximum force. From the result it can be seen that the outer nested helical wires close to the center strand faced with more load than the other wires in the outer strand.

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