Journal of Simulation and Analysis of Novel Technologies in Mechanical Engineering
13 (2) (2021) 0005~0011
HTTP://JSME.IAUKHSH.AC.IR

The analysis of failure for a stud bolt with reduced shank under dynamic loading

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(Manuscript Received --- 25 Dec. 2019; Revised --- 23 Dec. 2021; Accepted --- 25 Dec. 2021)

Abstract

In this research, the failure of a stud bolt was studied. This bolt is under periodic loading, in a multi-stage compressor. The undesired vibration of the system causes vibration load on the bolt. The bolt was modeled in Abaqus software and the generated stress was calculated. To determine the dynamic load on the bolt, the vibration of the system was measured by a digital vibration sensor and this load was simulated in Abaqus software. The boundary condition and loading were considered similar to the real working condition. The failure and fatigue of the bolt was investigated in the periodic loading. The factors such as the shank diameter, chamfer radius and material were changed and the corresponding response of sample and change in stress was studied. The most probable points of the bolt for failure were found and the effected of the reduced shank diameter on its life was considered. In the initial design, the shank diameter was considered 12 mm. The results shown that by decreasing the shank diameter, the stress first decreases and then increases and the minimum of stress occur at the shank with a diameter of 11.47 mm. Also, by increasing the chamfer radius, the stress first increases and then decreases and the minimum of stress occurs at the chamfer radius of 33 mm.

Keywords: Stud bolt; Dynamic loading; Abaqus software

1- Introduction

In joints, bolts are one of the most important and most commonly used fittings, which are classified as disconnect able joints. Because of wide application of bolts in the industry, one can appreciate the importance of researching and investigating these connections. Nowadays, depending on their application in the industry, bolts are loaded under different loads, such as tensile, torsional, or combined loading. Any failure in these parts causes serious damage, so it is important to examine the behaviour of the bolts as well as their design and structure.

In recent years, many studies have been done on bolts. Lee et al. [1] suggested a model for two plates fastened by a bolt and a nut. They employed the finite element method in their model to calculate the stress coefficient. Asi [2] studied the failure of a stud bolt. He used an electron microscope to have an image of cross-section of failure bolt and he concluded that the cause of the failure is low cycle fatigue. Walters et al. [3] determined the initial force needed to tighten the bolt and examined the way by which the torque is calculated. Brien et al. [4] presented a numerical model to determine the stress developed at the points of a stud bolt where maximum failure has occurred. Using the finite element method, Fransplass et al. [5] studied a threaded fastener, undergoing large strain, and determined the maximum load needed to failure occur. Paredes et al. [6] studied the modeling of a bolt with special geometry and employed experimental method as well as simulation with Abaqus software to examine the coefficient of friction and the contact area affected by the axial load. Sandro Griza et al. [7] used two types of bolts to fasten the flange/housing assembly of a gas compressor. While one of them was a typical one, the other had a reduced shank and these two models were compared. Cho et al. [8] used a numerical model and finite element method for a Bolt and flange and investigated its elastic-plastic behavior. Chen et al. [9] studied for the failure of steel high-strength bolts. The optical microscope were used on one of the failed bolts to investigate the reasons for its failure. Rodriguez et al. [10] were investigated the failure of a stud bolt wrench. In order to determine the failure cause, the fractured wrench was compared with an un-failed wrench from the same production batch.

In this research, the failure of a stud bolt was studied, which its material is corrosion resistant steel PH-17-4 (Fig. 1). This bolt is used in an air compressor to attach the propeller to the axis. From one side the stud bolt is attached to the axis and the

Fig. 1 The stud bolt.

propeller is fastened to the other side of the bolt by a nut. As the first step, two experiments were performed on the sample and we examined the tensile as well as vibration on the system in which the bolt is used. Based on experimental consequences, the bolt is simulated in Abaqus software and the resulting stress results from dynamic loading were determined. Considering the resulting consequences, we identified the most probable points on the bolt to be failed and we could suggest a way to increase the life span of the bolt.

2- Experimental study of study of the bolt

In a tensile test, the sample made from corrosion resistant steel PH-17-4, was produced in standard size for the tensile test. Fig. 2 shows the sample after the test and Fig. 3 presents the strain-stress diagram resulting from the experimental data for the sample.

Fig. 2 The sample after tensile test.

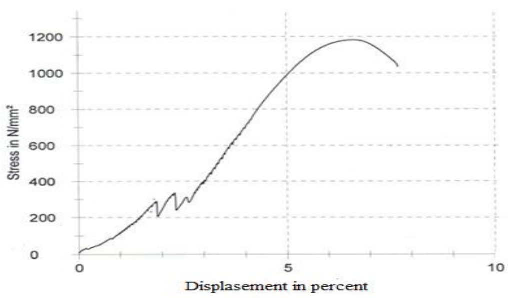

Fig. 3 Stress-strain diagram.

Table 1 shows the mechanical properties of the sample, based on the tensile test, which will be used in modeling in the Abaqus software.

Table 1: Mechanical properties of steel PH-17-4 based on experimental test

Yield stress (MPa)	Ultimate tensile strength (MPa)	Yong's modulus (GPa)	Elongation %
1087	1187	196	7.7

In vibration testing, a digital vibration sensor is used to record the vibration of the system. The vibration sensor is mounted at the closest point to the free part of the axis to record the vibrations of the system and transfer them to the Signal matching unit. In this part, the propeller is attached to the shaft, and there are no Bearings and supports. Fig. 4 shows 32,769 measurements recorded in a very minor interval by the vibration sensor during one second and it presents the change in the velocity versus time.

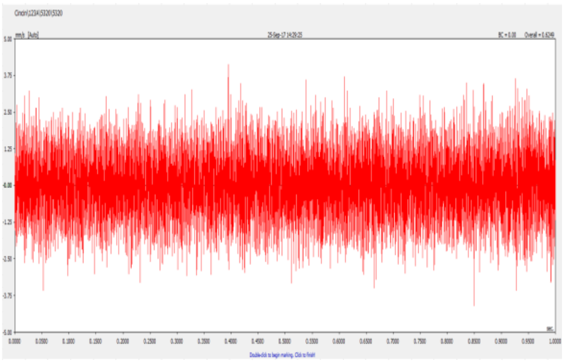

Fig. 4 Velocity change versus time, based on the data recorded by the digital vibration sensor.

3- Investigating the causes of failure from a metallurgical perspective

The cross-section of the bolt failure under vibrational loading is shown in Fig. 5. In this figure the lines of the crack growth is visible on the cross-section. The failure started with fatigue cracking and after fatigue cracking growth, the endpoint of the segment was fractured at a 45^{o} angle.

Fig. 5 Fracture of cross section.

To investigate further on the cause of failure, the metallography test was performed on the sample. In Figs. 6 and 7, the cross-sectional area of the sample in metallography experiment were shown with magnification of 100X and 200X that Photographed by an electron microscope.

Fig. 6 Cross section fracture (100X).

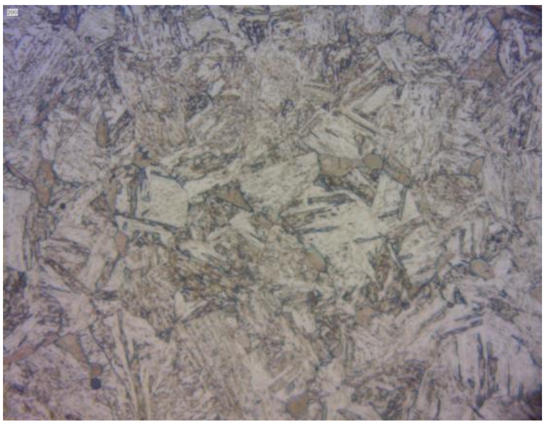

Fig. 7 Cross section fracture (200X).

The steel PH-17-4 is a martensitic hardened alloy steel with pseudo-austenitic corrosion resistant. Its structure consists of martensitic phase with delta ferrite phase that homogenization and hard deposition are usually provided under heat treatment. Metallography and microstructure images show the presence of the ferrite delta phase in a martensitic matrix. The brittle fracture of this material can be attributed to the type of heat treatment and its martensitic microstructure. The ferrite delta phase affects the mechanical properties and increases the yield stress of the material. On the other hand, it increases the brittleness. Increasing the brittleness of the material can cause the germination of fatigue cracking that by expanding the crack length; eventually the brittle fracture will occur. So we can say that the main reason for the failure of this steel is the high rate of this phase that has caused the piece to fail.

4- Simulation and validation

The characteristics of the bolt obtained from reverse engineering method are as follows. A stud bolt with size M16 which its length, shank diameter and chamfer radius are respectively 156 mm, 12 mm and 33 mm, that shown in Fig. 1. To simulate the bolt in Abaqus software, the technique of rotation of half of the cross-section around the central axis is used, so that in a two-dimensional environment, half of the cross-section of the sample is plotted, and after rotation.

The mechanical features of the material including, Yield stress ،Ultimate tensile strength And Yong's modulus, which is shown in Table 1 results from the experiment and we use them to the model. Considering that the load on the bolt is due to periodic tensile load and vibration load, to analyses it in the software, loading and application of boundary condition should be done dynamically. To apply the boundary condition related to the displacement, using the data resulted from the digital vibration sensor (Fig. 4), we find the maximum value of the displacement and then do a dynamic analysis. To have the maximum displacement, the maximum value of speed is multiplied by the period of oscillation. Fig. 8 shows the way by which the bolt is loaded.

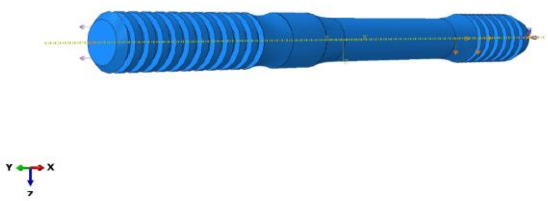

Fig. 8 Load on the simulated bolt.

To consider the boundary condition in the software, the simulation is done for two types of boundary conditions. The head stud is assumed to be fixed and the end of the bolt is assumed to have a periodic displacement.

For analysis, we have to choose the best type and number of elements. We selected the triangular elements as space gridding for the bolt. Although an increase in the number of elements may lead to more accurate results, but it increases the time needed for software analysis as well. Therefore, we should choose the least number of elements so that such reduction doesn't change the result of our analysis. In this study, using Trial and error method, we increase and decrease the number of elements and finally, we found that the most appropriate number is 23647. In this Abaqus analysis, the bolt tension caused by dynamic loading is shown in Fig. 9. Moreover, the resulting deformation in the bolt is presented in Fig. 10.

As we see in Figs. 9 and 10, the maximum displacement has occurred in the unfixed part of the bolt and the maximum tension is in the part where the shank attached to the thread.

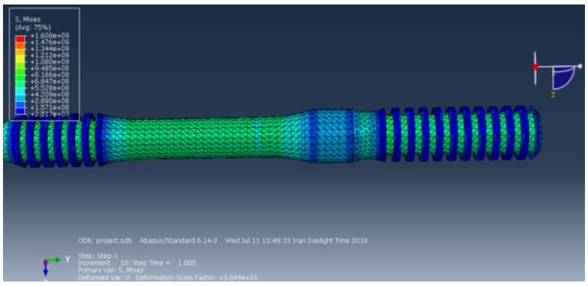

Fig. 9 Stress in the bolt caused by dynamic loading.

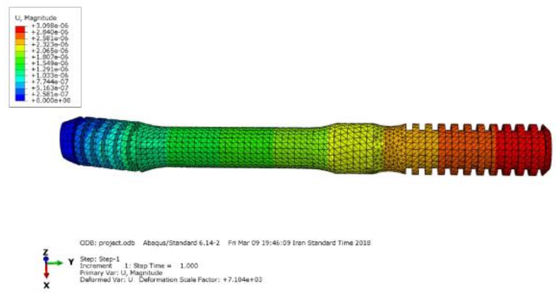

Fig. 10 Deformation of the bolt.

Fig. 11 shows the real failure happened in the bolt, confirming the results of our analysis in Abaqus software.

Fig. 11 Cross section of the failed bolt.

5- Result and discussion

In the initial design of this bolt, the shank diameter was considered 12 mm. The effect of reduction in the shank diameter on the stress by the constant type and loading rate is shown in Fig. 12. As we see in this figure, although, the reduction in the shank diameter results in a decrease in the stress however there is a limitation for such reduction in stress. Because, when the shank diameter decreases more than a critical value, the stresses increase. According to Fig. 12, the optimal value of the reduction in the shank diameter is 0.53 mm. Thus, the optimal value of shank diameter is 11.47 mm. Due to that the vibration loading for this bolt is chosen, that shown in Fig. 12, a small reduction in the shank diameter can cause significant reduction of stress in the critical points of the bolt shank.

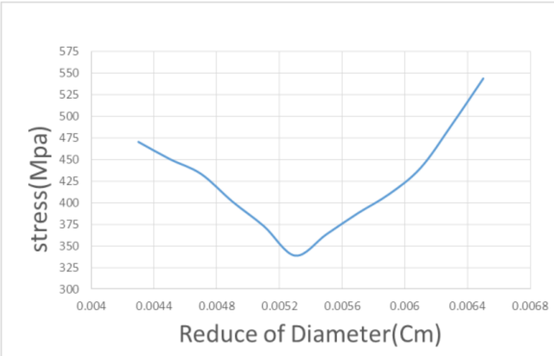

Fig. 12 Stress versus reduction of diameter.

In the following, the variation in the radius of the chamfer and its effect on stress was discussed and the effect of reducing the radius of chamfer, in the part where stud bolt was attached to the shank, on stress was examined. With the reduction of chamfer radius, stress decreases in some critical points and increases in other ones. Fig. 13 presents the effect of change in chamfer radius on stress in the critical points of the bolt where failure occurs. As we see, the reduction in the chamfer radius, at first, leads to an increase and finally results in a decrease in stress and, in this step; the stress is transferred to other parts of the bolt. According to Fig. 13, the best value of the chamfer radius is 33 mm.

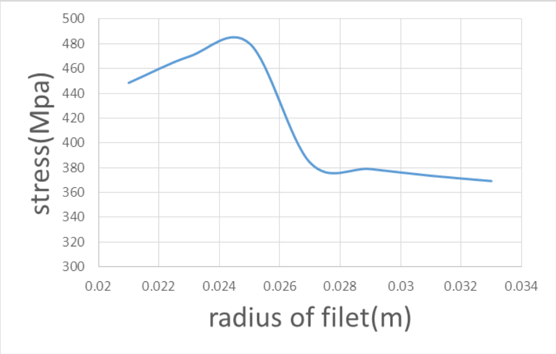

Fig. 13 Stress versus chamfer radius

The steel PH-17-4 is a martensitic hardened alloy steel. This type of steel has high yield stress but on the other hand, it is brittle steel. To fix this problem, a sample of bolt by considering the optimum shank diameter and chamfer radius from AISI415 steel was simulated in Abacus software. This steel has mechanical properties, such as yield stress and ultimate strength, similar to that of PH-17-4 steel. This new sample was simulated in the Abacus software and whit considering the boundary conditions and the type of loading, the location and values of maximum stresses were determined. The results show, there was little change in the stress values between the two types of steel. Since the yield stress and ultimate strength of the two types of steel are close together, this was predictable. There is no hard deposition in AISI415 steel to cause cracks to grow in the piece, so it was predicted; it is an important factor in preventing the brittle fracture.

6- Conclusion

In this research, the failure of a stud bolt under the periodic loading was studied. The bolt was modeled in Abaqus software and the generated stress was calculated. In the initial design of this bolt, the shank diameter was considered 12 mm. It is shown that by decreasing the shank diameter, the stress first decreases and then increases and the minimum of stress occurs at the shank with a diameter of 11.47 mm. Thus, the optimal value of the shank diameter is 11.47 mm. Also, by increasing the chamfer radius, the stress first increases and then decreases and the minimum of stress occurs at the chamfer radius of 33 mm.

A sample of bolt by considering the optimum shank diameter and chamfer radius from AISI415 steel was simulated in Abacus software. The results show, there was little change in the stress values between the two types of steel. By applying these changes that include, changes in the shank diameter, changes in the chamfer radius and change in the material of the bolt, a new sample was made. This sample was used in the compressor and tested. The new sample did not fail and the results were satisfactory.

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