Finite Element Modeling of Fatigue Life of Steel Wire

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Abstract

In this work, bending fatigue life of steel wire has been studied using finite element modeling by ANSYS program. To verify the finite element results; a fatigue setup was designed and constructed, and the wire was tested using this setup. The results showed that the fatigue life of the wire that bent over the smaller bending diameter has the lower fatigue life, while increasing the bending diameter has a great effect on increasing the fatigue life of steel wire. The finite element results were almost near the experimental results with an accepted percent of deviation. The other values such as, equivalent (Von-Mises) stress, elastic strain, plastic strain, total strain, and the total deformation were estimated using finite element modeling. The Von-Mises parameters results showed that the wire bent over the bigger bending diameter has the lower values in which affect its fatigue life in a positive way.

Key words

Finite Element Method, steel wire, modeling, and bending fatigue life.

Introduction

Many applications in different fields use wire ropes as very essential parts to make these applications get their function done properly. Such applications include bridges, cranes, elevators, and so on [1-3]. Because of the importance of wire ropes; various studies were conducted to estimate their mechanical properties under different circumstances and then enhance them to gain the optimum specifications that best fit their applications. Other studies were done to get better understanding of their behavior during the operating period. Some researchers studied the different types of faults, their causes, how they affect the performance of the wire ropes. Researchers like Juan Wu [4]; studied the mechanical properties of the wire rope under tension using FEM. The results were compared with theoretical and experimental results. Also, Gerdemeli, Kurt S., and Anıl A.S. [5], used FEM to estimate the fatigue life of one simple strand by applying axial force and using different parameters such as, force, helix angle and length of the strand. Sung-Yun Kim and Phill-Seung Lee [6], used the Finite Element Modeling to get the mechanical behavior of the wire rope under the effect of both axial and transverse types of loadings. Then, they compared their results to those of numerical analyzing and experimental tests. Consequently, these several approaches to inspect the wire ropes are used to ensure keeping acceptable level of effectiveness operating.

To study the wire rope; it is important to know its construction. Most of wire ropes consist of three main parts; wires, strands, and core, Figure 1. Wires are the main part of the wire ropes in which a group of them helically twisted to form the strands. A group of strands helically twisted around the core to form the final shape of the wire rope [6]. It is important to study the mechanical properties of the wires separately as they are the foundation stone of the wire rope.

Fig.1. Wire rope construction [6].

Tests such as tension and fatigue are the most common types of tests that can be used for wire rope evaluation [7-8]. Finite element modeling has been used in this work to estimate the fatigue life of steel wire. In addition, some other mechanical characteristics could be obtained. FE modeling is based on dividing any object into very tiny parts called elements, and then each element can be studied separately to determine the applied forces, displacements and other internal and external factors that could affect its mechanical properties [9-12].

By solving the stiffness matrix [1]; it became available to obtain the required properties.

$\{F\} = [K] * \{U\}$.

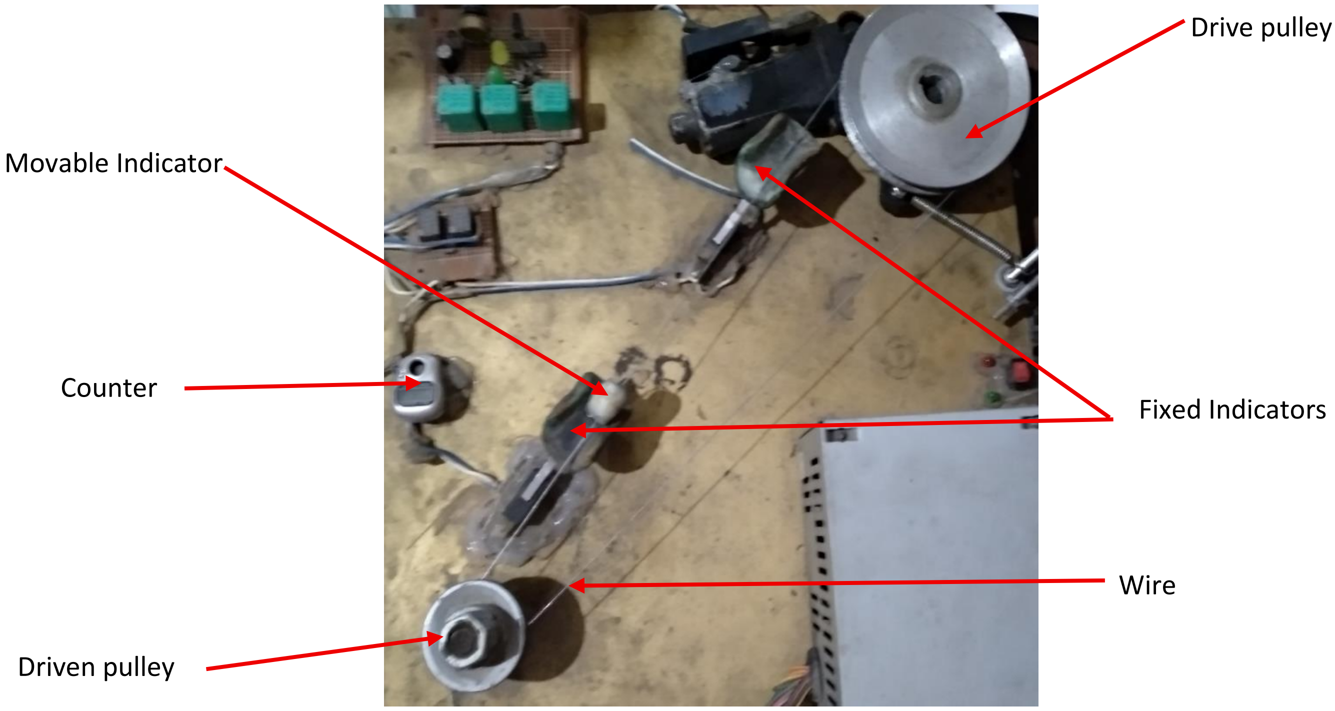
Where, {F} is the applied forces array,

[K] is the stiffness matrix, and

{U} is the displacement array.

Experimental work

Experiments were conducted using a fatigue setup that was designed and constructed to get the fatigue life of structural steel wire similar to that used in elevators wire ropes. Its concept is similar to that of the elevators and based on bending the wire around two pulleys one of them is the drive pulley which is connected to the motor as shown in Figure 2. The other is the driven one which transmitted the rotational force from the friction between the wire and the drive pulley which makes the wire move around the driven pulley. Because of the effect of friction, the driven pulley moves. The two terminals of the wire were held by the movable indicator. Other two fixed indicators were used to limit the start and the end of the stroke of the wire with the movable indicator.



(a) The fatigue test setup.

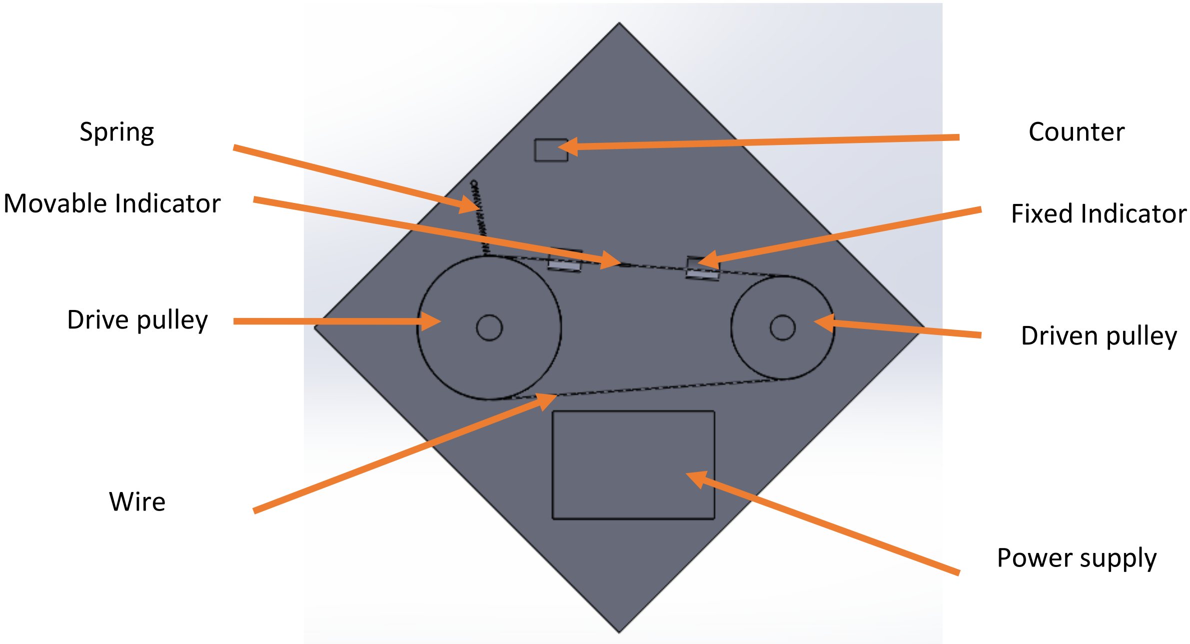


Fig.2. (b) Schematic drawing of the fatigue setup.

Variable diameters of test pulleys were used to estimate the fatigue life under bending. These diameters were (75, 45, & 35) mm. A steel spring was used to ensure that the wire was under tension all the time during the test. To calculate the spring force; the equation F=k Δx was used. Where, F is the spring force in N, k is the spring stiffness in N/mm, and Δx is the extension of the spring in mm. different weights were attached to the spring and the resulted extensions were measured, the spring stiffness was calculated using the previous equation. Then, the spring stiffness and the extension were substituted in the same equation to finally get the spring force.

Finite element analysis

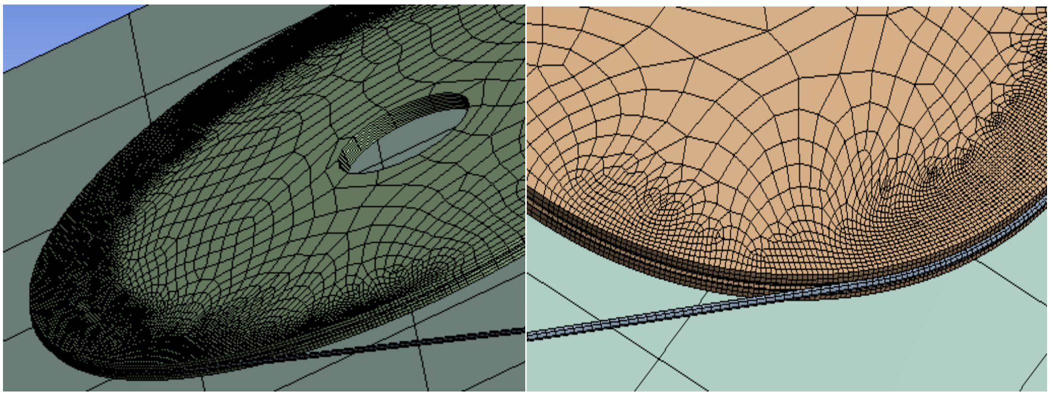
The finite element simulation was run out using ANSYS WB program, and the model geometry was drawn by SOLID WORKS. The finite element model was run out for two pulley diameters of 35 mm and 45 mm only due to the time consumption.

The model was prepared and parameters were set as following. The used material was non-linear structural steel from the ANSYS library as the Tensile yield strength = $2.5*10^8$ Pa, Young's modulus = $2*10^{11}$ Pa, Strength coefficient = $9.2*10^8$ Pa, Strength exponent = -0.106, Ductility coefficient = 0.213, and Ductility exponent = -0.47.

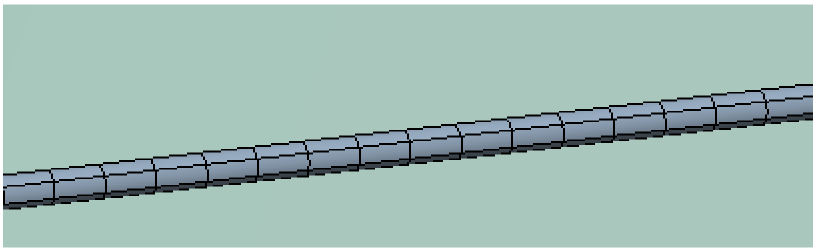
Three types of joints were used; rotational joints for the drive and driven pulleys, fixed joint for the machine base, and translational joint for the movable indicator.

Two types of contacts were chosen. Rough contact was used between the wire and the pulleys with the symmetric behavior using pure penalty formulation and the detection method of normal nodal from contact. While bonded contact was used between the movable indicator and the wire.

The chosen meshing type was contact sizing of 2.5 mm for the two areas of contact between the wire and the pulleys, and the other type of meshing was sweep method of the size of 2.5 mm for the wire, Figure 3.



(a) (b)



(c)

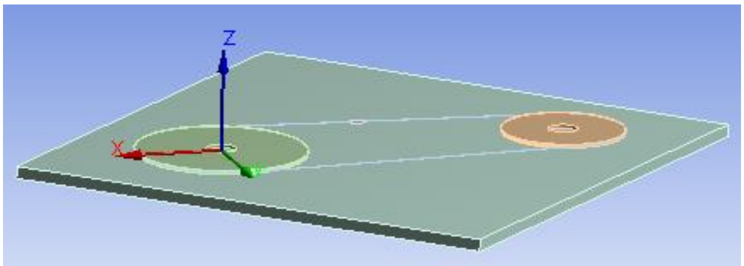
Fig.3. Element types and sizes of the wire, drive and driven pulleys. Where, (a) Mesh type of the contact between drive pulley and wire, (b) Mesh type of the contact between driven pulley and wire, and (c) Mesh type of the wire.

Table 1 summarizes the number of nodes and elements used in FE modeling in case of 35 and 45 mm bending diameters.

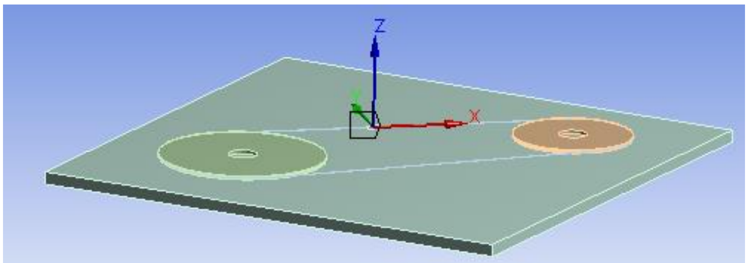
Table.1. Number of nodes and elements used in FE modeling.

No.	Part name	Number of nodes Bending diameter = 35 mm	Number of nodes Bending diameter = 45 mm	Number of elements Bending diameter = 35 mm	Number of elements Bending diameter = 45 mm
1	Wire	2156	2312	179	192
2	Drive pulley	23524	23733	4992	5034
3	Driven pulley	5378	12922	1044	2676
3	Movable indicator	2280	2280	360	360
4	Base plate	960	960	121	121
5	Total	34298	42207	6696	8383

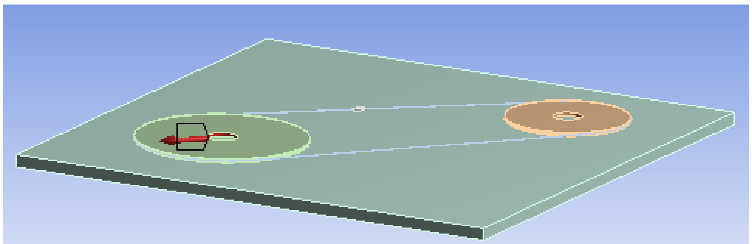
Force of 28 N was applied to ensure that the wire is under tension all the time during the test. Constrains were set; the wire motion was controlled to be in X-Y direction only, and not to run away from the pulleys, and the movable indicator was adjusted to move only in X direction, Figure 4. The chosen fatigue details used in FE model are summarized in Table 2.



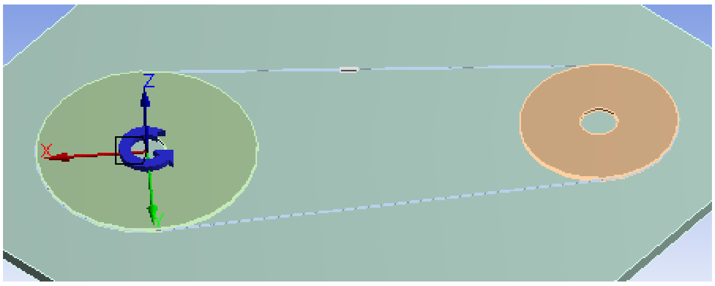
(a) Wire constrain to move in X-Y direction only.



(b) Movable indicator constrain to move in X-direction only.



(c) Force direction.



(d) Rotational direction of the drive pulley.

Fig.4. Setting of the model constrains.

Table.2. Fatigue details of the finite element model.

Fatigue details	**value**
Fatigue strength factor (kf)	0.78
Type of loading	Fully reversed
Display time	End time
Analysis type	Strain life
Mean stress theory	Morrow
Stress component	Max shear

Results

1- Fatigue test

The strain occurred in wire during fatigue test can be calculated as follow.

ε (Strain) = d (wire diameter in mm)/D (bending diameter in mm).

Where the wire diameter is 0.8 mm.

Table3 summarizes the fatigue test results. Figure 5 represents the relation between strain and fatigue life for tested wire using different pulley diameters.

Table.3. Fatigue life of the tested wire in cycles.

Bending diameter, (mm)	**Strain (ε)**	**N = fatigue life, cycles**
75	0.0107	13425
		14961
		16646
45	0.018	9490
		11796
		10487
35	0.0229	4097
		4488
		4612

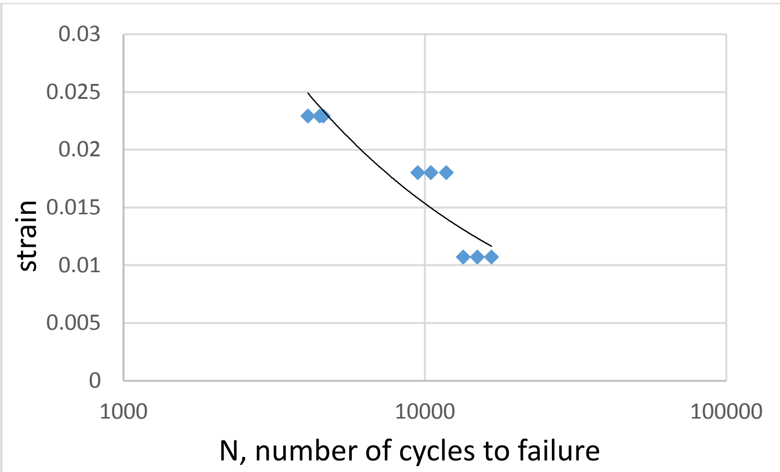


Fig.5. Relationship between fatigue life and strain

2- Finite element analysis results

Fatigue life

Table 4, summarizes the fatigue life obtained from FE Modeling for 35, and 45 bending diameters. Table 5, summarizes Von-Mises parameters, such as equivalent stress, equivalent strain, equivalent plastic strain, and total strain obtained from FE modeling for the same bending diameters.

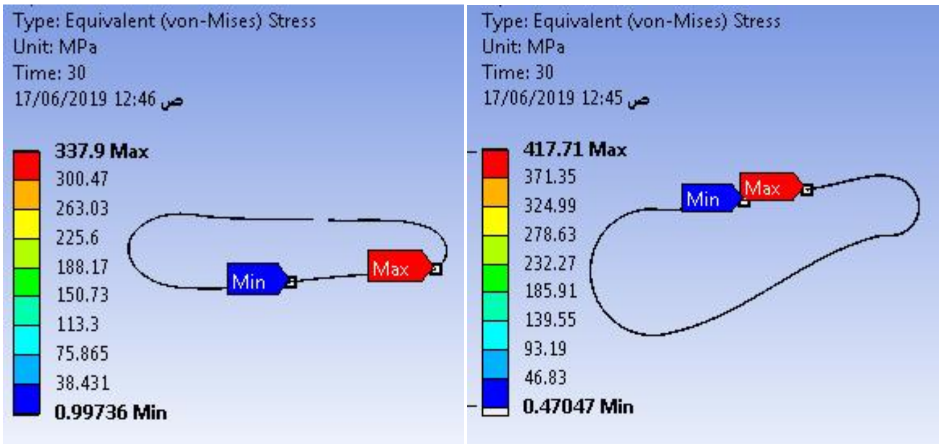
Table.4. fatigue life obtained from the finite element model.

Diameter (mm)	**Fatigue life (cycle)**
45	10759
35	4232

Table.5. Von-Mises parameters results.

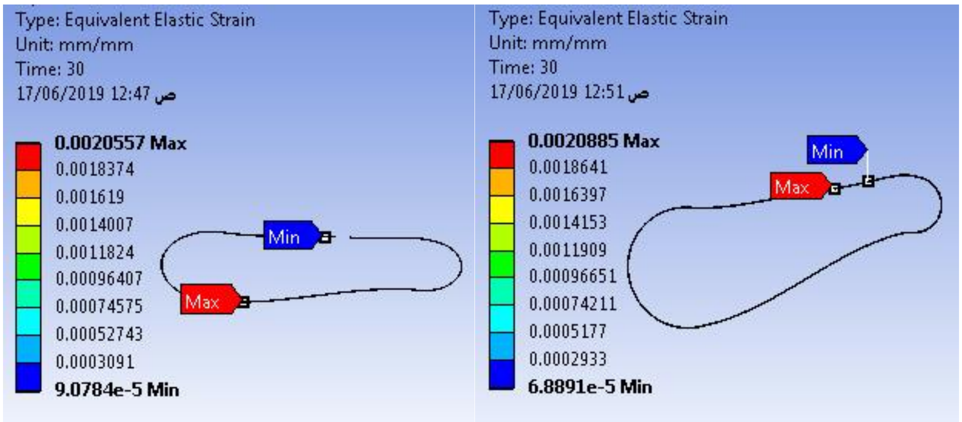
Bending Diameter (mm)	35 mm		45 mm	
	Minimum	Maximum	Minimum	Maximum
Average Equivalent Stress, MPa	0.47047	417.71	0.99736	337.9
Equivalent Elastic Strain	6.8891e-005	2.0885e-003	9.0784e-005	2.0557e-003
Equivalent Plastic Strain, mm	0	6.7661e-002	0	6.0595e-002
Equivalent Total Strain, mm	6.8891e-005	6.9414e-002	9.0784e-005	6.2288e-002

The results of Von-Mises parameters are shown in Figures (6:9).



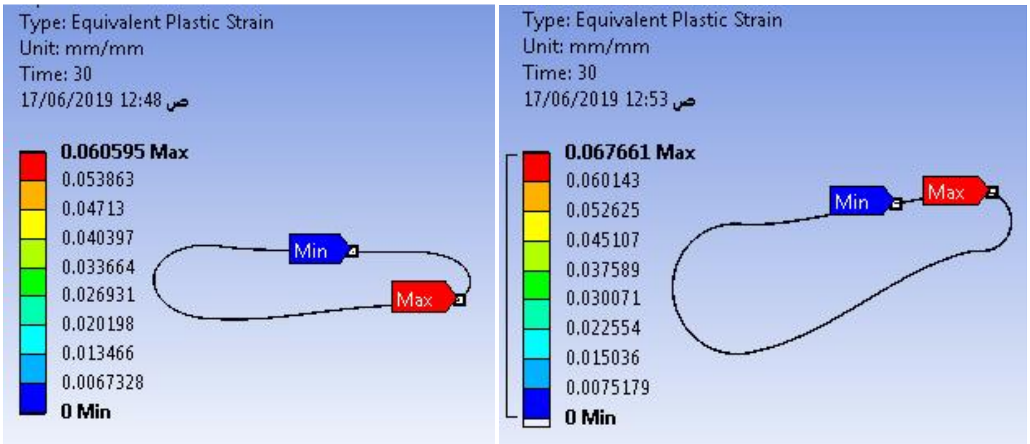
(a) Bending diameter 35 mm. (b) Bending diameter 45 mm.

Fig.6. Equivalent (Von-Mises) Stress



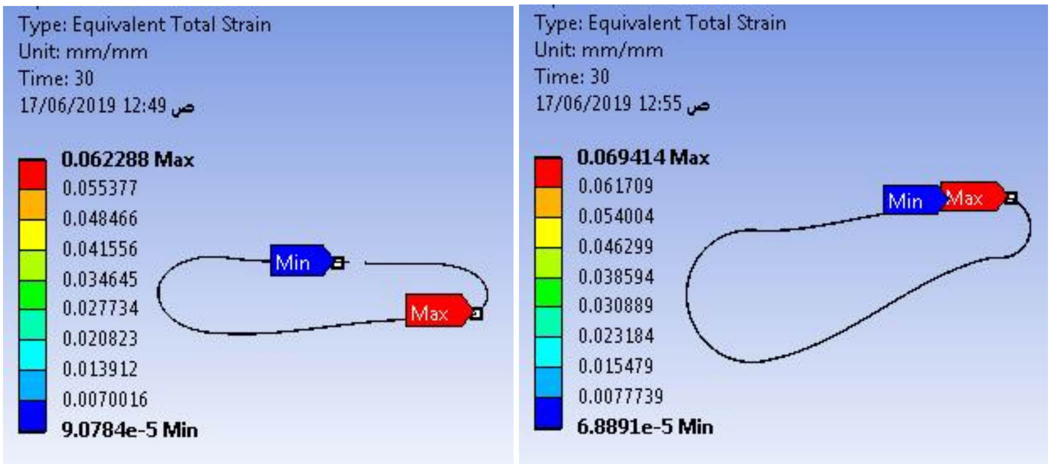
(a) Bending diameter 35 mm. (b) Bending diameter 45 mm.

Fig.7. Equivalent (Von-Mises) elastic strain



(a) Bending diameter 35 mm. (b) Bending diameter 45 mm.

Fig.8. Equivalent plastic strain



(a) Bending diameter 35 mm. (b) Bending diameter 45 mm.

Fig.9. Equivalent total strain

Discussion

Table 6 summarizes the comparison between the fatigue life obtained from experimental fatigue tests and from the Finite Element Method. From these results, it can be noticed that the fatigue life values obtained from Finite Element Method are very close to the experiment results with an acceptable % of deviation.

Table.6. Comparison of experiment and FEM fatigue life results.

Diameter, (mm)	Average Fatigue Life (Cycle) Experiment	Fatigue Life (Cycle) FEM	Difference	Deviation%
45	10591	10322	269	2.5415
35	4399	4232	167	3.7936

Conclusion

Fatigue life of steel wire has been studied using FEM by ANSYS program as well as conducting fatigue tests using fatigue setup.

From the results obtained from this work, the following conclusions can be drawn.

1- Fatigue test setup has been designed and constructed in order to conduct experimental fatigue tests for steel wire.
2- Fatigue setup has been used successfully to obtain the fatigue life of steel wire using different pulley diameter of 35, 45, and 75 mm.
3- Using smaller bending diameter achieved a higher values of Von-Mises equivalent stress, equivalent strain, equivalent plastic strain, and total strain.
4- Using smaller bending diameter resulting in reducing the fatigue life due to increasing the bending strain and bending stress.
5- The results obtained from Finite Element model were in a good agreement with the experimental results with an acceptable % of deviation.

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