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Assessment of steel wire's fatigue life using finite elements modelling and experimental testing

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Abstract. Various applications consist of wire rope as one of their most important construction parts. Wire ropes formed of three parts as basis; wires, strands and core. to get a deep understanding of wire ropes and their mechanical properties, it is essential to study their main part; the wire. For this reason, steel wire has been studied in this work to get its fatigue life as the number of cycles to failure using finite element modeling. FEM results have been verified using experiments; Flex tester machine and fatigue apparatus which is created and structured for this study. Outcomes have proved that using of bigger bending diameters resulted in increasing the fatigue life of the steel wire and vice versa. It is noticed that the FEM results have small and reasonable value of deviation comparing to the experimental results. Other mechanical properties of the steel wire have been obtained from FEM such as; equivalent Von-Mises stress, equivalent elastic strain, equivalent plastic strain and equivalent total strain.

1. Introduction

Wire ropes are considered as an essential element for many applications such as elevators, bridges, cranes and mining [1-3]. Multiple researches have been undertaken to examine the wire ropes and their mechanical specifications, performance, drawbacks and development of them during various conditions and using different forms of tests. Mechanical properties of the wire rope under tension have been studied by Juan Wu [4] using FEM. The results have been verified using theoretical analysis and experiments. Gerdemeli, et.al. [5], used FEM to estimate the fatigue life of one simple strand that has been projected to axial force, and several parameters such as, force, helix angle and length of the strand have been studied. While, Finite Element Modeling has been used by Sung-Yun Kim and Phill-Seung Lee [6], to get the mechanical properties of the wire rope using axial and transverse forces. Wire ropes have three fundamental components; wires, strands and core, Figure 1. Wires are the major parts of the wire ropes. These wires spirally convoluted to form the strands. Strands spirally convoluted around the core which is the interior part to form the final wire rope geometry [6]. It is significant to study the wires as they are the basic construction parts.

Figure 1.Wire rope construction [6].

Several types of tests such as; tension and fatigue have been conducted to evaluate the performance of the wire ropes [7-8]. Fatigue life and other mechanical characteristics could be estimated using finite element modeling. FEM basically depends on splitting the part concerned with the study into many small divisions each of them has to be studied individually. Applied forces, displacements and other factors that can affect the mechanical properties have to be studied as well [9-12]. The intended properties can be acquired by solving the stiffness matrix (1).

$$\{F\} = [K] * \{U\}. \quad (1)$$

Where, {F} is the applied forces array, [K] is the stiffness matrix, and{U} is the displacement array.

2. Experimental work

There are two types of experiments have been conducted to assess the fatigue life of steel wire similar to that used in elevator wire ropes. Fatigue life of the steel wire has been detected as the number of cycles that the wire can withstand till failure occurred. Tests have been done using three test specimens at least for each bending diameter for both types of tests. The two types of tests have been conducted using the Flex tester machine, figure 2 and the fatigue apparatus, figure 3 that has been designed and constructed for this study.

2.1 Flex tester machine

This machine is located at the Faculty of engineering, Ain Shams University. Flex tester machine consists of mandrel, supporting pulleys, counter, switch button, and two clips. It depends on bending the tested wire on the mandrel of two cylinders with different bending diameters (2, 4, 6, 8, 10, 12.7, 19.4 & 25) mm that have been used to evaluate the fatigue behavior of the steel wire with different strain values. The two ends of the steel wire have been fixed using two clips. The steel wire tested has 0.8 mm diameter

Figure 2. Flex tester machine.

2.2 Fatigue Test Setup:

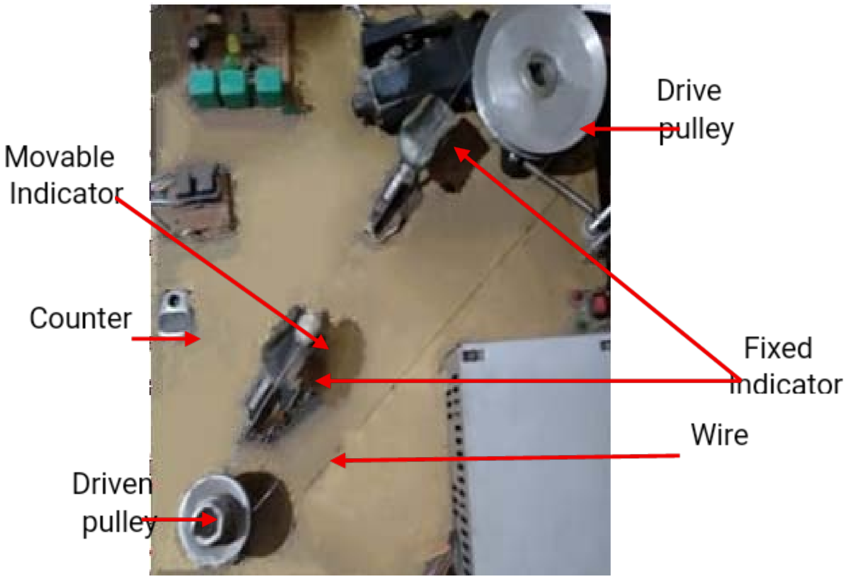
This fatigue test setup has been designed and constructed for this study. Fatigue setup consists of drive and driven pulleys, two fixed indicators, movable indicator, counter, steel spring, motor, and power supply. It relies on the notion of the elevator wire ropes that expose to tension and bending over drums. Mainly, the steel wire has to be bent on the two pulleys with center distance between them equals to 272 mm, two ends of the wire have to be grasped using the movable indicator which has two bolts to make sure that the wire is properly fixed and tied. The drive pulley with the diameter of 133 mm gets its rotational motion from the motor connected to it. Due to the friction between the pulleys and the wire, the rotational force transmits to the wire which consequently rotates around the pulleys. The two fixed indicators refer to the start and the end of the stroke and send signals when the movable indicator presses on one of them to reverse the direction of motion.

Different diameters (35, 45 & 75) mm of the driven pulleys have been used to evaluate the fatigue behavior of the steel wire with different strain values.

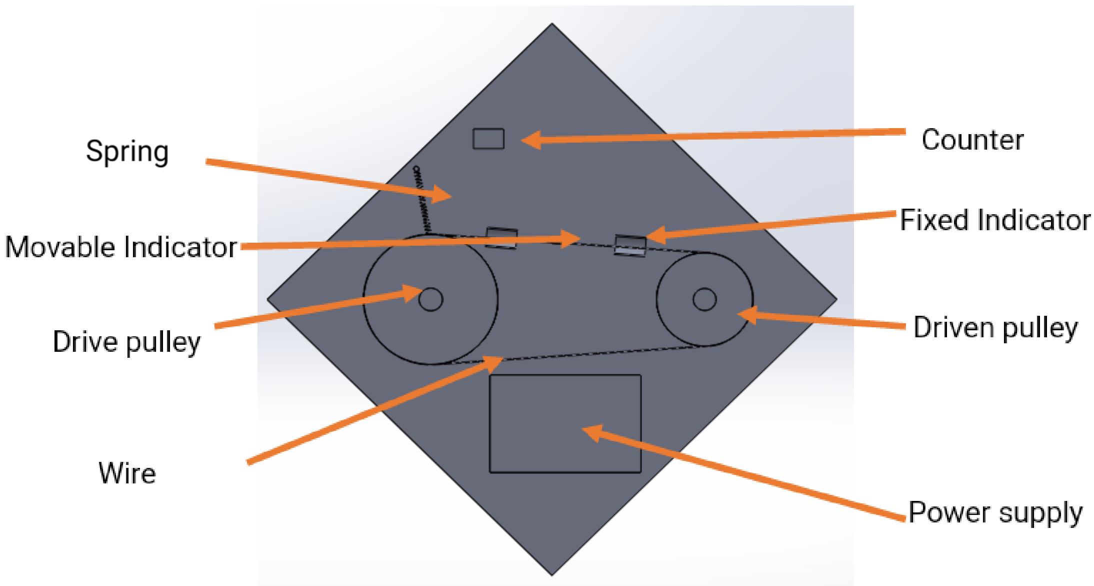
To guarantee that the wire will be under tension, a steel spring with calculated force has been used. The spring force has been calculated using different weights with different spring elongations, and then substituted in the equation (2) to get the spring constant. Once the spring constant is calculated, the spring force in return can be calculated using spring constant with the actual elongation of the spring when it has been installed on the machine and by substitution in the same equation.

$$F = k \times \Delta x. \qquad (2)$$

Where, F is the spring force (N), k is the spring constant (N/mm), Δx is the spring elongation (mm).



(a)



(b)

Figure 3. (a)The fatigue test setup. (b) Schematic drawing of the fatigue setup.

3. Finite element analysis

SOLID WORKS has been used for drawing of the models geometry and ANSYS WB program has been used for analyzing of finite element models. Two models have been set, the Flex tester machine model and the fatigue apparatus model. The model material's specifications have been obtained from tension test that has been done on the steel wire. 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.

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3.1 Flex tester machine

Only three diameters have been used to obtain the fatigue behavior using finite element modeling due to time concern. These diameters were 4, 6 and 8 mm which resulted in strain of 0.2, 0.133 and 0 1 respectively. Model joints have been set using two types, fixed joint for the machine base and rotational joints for all pulleys.

Contacts of the model have been adjusted to be frictionless between the wire and the mandrel, rough between the wire and the pulleys 1 & 2 and friction between the wire and the pulleys 3 & 4 with the symmetric behavior as the pure penalty formulation and normal nodal from contact as the detection method.

Meshing of the model has been determined to be 0.2 mm element sizing and inflation as summarized in Table 1 for the wire and the mandrel areas of contact, 2.5 mm element sizing for the wire and the pulleys 1 & 2 areas of contact, 0.5 mm element sizing for the wire and the pulleys 3 & 4 areas of contact and 1.5 mm face sizing for the wire. Number of nodes and elements are summarized in Table 2.

Table 1.Inflation details.

Mesh type	Geometry	Boundary	Inflation Option	Transition Ratio	Maximum Layers	Growth Rate
Inflation	Wire	1 Face (Symmetry Surface)	Smooth Transition	Default (0.272)	5	1.2

Table 2.Number of nodes and elements used in FE modeling for flex tester machine.

No.	Part name	Number of nodes Bending diameter = 4 mm	Number of nodes Bending diameter = 6 mm	Number of nodes Bending diameter = 8 mm	Number of elements Bending diameter = 4 mm	Number of elements Bending diameter = 6 mm	Number of elements Bending diameter = 8 mm
1	Wire	11570	11748	11996	5675	5728	5822
2	mandrel	7602	13990	21799	4184	7899	12610
3	Pulley 1	5206	5206	5206	858	858	858
4	Pulley 2	2200	2200	2200	400	400	400
5	Pulley 3	16546	16546	16546	3240	3240	3240
6	Pulley 4	8812	8812	8812	1719	1719	1719
7	Base plate	962	962	962	117	117	117
8	Total	52898	59464	67521	16193	19961	24766

Motion of the model parts have been restricted as shown in figure 4. The wire has been limited to move only in X-Y direction because not to move away from the pulleys. The mandrel has been limited to move only in Y direction. Force of 0.1 N has been applied on the two terminals surfaces of the wire.

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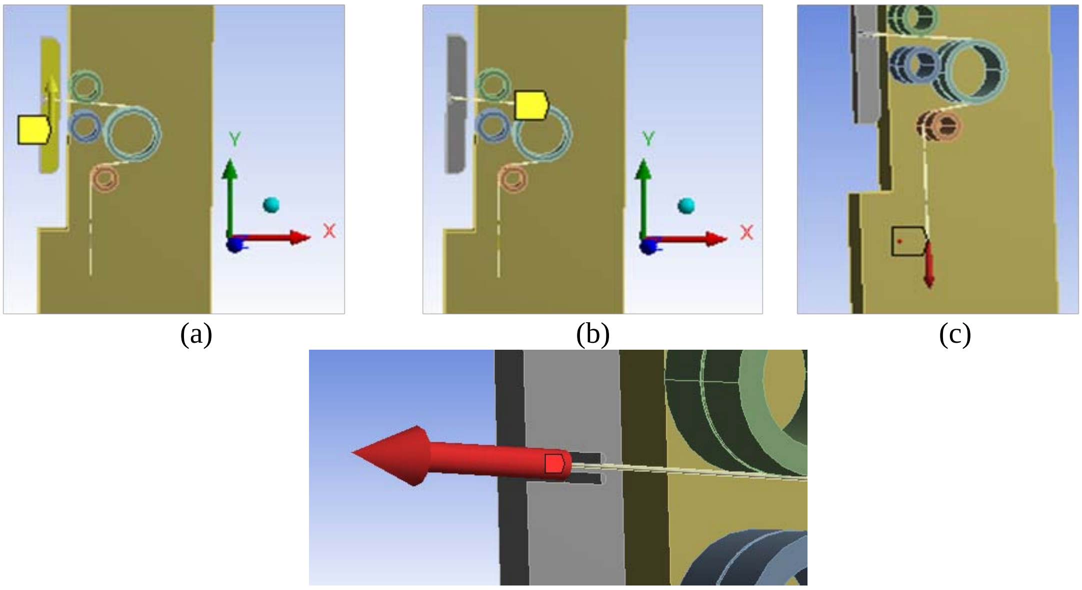

(a) (b) (c)

(d)

Figure 4. Setting of the model constrains. (a) Wire constrain to move in X-Y direction only. (b) Movable indicator constrains to move in X-direction only. (c) Force direction. (d) Rotational direction of the drive pulley.

Fatigue details of the model have been chosen to be 0.88 as the Fatigue strength factor (k_f), Fully reversed loading type (i.e. stress ratio (R) is equal to -1), Strain life as the analysis type, Morrow as the Mean stress theory and Max shear as the stress component.

3.2 Fatigue Test Setup

Only two diameters (35 & 45) mm have been used to obtain the fatigue behavior using finite element modeling due to time constrain. Model joints have been set using three types, fixed joint for the machine base, translational joint for the movable indicator and rotational joints for both drive and driven pulleys. Contacts of the model have been adjusted to be bonded between the wire and the movable indicator and rough between the wire and the pulleys with the symmetric behavior as the pure penalty formulation and normal nodal from contact as the detection method.
Meshing of the model has been determined to be 2.5 mm contact sizing for the wire and the pulleys' areas of contact, and 2.5 mm sweep method for the wire. Number of nodes and elements are summarized in Table 3.

Table 3.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

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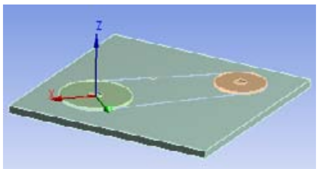
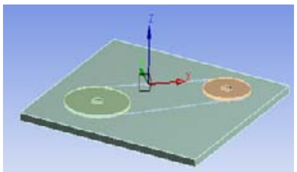
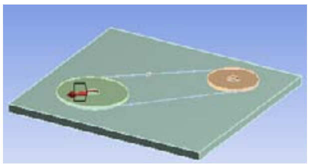
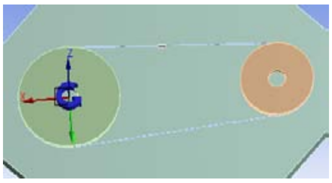
Motion of the model's parts have been restricted as the following, Figure 5. The wire has been limited to move only in X-Y direction to avoid wire slipping. The movable indicator has been limited to move only in X direction. To ensure that the wire is under tension all the time, a force of 28 N has been applied. The drive pulley has been set to rotate counter clockwise.

(a) (b)



(c)



(d)

Figure 5. Setting of the model constrains. (a) Wire constrain to move in X-Y direction only. (b) Movable indicator constrains to move in X-direction only. (c) Force direction. (d) Rotational direction of the drive pulley.

Fatigue details of the model have been chosen to be 0.78 as the Fatigue strength factor (kf), the strain ratio varies from 0.03 to 0.06 respectively according to bending diameter, Strain life as the analysis type, Morrow as the Mean stress theory and Max shear as the Stress component.

4. Results

4.1. Experimental Fatigue test

The resulted strain from both types of fatigue tests have been calculated using equation (3).

ε (Strain) = d (wire's diameter in mm)/D (bending diameter in mm). *(3)*

4.1.1 Flex tester machine. Table 4, summarizes the fatigue life obtained from FE Modeling for Flex tester machine of different bending diameters. Figure 6 represents the relation between strain and fatigue life for tested wire using different pulley diameters.

Table 4. Fatigue life of the tested wire in cycles for flex tester machine.

Bending Diameter, (mm)	Strain = (ε)	N = fatigue life, cycles
2	0.4	1805
4	0.2	2014
6	0.13	2250
8	0.1	2484
10	0.08	2700
12.7	0.063	10612
19.4	0.04	12505
25	0.032	16726

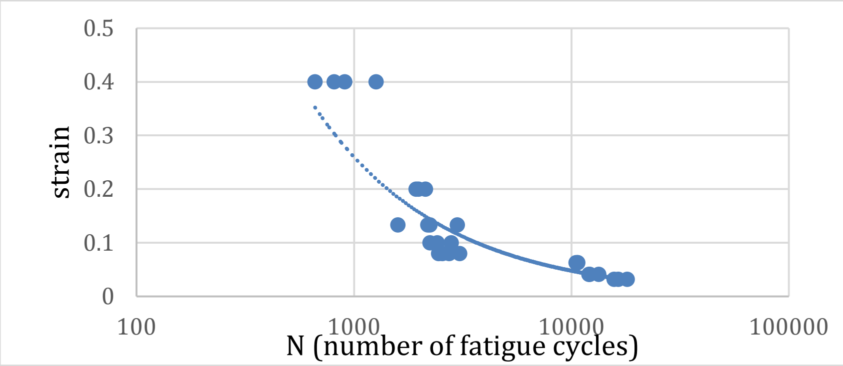


Figure 6.Relationship between fatigue life and strain for the flex tester machine.

From the previous results; it is noticed that using bending diameter of 2 mm which is the smallest bending diameter among the other values (2.5 times the wire diameter of 0.8 mm) has given the minimum fatigue life of the all results due to the higher value of strain and hence the stress applied on tested wire. Fatigue life values increased gradually with small values by increasing the bending diameter till reach the bending diameter of 10 mm which is 12.5 times the wire diameter. At this point the fatigue life increased to be 1.5 times of fatigue life resulted from using of 2 mm bending diameter. Then, the fatigue life increased relatively with high values by using bigger bending diameters from 12.7 mm which is near to 16 times of the wire diameter till 25 mm which is 31 times the wire diameter. Using of the biggest bending diameter which is 16 times of the wire diameter and 12.5 times the smallest one has given fatigue life of 9.3 times the value that resulted from using of the smallest bending diameter which is 2.5 times the wire diameter.

4.1.2 Fatigue Test Setup. Table 5 summarizes the fatigue life obtained from FE Modeling for fatigue apparatus of 4, 6 and 8 bending diameters. Figure 7 represents the relation between strain and fatigue life for tested wire using different pulley diameters.

Table 5.Fatigue life of the tested wire in cycles for fatigue test setup.

Bending diameter, (mm)	Strain (ε)	N = fatigue life, cycles
75	0.0107	15010
45	0.018	10591
35	0.0229	4399

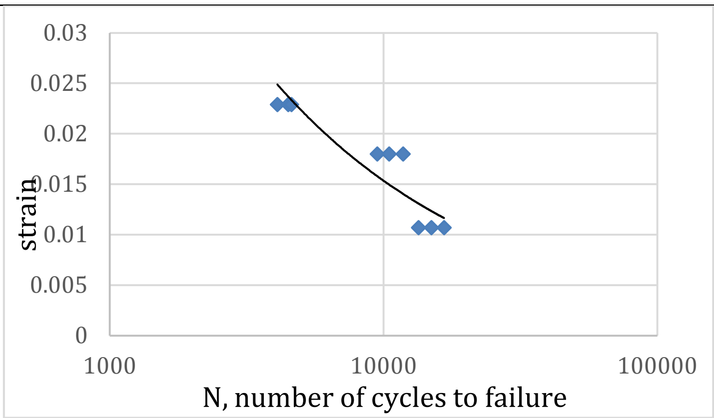


Figure 7. Relationship between fatigue life and strain for the fatigue test setup.

From the previous results; it is noticed that using of 35 mm as a bending diameter which is the smallest bending diameter among the other values (near to 44 times the wire diameter of 0.8 mm) has given the minimum fatigue life of the all results. Fatigue life values increased gradually by increasing the bending diameter till reach to 75 mm which is the biggest bending diameter that is near to 94 times the wire diameter and 2.1 times the smallest bending diameter which recorded the maximum fatigue life of the all results. The fatigue life resulted from using of the biggest bending diameter reached to be 3.4 times of using the smallest one.

Finally; it can be concluded that decreasing the bending diameter has a great effect on fatigue life, as it decreased sequentially due to the higher value of strain and hence the stress applied on tested wire.

4.2 Finite element analysis results

4.2.1 Fatigue life. Table 6 and 7 summarize the fatigue life obtained from FE Modeling for Flex tester machine and for fatigue test setup respectively for different bending diameters in mm.

Table 6. Fatigue life obtained from the finite element model of the flex tester machine.

Diameter (mm)	Fatigue life (cycle)
4	1967
6	2052
8	2206

Table 7. Fatigue life obtained from the finite element model.

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

From the previous results; it is noticed that the resulted fatigue life from both finite element models increased by increasing the bending diameter. Which is in a good agreement with experimental results.

4.2.2 Von-Mises parameters. Tables 8 and 9, summarize Von-Mises parameters, such as equivalent stress, equivalent strain, equivalent plastic strain, and total strain obtained from FE modeling for the flex tester machine and fatigue apparatus respectively for different bending diameters mentioned before.

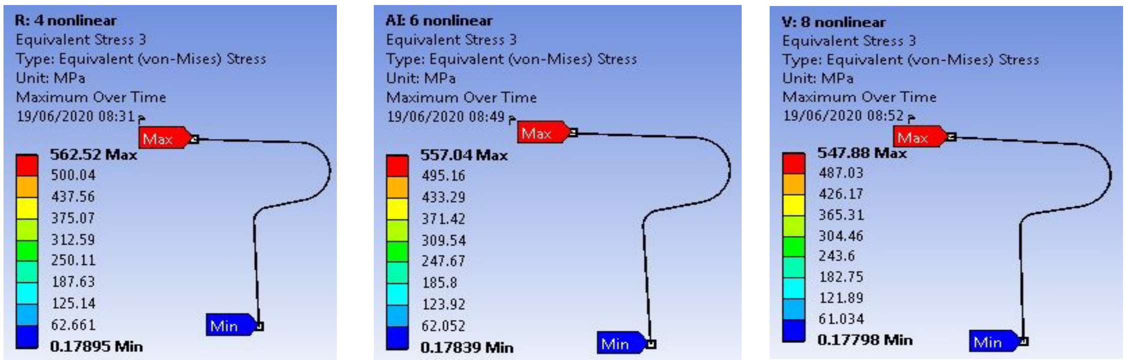
Table 8.Von-Mises parameters results.

Bending Diameter (mm)	4 mm		6 mm		8 mm	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Average Equivalent (Von-Mises) Stress, MPa	0.17895	562.52	0.17839	557.04	0.17798	547.88
Equivalent (Von-Mises) Elastic Strain, mm/mm	8.9935×10^{-7}	2.8133×10^{-3}	8.9433×10^{-7}	2.7862×10^{-3}	8.9405×10^{-7}	2.7435×10^{-3}
Equivalent Plastic Strain, mm	0	0.10357	0	9.5594×10^{-2}	0	7.9814×10^{-2}
Equivalent Total Strain, mm	8.9935×10^{-7}	0.10557	8.9433×10^{-7}	9.7542×10^{-2}	8.9405×10^{-7}	8.165610^{-2}

Table 9.Von-Mises parameters results.

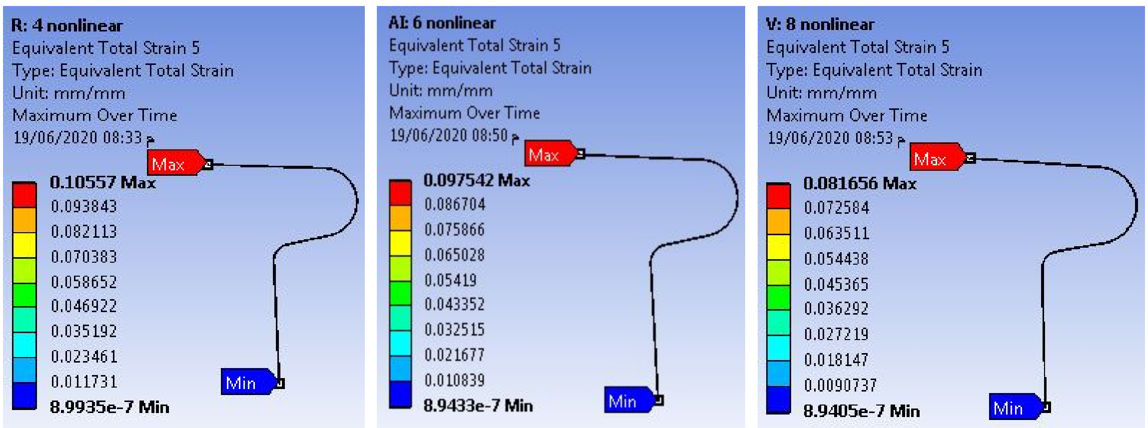
Bending Diameter (mm)	35 mm		45 mm	
	Minimum	Maximum	Minimum	Maximum
Average Equivalent Stress, MPa	0.47047	417.71	0.99736	337.9
Equivalent Elastic Strain	6.8891×10^{-5}	2.0885×10^{-3}	9.0784×10^{-5}	2.0557×10^{-3}
Equivalent Plastic Strain, mm	0	6.7661×10^{-2}	0	6.0595×10^{-2}
Equivalent Total Strain, mm	6.8891×10^{-5}	6.9414×10^{-2}	9.0784×10^{-5}	6.2288×10^{-2}

The results of Von-Mises parameters for the flex tester machine model are shown in figures 8 and 9.



(a) (b) (c)

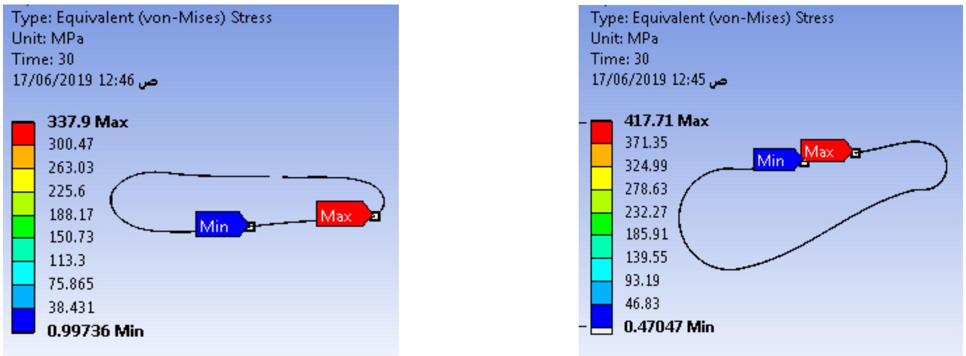
Figure 8. Equivalent (Von-Mises) stresses (a) Bending diamster 3mm (b) bending diameter 6 mm (c) bending diameter 8 mm



(a) (b) (c)

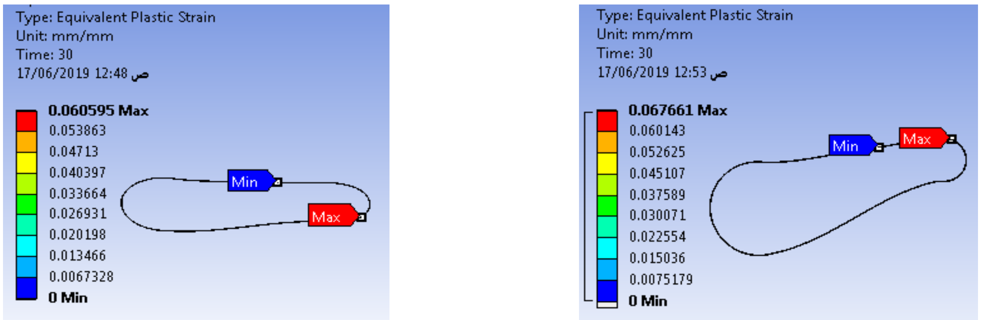
Figure 9. Equivalent (Von-Mises) totalstrainstresses (a) Bending diamster 3mm (b) bending diameter 6 mm (c) bending diameter 8 mm

The results of Von-Mises parameters for the fatigue test setup model are shown in figures 10 and 11.



(a) (b)

Figure10. Equivalent (Von-Mises) Stress. (a) Bending diameter 35 mm. (b) Diameter 45 mm.



(a) (b)

Figure 11.Equivalent plastic strain.(a) Bending diameter 35 mm. (b) Bending diameter 45 mm.

From the above results; it can be seen that the resulted Von-Mises parameters decreased by increasing the bending diameter for both finite element models.

Table 10 summarizes the comparison between the fatigue life obtained from experimental fatigue tests and from the FEM for the flex tester machine. While table 11summarizes the comparison between the fatigue life obtained from experimental fatigue tests and from the FEM for the fatigue test setup.

Table 10. Comparison of experiment and FEM fatigue life results for flex tester machine.

Diamete r, (mm)	Average Fatigue Life (Cycle) Experiment	Fatigue Life (Cycle) FEM	Differenc e	Deviatio n %
4	2014	1967	47	2.33
6	2250	2052	198	8.8
8	2484	2206	278	11.19

Table 11. Comparison of experiment and FEM fatigue life results for fatigue test setup.

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

From Tables 10 and 11, it can be concluded that the results obtained from the finite element models are fair and have reasonable drift percentage compared to the results obtained experimentally from conducting fatigue tests using both testing devices, flex tester machine and the fatigue apparatus.

5. Conclusion

Fatigue life of steel wire has been studied using FEM by ANSYS program as well as conducting fatigue tests using flex tester machine and fatigue apparatus. Fatigue test setup has been created and structured in order to conduct experimental fatigue tests for steel wire. Flex tester machine has been used successfully to obtain the fatigue life of steel wire using different bending diameters of 2, 4, 6, 8, 10, 12.7, 19.4 and 25 mm. Fatigue apparatus has been used successfully to obtain the fatigue life of steel wire using different pulley diameter of 35, 45, and 75 mm.
From the results obtained from this work, the following conclusions can be drawn.

- Decreasing the bending diameter of Flex tester as well as the Fatigue Test Setup has a great effect on fatigue life, as it decreased sequentially due to the higher value of strain and hence the stress applied on tested wire.
- Using of biggest bending diameter that is 16 times the wire diameter increased the fatigue life by 9.3 times compared to using of the smallest diameter, which is 2.5 times the wire diameter.
- Using of biggest bending diameter of Fatigue Test Setup that is 94 times the wire diameter increased the fatigue life by 3.4 compared to using of the smallest one, which is 44 times the wire diameter.
- Using smaller bending diameter achieved a higher values of Von-Mises equivalent stress, equivalent strain, equivalent plastic strain, and total strain.

- Using smaller bending diameter resulted in reducing the fatigue life due to the increase of the bending strain and bending stress.
- The results have been obtained from Finite Element model were in a good agreement with the experimental results with an acceptable percentage of drift.

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