Fatigue and fracture behavior of A516 steel used in thick-walled pressure vessels

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Abstract

In this paper, the growth of semi elliptical crack in the walls of thick walled cylindrical pressure vessels has been investigated. Considering the importance of the crack growth problem in cylindrical pressure vessels provides a numerical and experimental 3D model for the growth of fatigue crack and estimating the fatigue life of pressure vessels. Because of available geometric geometric and physical parameters, it can be predicted the problem of the fatigue life of these pressure vessels more precisely in comparison with existing standard tests which are experimental and numerical. A most common specimen of thick walled tanks, steel, is analyzed for conducting experimental tests. The mechanical properties and fatigue behavior of A516 steel have been determined experimentally. For estimating the crack growth and calculation of fatigue life, boundary element method and linear fracture mechanics equations have been used. Finally, the experimental results for fatigue crack

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growth were compared with numerical method, which yielded acceptable results. The overall results show a good agreement between the experimental data and the numerical results.

Keywords: Fatigue crack growth, Pressure vessel, Fatigue life, Fracture mechanics, Boundary element.

1- Introduction

Fatigue crack growth is one of the most important issues in fracture mechanics. The main culprit of many of destructions in pressure vessels, which are used in the oil and gas industry a lot, is the existing crack in their walls. These cracks may be created by corrosion in the procedures of sheet manufacturing, welding or during the installation of the pressure vessels. In the oil and gas industry, because of noxious chemicals, flammable and explosive materials, it is important to dramatically increase the security of storage systems [1]. According to this, many investigations have been carried out on cylindrical pressure vessels, most of these cases are related to the growth of cracks in these pressure vessels [2]. Fatigue crack growth is a phenomenon in which the crack grows very slowly in each loading cycle [3-6]. Most of the systems and pieces, having been cracked and broken, are subjected to alternating loads, in which sometimes the magnitude of load was significantly less than the static failure load [7]. In these cases, the main cause of failure, is the growth of small cracks in the material, which gradually grow from a very small size to a critical extent. This type of crack growth, which leads to fracture failure, is called fatigue [8-10]. The amount of cracks growth in each loading cycle can be calculated by counting the cracks growth lines and comparing them with the loading profile [11]. In the early 1960s, for the first time Paris showed that the amount of crack growth in each fatigue loading cycle is controlled by the stress intensity factor at the cracks tip. According to studies by William on the distribution of stress around the crack tip, it has been shown that the elastic stresses surrounding the crack tip, can be expressed by series. The methods for measuring the stress intensity factors in cracked pieces are the analytical, experimental and computational methods. Different types of loading in cracked pieces include four loading modes [12-15]. The four loading modes are the opening of crack surfaces, the slide of cracks on each other, the slide on the outside of sheet surface, and if loading is a combination of two or three loading modes, it is called the compound loading. In summary, each of the load modes has its own equations. For the first time, the calculation of stresses in the cylindrical pressure vessels was done by g. lame, which was called after him [16]. The most important causes of failure are the appearing of surface imperfections during
production and corrosion of pressure vessels inner surface, because of an inappropriate acidic environment or the oxidation of that area in the presence of a specific substance inside the pressure vessel. Because of these corrosions, on the surface, fine imperfections are formed as a line of small porosities which cause a stress concentration in the corrosion zone. In many cases, when the pressure vessel has a weld line, failures will begin from those surface imperfections which occurred on the weld line during welding. These superficial surface defects are the source of semi elliptical cracks growth and development that grow to some extent, then join each other and form a single crack [17]. Surface cracks under tensile load, grow in the form of elliptical shape on a thick wall. These walls can be flat, cylindrical or spherical. Because of the complicated structure of semi elliptical cracks growth on curved surfaces, for facilitating, crack growth in the flat wall is also considered as an approximation of crack growth in the curved walls, however, by increasing wall thickness and curvature of pressure vessel surfaces, these approximations are not very accurate and reliable. In [18], an attempt has been made to improve these approximations for a cylindrical pressure vessel by using weight functions. The required calculations for finding the stress intensity factor were calculated on a perimeter of a semi elliptical crack in a flat plate under the tensile load. The existing equations are presented in [19], which are used for calculating the stress intensity factor at the crack tip in a radial direction. Also, Newman and Raju have proposed the equations in [20] for calculating the stress intensity factor on a perimeter of a semi elliptical crack in a pressure vessel. In calculations of pressure vessels designing and, in general, any other structures, there are mainly two criteria for avoiding failures which should be considered. First, the stress intensity factor should not reach critical value, and secondly, the stress applied to the uncracked section should not exceed the critical stress or in other words should not reach the plastic deformation region. In order to achieve this purpose, the relationship between the stress intensity factor during failure and the amount of stress at the time of failure can be found by using the experimental data obtained from many failures. Also, failure-resistance can be predicted for every situation. The results of these studies [21, 22] show that when the pure stress of fracture is less than the flux stress, a linear equation between maximum stress intensity factor and amount of stress at the time of failure can be identified [23, 24]. In the literature, various problems concerning the fatigue crack growth under pure mode conditions (modes I, II, III) can be found, such as reported by Silva et al. [25] or Rozumek et al. [26] and Lesiuk et al. [27]. Correia et al. [28] and Abílio et al. [29] have used fatigue local models based on strain and SWT relations to model the fatigue crack propagation curves. Correia et al. [30-33] proposed a procedure for a modification of the
UniGrow model which uses an elementary material block size, which is obtained from existing FCG data.

In experimental tests, the geometry of standard specimens has always been used as the basis for measuring experimental data. In this paper, experimental data is obtained by using standard specimens and a new confirmed standard specimen that is more accurate. The methods of fatigue cracking test and the way of displaying and processing test data are presented in different standards [34]. The study of crack growth behavior is carried out by using the rules and equations of linear elastic fracture mechanics under fatigue loads. For analyzing of crack growth, it has been used boundary element method. Then, the Paris law was used to obtain fatigue life [35]. The intensity factor mode I which is created in cracking, are more important than the other factors, calculated by numerical method [36].

2- Materials and Methods

Mechanical properties including hardness, tensile, Charpy impact and fatigue growth tests has been carried out at room temperature. For this purpose, A516 steel is used because it is the kind of steel which has been used to manufacture thick walled pressure vessels. To determine material elements and by using a metallographic method and observing atomic microstructure in non-destructive methods, including the use of quantum devices, it can be determined the initial operations, such as thermal operations and the basic state of the material. By testing, the elements of A516 steel are determined and presented in Table 1.

Placement of Table 1

To extract the mechanical properties of A516 steel the tensile test was performed. According to standard tensile test ASTM E8 [34] specimens as shown in Figure 1.a were machined and were ready for testing. Mechanical properties including yield strength, ultimate tensile strength, relative elongation and Elastic modulus, E, were calculated according to strain-stress curves. Impact resistance of most materials has a direct relation with their malleability. The Charpy impact test was performed according to the ASTM E23 standard at room temperature [37]. For all tests, the impact velocity during impact should be a constant number. The impact velocity in this method is 5-5.5 m/s. For this test, specimens were manufactured with standard dimensions and V-notch for specimens was formed by standard device. The initial angle for the pendulum velocity of 5 m/s is 134 degrees. Figure 1.b shows the standard specimen of Charpy impact test. To perform a hardness test, the hardness tester was first calibrated, and then a part of the steel was placed under the device. According to the
ASTM E10 standard, a 2.5 mm ball bearing was used. According to the ASTM standard tables for a 2.5 mm ball bearing, and the Brinell hardness test method, a force of 187.5 kg was chosen [38]. Rotating bending fatigue test was performed to extract fatigue behavior of A516 steel. Fatigue tests under time-control conditions at room temperature and in order to get the S-N curves have been done in fatigue mode. These curves are plotted in the conditions of the recurrent variable stress cycles (i.e., $\sigma_m = 0$). The amount of stress can be $\sigma_a$ or $\sigma_{max}$.

Rotating bending fatigue tests can be performed with different specimens. According to the ASTM E466 standard, the fatigue test specimens are ready to be tested according to Figure 1.c [39]. In S-N curve, which shows the fatigue strength in terms of the number of cycles, under the $10^3$ cycles, is called Low-Cycle Fatigue and above that is High-Cycle Fatigue. On the other hand, under $10^6$ or $10^7$ cycles, the specimen has a finite life (due to the high operating stress) and above $10^6$ cycles, the specimen will have an infinite life. For this test, 10 specimens were manufactured with the standard dimensions by CNC machine and excellent surface quality.

In the fatigue crack growth the ratio of changes in the cracks length to the changes in the loading cycle ($\frac{da}{dN}$) show the amount of crack growth in each loading cycle. In the early 1960s, for the first time Paris showed that the amount of crack growth in each fatigue loading cycle is controlled by the stress intensity factor at the crack tip [40, 41]. For the first time, Paris showed that $k, \frac{da}{dN}$ quantities can be in the form of an exponential equation like Eq. (1):

$$\frac{da}{dN} = C(\Delta K)^n$$

In which $n$ and $C$ are the material constants dependent on the material fatigue crack growth under tensile load when $R_{ratio} = 0$.

To investigate the fatigue crack growth, the test specimens can be of the compact tension C(T) type, or sheet with a central crack. This test is usually carried out under constant loading in which the maximum and minimum loads are constant during the experiment. According to the ASTM E647 standard, the dimensions of C(T) specimen are shown in Figure 1.d [42]. Although the above specimens have already been used as a standard approximation for predicting the cracks behavior in pressure vessels, either semi elliptical or general, but in fact there is a significant difference between the life of a pressure vessel containing a semi
elliptical crack and standard specimens under the conditions of the same crack growth, which is because of the difference between the fatigue crack growth behavior in a pressure vessel and current standard specimens. For this reason, by using the research carried out in [43], it has been proved that the new proposed specimen is closer to the actual situation. Thus, using the geometry of new specimen for A516 steel, which is most used in the pressure vessels manufacture, crack growth test was also performed with the new specimen. Figure 1-e shows the new specimen geometry [44].

Placement of Figure 1
To perform this test, the Santam hydraulic device was used. This device is controlled by a computer and has the ability to load up to 50 kN with a frequency of 10 Hz. Figure 2 shows the Santam Fatigue Test device.

Placement of Figure 2
To measure the fatigue crack growth, a camera was installed at the proper location for filming the specimen during the test. For this purpose, it was necessary to install an appropriate index in the place of the crack growth, which measured the amount of crack growth. Figure 3 shows the test specimens of fatigue crack growth along with the index mounted on them.

Placement of Figure 3
After preparing the specimens by using Eq. (2), following equations can be used for calculating the critical value and load applied to the specimens according to the geometric parameters [45]:

\[ P_L = 1.072 \times \eta \times B \times b \times \sigma_y \]  

(2)

In this equation, B is the thickness of the specimen, b is the width of the specimen, \( \sigma_y \) is the yield stress obtained in the tensile test, and \( \eta \) is a geometric constant calculated by Eq. (3) [45]:

\[ \eta = \sqrt{\left(\frac{2a}{b}\right)^2 + \frac{4a}{b} + 2 - \left(\frac{2a}{b} + 1\right)} \]  

(3)
Through the use of provided equations and inserting geometric values, the critical loading value for C(T) specimens is about 12 kN and for the new specimen is 20 kN. The loading force ratio in this test was considered to be 0.1 ($R = \frac{P_{\text{min}}}{P_{\text{max}}} = 0.1$). After the specimens were prepared and placed in the device, the load and a frequency of 5 Hz were applied to the controller computer. The camera was installed in front of the specimen notch and the camera shutter was timed to shoot every 20 seconds. Figure 4 shows broken specimens after the test.

Placement of Figure 4

3. Experimental results and discussion

3.1. Metallography

The surface images are magnified 1000 times (Figure 5). Test result show that the basis structure is ferrite-pearlite, in which the grains are drawn in the direction of rolling. Metallographic investigation showed that the steel has a ferrite-pearlite. Due to differences in intragranular crystal orientation, interlayer distance from a grain to another grain is different. The average distance between the layers utilizing quantitative metallography is 0.679 $\mu$m.

Placement of Figure 5

3.2. Tensile Behavior

Mechanical properties of A516 steel has been presented in Table 2. The results show that this alloy has a sufficient standard tensile strength for using in pressure vessels. Yield strength and ultimate tensile strength are respectively obtained as 408 and 580 MPa, while the elongation at break is 10%. The material has high strain hardening rate with hardening rate of 0.238, which is a high value for engineering steels.

Placement of Table 2

3.3. Charpy Impact

Table 3 shows the average Charpy energy for A516 steel. A516 steel requires more energy to fracture the specimens. Lateral expansion of CVN specimens in the side of impact and percentage of shear failure fracture surface has been inserted in the table. The impact test results show that the energy absorption for this alloy is very high, which can withstand possible impact and reduce the possibility of explosion.
3.4. Hardness

Here Brinell static test and the results are presented in Table 4. The results show that this alloy has a sufficient standard hardness for using in pressure vessels. According to the test results, all measured hardness data conformed to the A516 steel specifications.

3.5 Fatigue Performance

This test is performed according to the ASTM E466 standard. As seen in the general form of S-N curve, by reducing stress applied to the specimen, the fatigue life increases along a horizontal Asymptote. This reduction will stop in a range that the specimen does not fail anymore, and it is called durability of the material. According to the test results, A516 steel does not fail at stresses less than 250 MPa and it has a finite life in stresses of 400 to 550 MPa. Figure 6 shows the S-N curve.

3.6. Evaluation of fatigue crack growth

After testing and measuring the crack growth from the recorded images, the fatigue life curves are plotted in Figures 7 and 8. Using the gradient of obtained results and calculating the stress intensity factor with Eq. (4), the crack growth rate is obtained in terms of stress intensity factor. To calculate ΔK, the following equation was used [45]:

\[ \Delta K = \sigma \sqrt{\pi a} \]  

(4)

Here, \( a \) is the crack length and \( \sigma \) is the stress applied to the cross-sectional area of the specimen.

In order to find the constant values of the Paris equation, the crack growth rate curves are plotted in terms of the stress intensity factor. Figures 9 and 10 show fatigue crack growth rate in terms
of stress intensity factor for C(T) specimen and new specimen. After plotting the curves, the constants of Paris equation for each specimen are presented in Table 5.

Placement of Figure 9

Placement of Figure 10

Placement of Table 5

4. Numerical Method for Fatigue Crack Growth

Nowadays, Numerical Methods by means of computers solve many complicated problems easily in a short time. One of the Numerical Methods is the use of Finite Element Method (FEM) or Boundary Element Method (BEM). While the stress intensity factors for a number of specific geometries exist in books and references, there is no reference for complicated geometries. The best method for calculating crack tip parameters in complicated geometries is using FEM. Because of the singular terms near the crack tip, the stress around the crack tip calculated by Eq. (5):

$$\sigma = \frac{K_I}{\sqrt{2\pi r}} f(\theta)$$

In the above equation the stress is a function of $\frac{1}{\sqrt{r}}$ which near the crack tip, $r$ tends to zero, and as a result stress tends to infinity. After defining the loading vector, the hardness matrix and applying the fixed boundary conditions, the finite element software performs static analysis, and consequently calculates the stress-intensity factor using the analysis results and the Eqs (6-10):

$$\sigma_{xx} \sqrt{2\pi r} = K_I \cos \frac{\theta}{2} \left( 1 - \sin \frac{\theta}{2} \cdot \sin \frac{3\theta}{2} \right)$$

$$\sigma_{yy} \sqrt{2\pi r} = K_I \cos \frac{\theta}{2} \left( 1 + \sin \frac{\theta}{2} \cdot \sin \frac{3\theta}{2} \right)$$

$$u_x = \frac{K_I}{2E} \sqrt{\frac{r}{2\pi}} \left( 1 + \nu \right) \left[ (2\kappa - 1) \cos \frac{\theta}{2} - \cos \frac{3\theta}{2} \right]$$

$$u_y = \frac{K_I}{2E} \sqrt{\frac{r}{2\pi}} \left( 1 + \nu \right) \left[ (2\kappa + 1) \sin \frac{\theta}{2} - \sin \frac{3\theta}{2} \right]$$
In the above equations, \( r \) is the distance from the crack tip and \( \theta \) is the angle at which the stresses are calculated.

In order to simulate fatigue crack growth and estimation of A516 steel life, modeling was done in Franc 3D software which is designed by researchers at Cornell University [46], a software for studying crack growth in 3D geometric shapes.

4.1. Finite Element Method

The number of elements will be selected after different meshing. Here the size of elements is 3 mm and Quadrilateral element shape is selected. The number of appropriate elements for the C(T) specimen was 1216 and for the new specimen, was 4130. Figure 11 shows the finite element model of C(T) specimen and the new specimen. Also, all the properties of the material and the applied load are same as the experimental tests.

Placement of Figure 11

The stress-strain analysis results with a similar loading in the experimental tests for the C(T) specimen are shown in Figure 12.a. All the steps were also performed for the new specimen. Also, the maximum stress obtained for the new specimen is shown in Figure 12.b.

Placement of Figure 12

4.2. Boundary Element Method

FRANC3D software has been created and developed by Cornell University. The purpose of this software is to simulate the three-dimensional crack growth of industrial components in relatively complicated conditions. Figure 13 shows the specimens’ geometric modeling in the software.

Placement of Figure 13

To solve the problem in a correct way and to ensure its accuracy, the meshing must be done correctly. The more the number of elements, the higher the accuracy, but the problem-solving speed decreases. In order to make sure the problem is solved accurately, the number of
elements must be increased as much as possible. To find the number of appropriate elements, the problem was solved with the number of different elements several times. According to Tables 6 and 7, the number of appropriate elements was selected for the C(T) specimens and the new specimen, respectively. The number of appropriate elements for the C(T) specimen was 1218 elements, and for the arch form of the new specimen, was 2799 elements.

Placement of Table 6
Placement of Table 7

To create the initial crack on the specimen, the semi elliptical crack is used according to Figure 14 with dimensions of \( a = 5\) mm and \( b = 3\) mm. Figure 15 shows the location of the initial crack and its surrounding element.

Placement of Figure 14
Placement of Figure 15

The next steps of the boundary element model, such as the definition of material properties, meshing, boundary conditions, and solving, are carried out. For meshing can be used Quadrilateral elements with four nodes. After loading, the specimen is meshed and the stress analysis is performed through the BES software. Then, the stress-intensity factor values are calculated for all three modes. In the presence of stress intensity factor, the direction of crack growth is also determined. The crack growth rate is optional. The crack tip curve can be fit after determining the direction of crack growth and crack growth can be simulated for another step. In order to develop the crack by BEM, first, the crack tip is divided into several elements. The number of divisions is optional and the user will choose it. After the crack growth, the specimen is re-meshed and prepared for solving. This process is repeated for each step to develop the crack to the expected rate. Figure 16 shows the crack after 44 growth steps in C(T) specimen. Figure 17 also shows the crack after 40 growth steps.

Placement of Figure 16
Placement of Figure 17

The results for the stress-intensity factors at the crack tip in terms of the crack length for the C(T) specimen and the new specimen are given in Figures 18.a and 18.b, respectively.

Placement of Figure 18
4.3. Comparison between results

In this study, the measurement of fatigue crack growth rate in pressure vessels was investigated through experimental and numerical methods. A new standard specimen was chosen for this test [20]. For the first time, a pressure vessel made of sheet with a new specimen in the form of arch was tested for fatigue crack growth. Standard specimens were loaded with a constant range and values of 21 kN for the new specimen and 12 kN for the C(T) specimen. According to the loading, the amount of stress applied to the new specimen notch is 180 MPa and the amount of stress applied to the C(T) specimen is 115 MPa. In the following, the results obtained from experimental and numerical tests are compared. Figure 19.a shows the fatigue life of C(T) specimen in comparison with the numerical results. Figure 19.b also shows the fatigue life curve of the new specimen in comparison with the numerical results.

Placement of Figure 19

The maximum lifetime of the new specimen and the standard specimen after reaching the threshold of the stress intensity factor are tabulated in Figure 19. This means that by increasing the length of the initial crack, the volume of the load will decrease to some extent such that the stress intensity factor at the top of the crack will be equal to the threshold value. From the obtained results, it is inferred that the conformity of the new introduced specimen for testing the pressure vessels crack, is much more than the existing ones. The average error of the C(T) specimen is 20%, The average error of the new specimen is 7%. As it is indicated in Figure 19, there is a very good agreement between the results for the new specimen and the cylindrical vessel. This specimen can also be suggested to measure fatigue crack growth in the thick-walled pressure vessels.

5. Conclusions

In this study, the mechanical performance focusing on the fatigue and fracture behavior of A516 steel was evaluated by considering a set of related parameters, both experimentally and numerically. The results of this study can be used to determine the fatigue life of thick-walled pressure vessels accurately, by considering the shortest time, the lowest price and calculations. To measure the fatigue crack growth rate in this study, a new proposed specimen was used which for the first time the steel used in pressure vessels was investigated with this new specimen. The results of fatigue loading on new specimen are compared with the results of fatigue loading in standard specimen. Finite element method, boundary element
method and experimental method are used to investigate the behavior of fatigue crack growth in specimen. For this purpose, a three-dimensional model is conducted using model. Fatigue test is carried out on a couple of specimens with new geometry and made of A516 in order to verify the numerical results. The most significant results of this study can be presented as follows:

1. According to the flat S-N curve with high fatigue limit slightly higher than the yield point of the material, A516 steel showed high fatigue strength. Also, the level of fatigue failure of this steel is cleavage type, which generally leads to brittle behavior of the material.

2. Cracks play an important role in fatigue crack initiation in thick-wall pressure vessels. Effects of size and direction of cracks is important.

3. The results of boundary element method have been compared with those achieved from experimental tests. The numerical analysis results obtained show good agreement with those obtained from experimental results.

4. Slope of fatigue life curve in terms of crack length, in initial part and along small cracks is very low. In other words, a small increase in crack length lead to a great growth in life. Therefore, direction of stress intensity factor along small cracks is considered much more important than stress intensity factor along big cracks.

5. By comparing the new specimen results with other existing specimens, it was found that the new specimen had more accurate results and less error than the other existing ones.

Also, other effects, such as loading frequency, temperature and surface smoothness in the material life and the ratio of surface properties need to be investigated in the future.

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Table 7.

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Figure 1.
Figure 3.
Figure 4.
Figure 5.
Figure 6.
Figure 8.
Figure 9.
Figure 10.
Figure 11.
Figure 12.
Figure 13.
Figure 14.
Figure 15.
Figure 16.
Figure 17.
Figure 18.
Figure 19.
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