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Finite Elements Modeling and Analysis of an Axially Loaded Prestressing Strand

Eksenel Yüklü Bir Öngerilmeli Demetin Sonlu Elemanlar Modellenmesi ve Analizi

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Abstract

Wire ropes and strands have found an important place in many different engineering disciplines with their strengths and flexibilities. Ropes are frequently used in elevators, cranes and bridges as material handling equipment due to their constructional advantages. The purpose of this study is to reveal mechanical behavior of a prestressing steel strand subjected to axial tension load by means of finite elements method. Twisting moment, wire stress, wire strain at each layer of investigated prestressing strand and safety factors have been determined. It can be concluded that safety factors are 2.44 for frictional contact condition and 2.39 for frictionless contact condition in accordance with total axial load carried.

Keywords: Finite elements method, Prestressing strand, Safety factor, Wire rope

Öz

Tel halatlar ve demetler, mukavemetleri ve elastikiyetleri ile çoğu mühendislik disiplinlerinde önemli bir yer bulmuşlardır.Halatlar, konstrüksiyonel avantajları nedeniyle, asansörler, vinçler ve köprülerde malzeme taşıma ekipmanı olarak sıklıkla kullanılırlar. Bu çalışmanın amacı, sonlu elemanlar metodu ile eksenel çekme yüküne maruz bir öngerilmeli çelik demetin mekanik davranışını ortaya koymaktır. İncelenen öngerilmeli demetin her kademesindeki burulma momenti, tel gerilmesi,tel birim şekil değiştirmesi ve emniyet katsayıları tespit edilmiştir. Taşınan yüke göre sürtünmeli temas durumunda emniyet katsayısının 2.44, sürtünmesiz temas durumunda 2.39 olduğu sonucu çıkarılabilir.

Anahtar Kelimeler: Sonlu elemanlar metodu, Öngerilmeli demet, Emniyet katsayısı, Tel halat

1. Introduction

It is very important to know the safely transportation limits and maximum load lifting capacities of steel wire ropes. In particular, steel wire ropes have flexible structure and consist of many wires to share the total carried load in order to increase operational safety. Steel wire ropes and strands are widely used as hauling element for lifting and transporting loads due to their flexibility and comfortable usage. The strand is manufactured by winding a number of thin steel wires around the center wire in one or more layers at various pattern (Cürgül 1995, Onur 2019).

Various experimental, analytical and numerical studies have been conducted to attain to strength and lifetime values occurred on strands and wire ropes by means of computer simulations. Ghoreishi et al. (2007) evaluated the validity the results from nine linear elastic models of a 6+1 wire single layered strand (simple straight strand) subjected to static axial loads being compared with values from 3D finite element modeling. Wang et al. (2015) CATIA V5 and MATLAB were used for implementation of derived geometric equations and calculation of mathematic optimal rope models. Elata et al. (2004) proposed a new model for simulating the mechanical response of a wire rope with an independent wire rope core. In contrast with previous models that consider the effective response of wound strands, their model fully considers the double-helix configuration of individual wires within the wound strand. Jiang et al. (1999) presented an accurate and general strand model using the finite element method. The model was capable of predict the global behavior of simple straight. Jiang et al. (2000)

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presented concise finite element model of three-layered straight helical wire rope strand under axial loads. Stanova (2013) tried to implement computer-aided modeling of ropes which have oval, circular and triangular shaped wires by means of ProEngineer Wildfire software. Vukelic and Vizentin (2017) considered three design types of wire (6x7, 7x7, 8x7) to investigate the effect of cross-section area reduction on stress levels. Von Mises stress was obtained using finite element analysis (FEA). Ziegler and Wehking (2006) modeled the spiral rope having 1x19 structure and ANSYS was used to provide knowledge of the stresses in investigated rope. Shi et al. (2017) proposed strand-traction sheave interaction model and simulations with Abaqus software were performed to reveal investigate effects of pretension and groove angle values on the traction behavior. Kastratovic and Vidanovic (2011) explored some aspects of 3D modeling of independent wire rope core (IWRC) by using CATIA and Ansys with special emphasis on different types of contacts and different types of axial loading. Onur (2016) investigated the response of the prestressing strands to axial tensile load theoretically and experimentally. Onur et al. (Onur et al. 2017, Onur and İmrak 2017, Onur et al. 2019) put effort to determine fatigue lifetime of steel wire ropes subjected to bending over sheave fatigue. Wokem (2015) studied on finite element modeling, analysis and fatigue prediction of wire ropes and strands. Erdönmez (2010) tried to mathematically formulate path of each wire of steel wire ropes in Frenet-Serret frame. Erdönmez and İmrak (2011) presented a more realistic three-dimensional modeling approach and finite element analysis of independent wire rope core. Demir and Ala (2017) performed theoretical and experimental natural frequency analysis of prestressed monotron ropes with single helix angles and different diameters. The purpose of this paper is to investigate mechanical response of a presstressing strand under tensile load through finite element method. Presstressing strand is computer aided modeled and stress analyses have been carried out using the Ansys Workbench and safety factors have been determined. In the stress analysis, friction and frictionless situations are considered separately.

2. Finite Elements Analysis of Prestressing Strand

Prestressing steel strand is used in bridges, concrete structures, nuclear power stations, water tanks, anchorages and hoisting member for lifting heavy loads. It consists of one center wire which is also known as core wire and six helical wires wrapped around center wire. ASTM A416 standard (2012) covers dimensions and some mechanical properties of prestressing strands. In this study, 11.11 mm diameter prestressing strand is adopted to determine twisting moment, wire stress and wire strain at each layer of strand by virtue of FEA. Some properties of investigated prestressing strand is given in Table 1.

Table 1. Properties of investigated prestressing strand.

Diameter of prestressing strand	11.11 mm
Radius of core wire	1.875 mm
Radius of outer wires	1.84 mm
Strand pitch	165 mm
Lay angle	81,947976°
Modulus of elasticity	196500 MPa
Strand grade	1860 MPa
Minimum breaking load	138 kN
Number of outer wires	6
Poisson's ratio (ν)	0.3

Six outer wires do not come into contact with each other but each one comes in contact with the center wire. A circle representing the center wire is extruded and one circle touching the center wire representing one outer wire at same plane is swept on the helix. Circular pattern is made to form six outer wires. Solid modeling is done at one pitch length by using Solidworks and imported Ansys Workbench. Solid model is shown in Figure 1.

The rope length does not significantly affect the torsional moment which is transmitted by the rope and the axial load to be carried (Ghoreishi 2007). However, in case of using increased number of length the number of finite elements and nodes to be used in the solution domain will increase. Therefore, it is expected that there will be an increase in the solution time of FEA.

Solid 186 meshing element including intermediate node was used in the mesh structure and a homogeneous mesh distribution was tried to obtain. Meshed geometry has 25463 elements and 126308 nodes.

It is possible to define the contact of the wires each other in different ways during FEA. According to the friction coefficient values in the problem, two different solutions have been made through two different contact definitions: frictional and frictionless contacts. The friction coefficient is taken to be 0.115 when frictional contact condition is considered. Surface to surface contact condition is identified

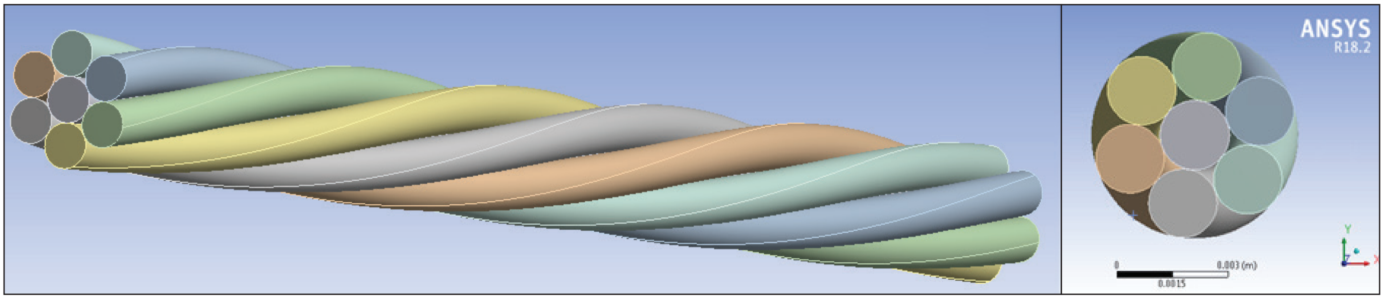

Figure 1. Solid model and cross section of prestressing strand with 11.11 mm diameter.

at each touching neighbor surface of wires. As boundary conditions, one end of the strand is fixed. Displacements on x and y axes and rotations on x, y and z axes are fixed at the other end due to the use of lead alloy casting or connection fixtures to prevent the ropes from rotating while the ropes are being mounted, and only displacement in the pulling direction is allowed. The reason is of ropes other than the rotation resistant ropes are sensitive to untwisting. Tombak (2019) prepared a MSc thesis about modeling and analysis of axially loaded rope strands and tried to compare the solution of Costello's theory with the finite element solution. Author solved wire loads generated separately by using Costello's theory while prestressing strand was strained by value of 0.003. In this study, those wire loads are exerted upon wires of prestressing strand at the free end and finite element analyses are performed under two different contact conditions. Wire load of 6510.847 N is exerted upon center wire and 6050.906 N is exerted upon each outer wire. The applied loads are given in Figure 2.

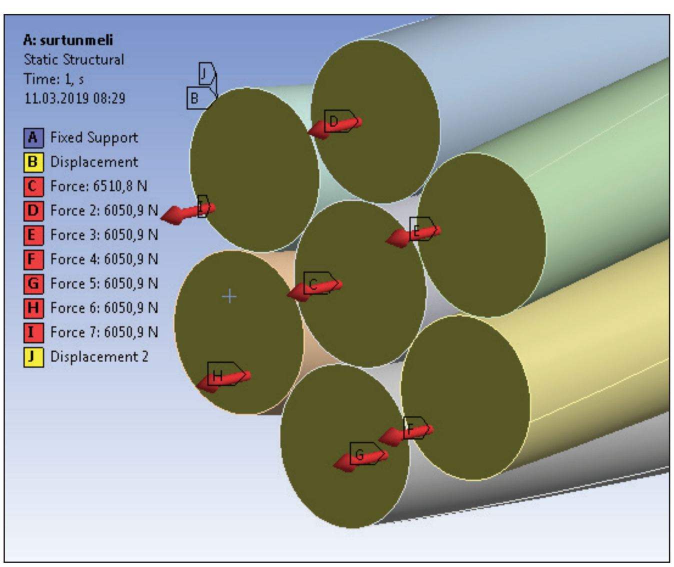

Figure 2. Loads applied to the center and outer wires of prestressing strand.

3. Results and Discussion

In this study, a prestressing strand having 11.11 mm diameter has been modeled and finite element analyses have been performed by frictional and frictionless conditions in order to reveal mechanical behavior of investigated prestressing steel strand subjected to axial tension load. Results obtained by ANSYS simulations have been presented and discussed. Twisting moment, wire stress and wire strain at each layer of investigated prestressing strand in accordance with FEA studies have been presented in Table 2.

Strain is determined as 0.00324 when friction is taken into account and strain is determined as 0.00322 in frictionless contact condition if 42816.247 N load is applied to the prestressing strand. The variation of total carried load with axial strain for various helix angles were plotted in (Erdönmez 2010). A strand having 11.40 mm diameter and 80° lay angle were considered. Author found that when strand was strained 0.003, total carried load by investigated strand was 40000 N and author determined that total twisting moment was 20000 Nmm. Xiang et al. (2017) constituted analytical model to determine elastic–plastic response of 1x7 strand with a diameter of 11.4 mm. They presented axial force-strain and axial torque-strain variations graphically. Axial force and axial torque values were determined as approxiametely 40 kN and 21 kNmm respectively. In this study, axial force and axial torque were 42.816 kN and 18.612 kNmm in accordance with strain value of 0.00324 in frictional state. Parameters and strand configuration considered were little different than this study but the results were observed to be consistent with each other. Tensile stress in the center wire is determined as 661.020 MPa in frictional contact state and 661.46 MPa in frictionless contact state. Tensile stress in the outer wire is determined as 584.48 MPa in frictional contact state and 584.53 MPa in frictionless contact state. Erdönmez's work presented that Von-Mises stress on the center wire was 550 MPa and Von-Mises stress on the outer

Table 2. FEA results for investigated prestressing strand

Results	Unit	FEA Results	
		Frictional ($\mu = 0.115$)	Frictionless
Strand strain, ε	m/m	0.00324	0.00322
Center wire tensile stress, σ_1	MPa	661.020	661.460
Outer wire tensile stress, σ_2	MPa	584.480	584.530
Maximum axial load carried by center wire, F_1	N	6510.847	6510.847
Maximum total axial load carried by outer wires, F_2	N	36305.44	36305.44
Total axial load carried by strand, F	N	42816.287	42816.287
Maximum twisting moment on center wire, M_1	Nmm	4	18
Maximum total twisting moment on outer wires, M_2	Nmm	18608	18631
Maximum total twisting moment on strand, M	Nmm	18612	18649

wire was 600 MPa in frictional contact condition. Von-Mises stress covers normal stress and shear stress together. Tensile stresses on center and outer wires presented in this study only consider normal stresses. It was observed that the stress in the center wire was slightly larger than the stress in the outer wire. Ziegler and Wehking (2006) examined the 1x19 spiral rope with a diameter of 11.64 mm. They conducted FEA by applying 50% of the rope breaking load (58.64 kN) as axial tensile load. Maximum axial tensile stress was found as 952.103 MPa. In this study, 31% of the rope breaking load (42.816 kN) was applied as axial tensile load and maximum axial tensile stress was determined as 661.02 MPa in frictional state. When the obtained results were compared, it was observed that when the axial tensile load was increased by 36.96%, the axial tensile stress increased by 44.03% as well. Stanova et al. (2011) performed FEA by means of Abaqus software in order to determine maximum stress values occurred on core wire and outer wire of 1x37 multilayered strand having 7.09 mm diameter. They found that maximum stress on core wire having 1.09 mm diameter was 1050 MPa and outer wire having 1 mm diameter was 950MPa under 30 kN tensile load. In this study stress value occurred on core wire having 3.75 mm diameter was 661.02 MPa and outer wire having 3.68 mm diameter was 584.48 MPa under 42.816 kN. When the results are examined, it was seen that the increase in the wire diameter decreases the stress value. Since the center wire is straight, it does not twist under the influence of load and therefore the torsional moment in the center wire is very close to zero. The total torsional moment in the outer wires was found to be 18612 Nmm in frictional contact state and 18649 Nmm in frictionless contact state.

Stress probe properties are used to extract center wire and outer wire tensile stresses separately at z-direction as shown in Figure 3.

Moment reaction properties are used to extract center wire and outer wire tensile stresses separately at z-direction as shown in Figure 4.

Equivalent Von-Mises stress contours are shown in Figure 5 and Figure 6 considering frictional and frictionless contact conditions by applying the total axial load carried.

It is seen that maximum Von-Mises stresses occurred on the side of fixed end of the prestressing strand and maximum stress values were almost equal for frictional and frictionless contact conditions. Wokem (2015) perfomed FEA for same strand to predict it's fatigue lifetime. Author presented that maximum Von-Mises stress was 802.8 MPa when 42000 N load was applied to strand in frictional contact condition. In this study, maximum Von-Mises stress has been found as 760.13 MPa under axil load of 42816.247 N. Abdullah et al. (2016) investigated a prestressing strand which has 15.24 mm diameter using an efficient finite element model. They obtained that the center wire initially carries a greater share of axial force as long as the material remains elastic. The center wire was determined to carry 31.3 kN (14.94% of total carried load) and the each outer wire was determined to carry 29.7 kN (14.18% of total carried load). It is determined from this study that center wire carries 15.2% of total load and each outer wire carries 14.13% of total load. Results were found to be harmonic with each other. Chiang (1996) and Raoof and Kraincanic (1994) used analytical methods and finite element method to reveal mechanical

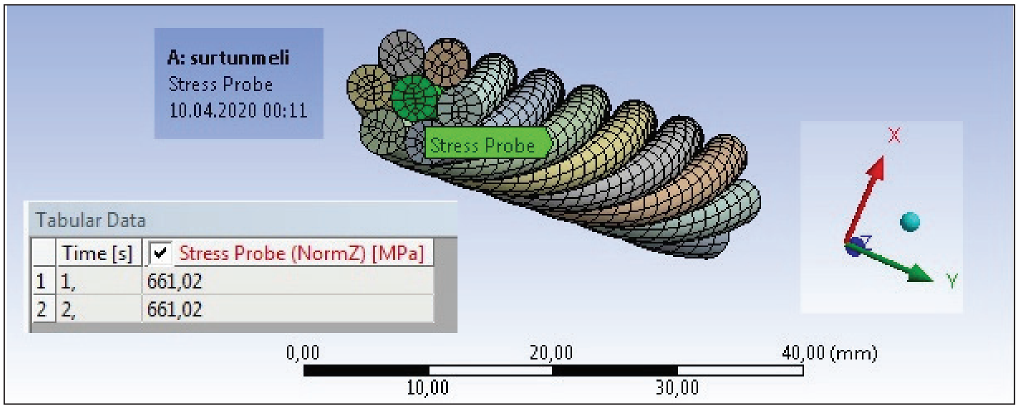

Figure 3. Stress probe used for reading center wire tensile stress in frictional contact.

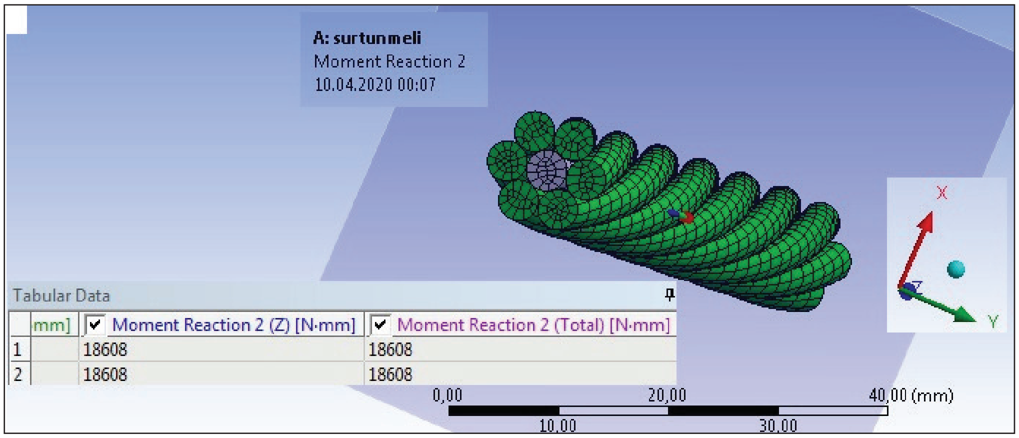

Figure 4. Moment reaction used for reading maximum total twisting moment on outer wires in frictional contact.

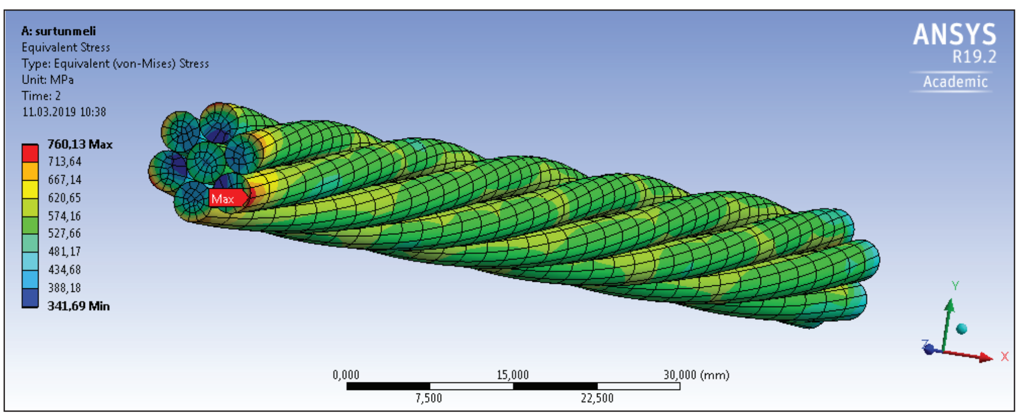

Figure 5. Equivalent Von-Mises stress contour considering frictional contact condition.

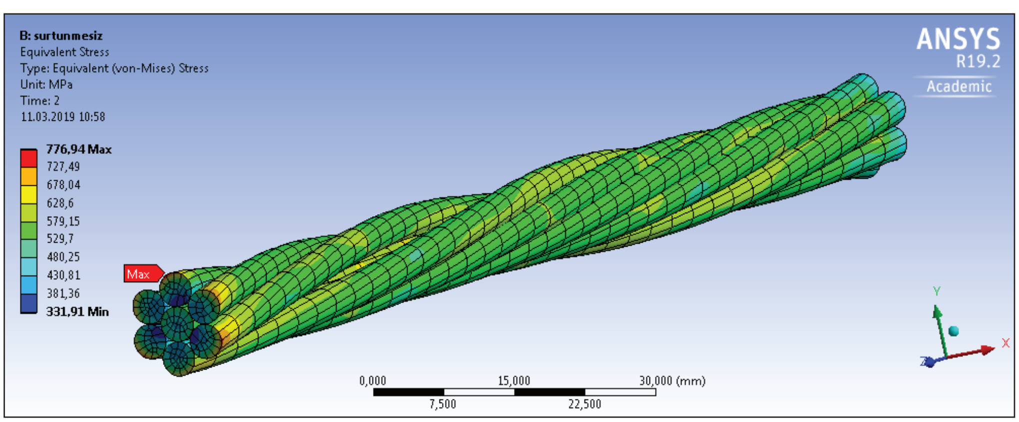

Figure 6. Equivalent Von-Mises stress contour considering frictionless contact condition.

behavior of helical strand having 11.4 mm diameter. They also presented obtained strain/axial load ratio. Chiang found strain/axial load ratio as 66.2 kN-1.10-6. Raoof and Kraincanic stated that strain/axial load ratios were found by different researchers in the range of 67-75.4. In this study, strain/axial load ratio is found as 75.67 in frictional state. The maximum Von-Mises stresses shed light on researchers in finding the safety factor. Safety factor can be found by dividing the strand grade to the Von-Mises stress. Safety factor has been found as 2.44 for frictional contact condition and 2.39 for frictionless contact condition. There is slight difference between safety factors in frictional and frictionless contact conditions. Coefficient of friction is assumed as zero in FEA where frictionless contact condition is considered. It causes the free sliding between adjacent wires. Unlike frictionless contact condition, friction between adjacent wires is regarded in FEA where frictional contact condition is considered. Contacting surfaces do not slip if a certain shear stress is not exceeded in frictional contact condition. The friction between wires creates a resistance in favor of the strand. This keeps the wires together and allows them to move together. It causes reduction in Von-Mises stress in frictional contact condition.

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