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Failure analysis of a centrifugal pump shaft experiencing plastic deformation using the exact and finite element method

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Abstract. An eight-stage centrifugal pump that was used in the oil and gas industry had plastic deformation on the shaft because of the torque load. Thus, this study was aimed at analyzing the shear stress that occurred on the shaft by an exact and finite element method. The shaft, with a length of 1.5 m and diameter of 0.05 m, was made of SUS 304 material. From the exact and finite element analysis results, the shear stress that occurred on the shaft was higher than the shear stress of the shaft material. Therefore, the pump shaft became plastically deformed and twisted. The results of the finite element analysis showed that the torque, shear stress, and strain were increased when the twist angle on the pump shaft was increased.

1. Introduction

The shaft is one of the components that transmit power by a rotary or axial movement. The load applied on the shaft varies during use, namely, in terms of the tension, torsion, compression, bending, or a combination of these [1,2]. During its operation, the shaft often suffers failure and many researchers have studied the causes of this failure.

A steel shaft has much greater strength and stiffness than one made of a composite material [3]. A torsional load that is not uniformly distributed on the shaft can produce shear stress leading to deformation and may damage some parts of the shaft [4]. The torque load varies with the rotational speed of the shaft [5].

Heat treatment on a welded shaft can protect the shaft from fatigue failure [5-7]. The non-uniform hardness of the shaft surface is one of the causes of shaft failure [8]. Many parameters can causes shaft failure, such as an incorrect fillet radius on the shaft [9], the disproportionate fillet radius on segments of the shaft [10]; a chemical composition that does not meet the standard will affect the mechanical properties [11], improper installation, wrong choice of material, and poor maintenance [12].

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This study was aimed at analyzing the stress on an eight-stage centrifugal pump shaft that had deformed plastically. This type of centrifugal pump is used in the oil and gas industry to pump diethanolamine (DEA) fluid to decrease the H_2S and CO_2 content of natural gas. This study used the exact and finite element analysis (FEA) methods to analyze the shear stress and strain that occurred on the twisted centrifugal pump shaft [13].

2. Method

2.1. Material Properties

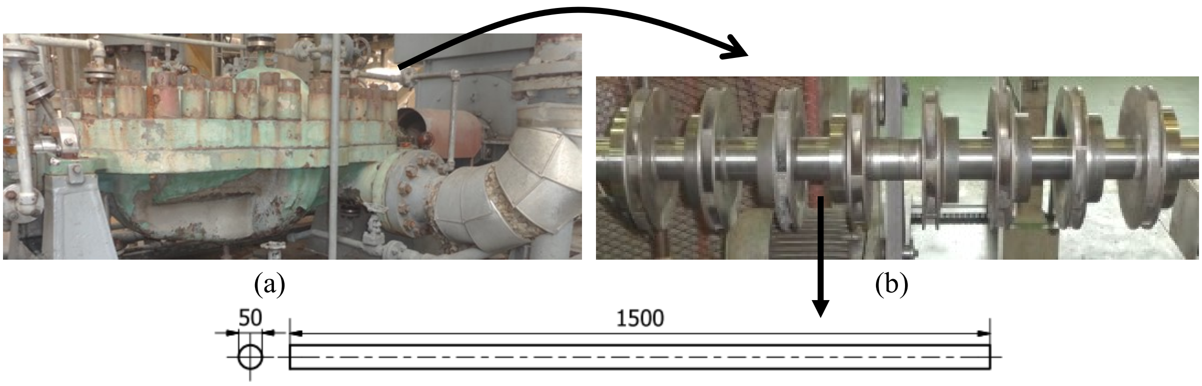
The shaft of the eight-stage centrifugal pump was made from SUS 304/ASTM 240 material [14]. Table 1 shows the mechanical properties of this steel.

Table 1. Mechanical properties of ASTM A240.

No	Description	Value
1	Density, ρ	8000 kg/m^3
2	Elastisity Modulus, E	193 - 200 GPa
3	Shear Modulus, G	83 GPa
4	Maximum Tensile Strength, σ_u	505 MPa
5	Yield Strength, σ_y	215 MPa
6	Poisson Ratio, ν	0.29
7	Shear Strength, τ_a	42 MPa

2.2. Centrifugal Pump Shaft

80% to 90% of the oil and gas industry uses a centrifugal pump [15]. Figure 1 shows the centrifugal pump used in the oil and gas industry that was analyzed in this study. For the FEA, the pump shaft was modelled using computer-aided design software.



(c)

Figure 1. Eight-stage centrifugal pump: (a) lean DEA G3X03 pump used in the oil and gas industry; (b) maintenance of centrifugal pump shaft; (c) pump shaft model.

2.3. Exact and Finite Element Analyses

The purpose of the exact analysis was to measure the torque load and shear stress that occurred on the centrifugal pump shaft. After the exact analysis, a FEA was carried out to compare the results with the data from exact analysis.

The following steps were taken to analyze the centrifugal pump shaft by means of a FEA: (a) torque load of 500 Nm, 1000 Nm, 1500 Nm, 2000 Nm, 2500 Nm, 3000 Nm, 3500 Nm, 4000 Nm, 4015 Nm and 4050 Nm were applied periodically to the shaft to analyze the twist angle that occurred in each torque load condition, and (b) a twist angle of about 8^O was applied to the shaft to analyze the torque, shear stress, and strain that occurred.

3. Results And Discussion

3.1. Exact Analysis

The purpose of the exact analysis was to analyze the torque load that occurred on the shaft by using Eq. (1) [16]. In this case, the shaft was twisted by about 8^O. The shaft length L was about 1.5 m and the diameter D was about 0.05 m. The shear modulus G of the SUS 304 material was about 83 x 10^9 N/m^2.

$$\theta = \frac{L \cdot T}{I_p \cdot G} \quad (1)$$

$$T = 4542\ Nm$$

Eq. 2 was used to calculate the maximum shear stress that occurred on the shaft [16]. The torque T from Eq. 1 was about 4542 Nm. The radius of the shaft r was about 0.025 m, while I_p was the inertia moment of shaft surface.

$$\tau_{shaft} = \frac{T \cdot r}{I_p} = 186\ MPa \quad (2)$$

Based on the failure theory, Eq. (3) and Eq. (4) were used to analyze the shear stress using the von-Mises and Tresca methods [16]. The yield stress σ_y of the SUS304 material was about 215 MPa.

- Von Mises $$\tau_{oct} = \frac{\sigma_y}{3}\sqrt{2} = 101{,}352\ MPa \quad (3)$$
- Tresca $$\tau_{max} = \frac{\sigma_y}{2} = 107{,}5 MPa \quad (4)$$

From the exact analysis, the shear stress that occurred on the shaft was higher than the shear stress of the shaft material (table 1). The shear stress that occurred on the shaft was about 164 MPa and the shear stress of the material was about 42 MPa. Therefore, the shaft was deformed plastically. The shear stress that was calculated using Eq. (1) was greater than the shear stress based on von Mises and Tresca methods.

3.2. Finite Element Analysis

3.2.1. Modelling shaft by Torque Load

In this analysis, a torque load was applied to the shaft periodically to twist the shaft by up to 8^O. Figure 2 shows the shaft that was analyzed by FEA.

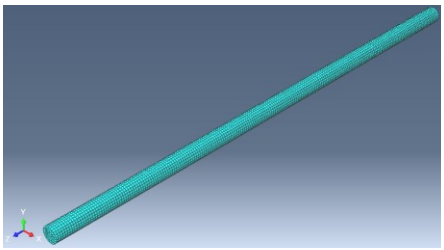


Figure 2. Pump shaft analyzed by FEA.

The twist angle that occurred were dissimilar depending on the torque load that was applied to the shaft. The torque increased with an increase in the applied twist angle. Figure 3 shows the relationship between the torque load and the twist angle. The shaft was twisted for about 8^{O} if the torque load was 3900 Nm.

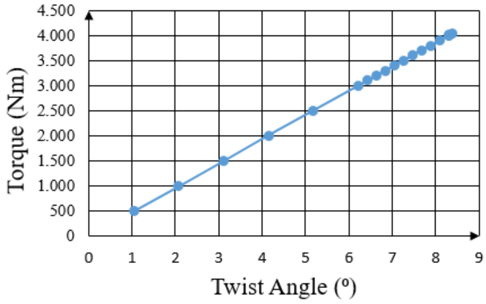


Figure 3. A curve showing the relationship between torque load and the twist angle.

3.2.2. Modelling Shaft by Twisted Angle

In this analysis, a twist angle of about 8^{O} was applied to the shaft. The shear stress that occurred was about 255 MPa and the strain was about 0.034. The shear stress and strain increased with an increase in the twist angle on the pump shaft. As the twist angle increased, there was an increase in the shear stress and strain, as shown in Figure 4.

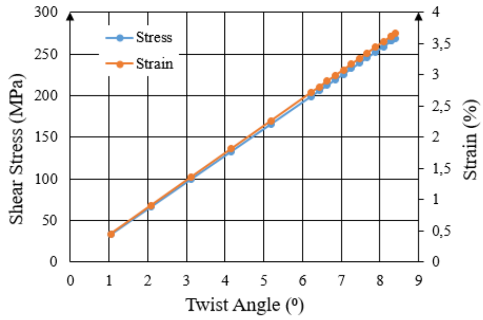
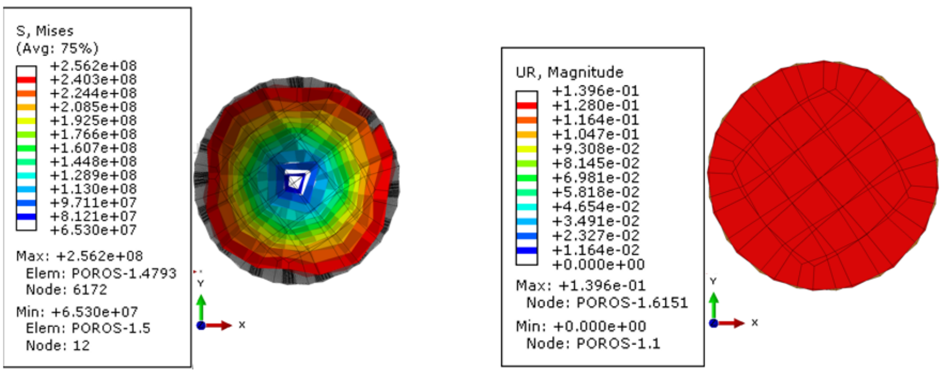


Figure 4. A curve of shear stress and strain against twist angle.

Figure 5 show details of the shaft surface section with the torsion load. Figure 5 (a) shows the shear stress distributed on the shaft. When the twist angle reached 8^{O}, the shear stress that occurred at the outer shaft section was greater than the shear stress near the shaft axis. Figure 5 (b) shows the strain that occurred when the torque load was applied to the shaft.



(a) (b)

Figure 5. The condition of the shaft when plastic deformation occurred:
(a) change of stress; (b) change of strain.

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Figure 6 shows the shear stress for each node of the shaft obtained by the FEA. The nodes in the red box, which were a part of the shaft that had maximum shear stress, were analyzed. It appeared that each observed node had a different shear stress value. Figure 7 shows the curve of the torque and shear stress to the twist angle that occurred on the shaft. Increasing the twist angle led to an increase in the torque and shear stress that occurred on the shaft. When the twist angle reached about 8^{O}, the shear stress that occurred on the shaft was about 255 MPa and the torque was about 3900 Nm. Both the exact and FEA revealed that the shear stress that occurred on the shaft was higher than the shear stress of the shaft material (table 1). Therefore, the results showed that the shaft had deformed plastically.

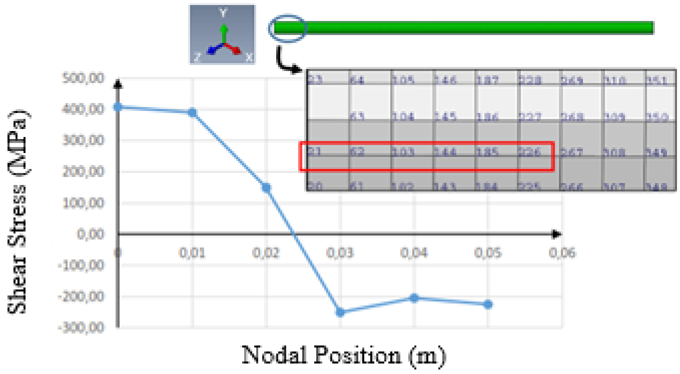

Figure 6. Some observed noded for the shear stress analysis at the end of the pump shaft.

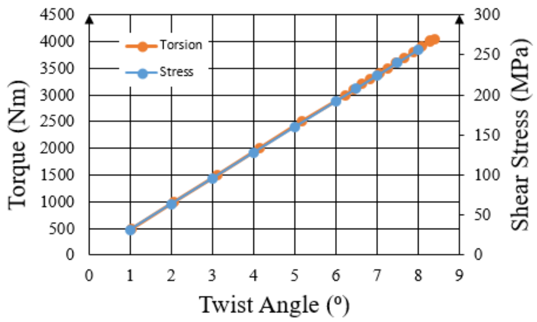

Figure 7. A curve of torque and shear stress to twist angle on the shaft.

4. Conclusions

The following conclusions could be drawn from the results of the exact and FEA on the centrifugal pump shaft that was deformed plastically and twisted about 8^{O} as:

1. The exact and FEA revealed that the failure of the pump shaft that had deformed plastically was caused by the shear stress, which was greater than the shear stress of the SUS 304 pump shaft material.
2. The maximum shear stress that occurred on the twisted pump shaft was about 255 MPa and the maximum strain was about 0.034.
3. The torque, shear stress, and strain that occurred on the shaft increased with an increase in the twist angle on the shaft.

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