Failure Pressure Prediction in Oil Transfer Pipe Lines with Incomplete Penetration and Undercut Welding Defects

N A Salih', R J Jasim2 and H S Jasim3

1Department of Mechanical Engineering, University of Basrah, Iraq
Email address Nathera1971@yahoo.com
2Department of Mechanical Engineering, University of Basrah, Iraq
Email address Raadjamal28@yahoo.co.uk
3Department of Mechanical Engineering, University of Basrah, Iraq
Email address Hamzah.eng@gmail.com

Abstract. The main target of the current study is the assessment of API 5L X52 pipe line containing lack of penetration and undercut welding defects and to study the influence of the defect length and depth on the failure pressure of the pipeline. The failure pressure is calculated by using Finite element software ANSYS ver19. The results from finite element analysis are used to train an artificial neural network for easily predicting the failure pressure with a wide range of defect depths and lengths. Also the results obtained were also used in the regression analysis to find equations linking the maximum pressure to the defects dimensions. The results revealed a Good agreement between finite element modeling and the experimental tests, theoretical values and available design codes with maximum average error of (13.4%). The failure pressure varied significantly as a function of the defect length and depth.

Key words: Burst pressure, Welding defects, Finite element method

1- Introduction
Petroleum pipelines represent a major artery of the national economy. Pipeline safety is closely related to people’s lives. These pipe lines are constructed by welding processes which its quality are difficult to control resulting in several types of welding defects that can have a significant effect on the performance of the defective pipe [1]. The common types of welding defects are cracks, lack of penetration, undercut, porosity, slag inclusion, misalignment etc. Many researchers have been studied the prediction of burst pressure and focused on the corroded pipelines in welding region and base metal. But enormous numbers of papers are published to assess the pipelines with welding defects. Moke et al, [2] studied the corrosion in spiral welded pipes and proposed a formula to predict the failure pressure in a long a pipe having long external spiral corrosion. In his assessment the flow stress were based as a failure criteria and provide a table for calculating spiral correction factor. The results revealed a good agreement with experimental burst tests. Yeoma et al. [3] studied the influence of corrosion defect dimensions on the failure pressure of API X70 pipe having corroded girth and seam welds. They used full-scale hydro tests to validate the finite element modeling (FEM). Also, the predicted failure pressures were compared with the ASME B31G, Modified ASME B31G, DNV RP-F101, and PCORRC standards to obtain a formula that can predict the failure pressure of corroded girth and seam welds. Hertelé et al, [4] presented an experimental study to assess the girth welds that having corrosion defects subjected to axial load. They studied three cases of weld having (misalignment, weld strength mismatching, and Charpy V notch toughness). They found that the plastic collapse criteria can be used to assess the acceptance limitations of butt weld defects in old pipes. Yaorong et al [5] used the fitness-for-service calculation by using fracture mechanics method to
predict the remaining life for new oil pipe line having absence of fusion imperfection caused by improper welding heat input in electric resistance welding. The results show that the pipe line may fail before bursting under designed operating pressure, and the lack of fusion defects in the welds may propagate under the effect of variable pressure, and the lack of fusion defects decrease the service life of the pipe line. Nagy et al.[6] offered two ways to assess the failed circumference welds of oil and gas transmission pipelines. The first one was established on the basics of linear elastic fracture mechanics and stress intensity factor idea for planar material imperfections. Their results from the two assessment approaches are paralleled to the results of rupture exam of pipeline segments having ruptured girth weld and cut from in service pipes. They suggested using the basis of fitness for purpose idea as a replacement for of the assessment rules of welded joints. Chen et al, [7] tried to assess the defects in spiral welded pipe line. They did numerous rupture examinations of pipeline with different helix weld imperfections used different projection calculation techniques based on BS7910. The obtained results showed that the failure was started from the defect in the welding line and their assessment revealed that the axial projection way based on BS7910 was recommended to measure spiral weld flaws regardless of its conservatism. Tsuji and Meshii [8] calculated the influence of the circumferential angle on the rupture stress experimentally using the rupture exam and numerically via a large strain elastic-plastic FEA. From the experimental outcomes, the circumferential angle be likely to affect the burst pressure for cases with large axial flaw length, and moreover, defect depth ratio was correlated with a reduction in the failure pressure complemented by an rise of the circumferential angle. Lei et al, [9] presented experimental and numerical study on 32 inch oil pipe with three types of girth weld flaws which are lack of penetration, incomplete fusion and incomplete external weld. They used finite element analysis to study the effect of girth weld imperfection geometry on the burst pressure. The simulations results are compared with full-scale burst examinations of pipes contain the studied three welding defects. The results were compared with (fitness-for-service) FFS methods including API 579, BS 7910, Miller and Kastener. The assessment results revealed that these methods agree well with the failure stress when the real strength of the material was used. Jin et al [10] developed a theoretical analyzing method of plastic limit capacity for pressure pipe with inadequate welding defects based on the stretched NSC Principles and deduced the correlative formulas. The effect of pipe curvature, circumferential length and the depth of inadequate welding defects have been considered. The plastic limit loads are calculated by the finite element method and compared with the theoretical values. The results show that the expressions of plastic limit load of pressure pipe with lacking welding defects under bending, torsion and internal pressure based on extended NSC criteria are reliable. A. Bastola et al. [11] investigated an experimental and numerical study on the strain capability of girth-welded X80 pipes subject to displacement-controlled environments. The influence of internal pressure on strain capability was inspected through full-scale bending examinations. Wide supplementary Finite Element Analysis has been carried out with a concentration on weld overmatch combined with HAZ. In the recent development of prediction methods there is a new way of predicting burst pressure of defective pipes by using artificial neural network. The main benefit of the artificial neural network (ANN) is an ability to learn information from examples. Moreover, ANNs have the capability to implicitly distinguish complex non-linear relationships between independent and dependent variables [12]. Following teaching based on samples, ANNs can forecast accurate solutions under any undefined inputs in many research fields. R.C.C. Silva et al[13] applied neural network technology for the calculation of pipes with intermingling imperfections depending on finite element
models of a pipe having two aligned and similarly shaped flaws of 80 x 32 mm and numerous flaw positioning. He related the neural networks results with those derived from the Det Norske Veritas code (DNV RPF101. Wen-Zheng Xu et al, [14] studied the failure performance of pipelines with intermingling corrosion flaws using a finite element modeling, and then a solution was used to forecast rupture pressure using an artificial neural network. They applied ANN model to predict the burst pressures of pipelines with two interacting flaws. From the above mentioned studies, it's clear that few numbers of researches in regard of predicting the burst pressure of pipe lines with welding flaws specially the undercut defect. As a result, in the present study more than 60 models including wide ranges of welding defect lengths and depths of incomplete penetration and undercut defects have been simulated via finite element modeling and the data obtained from the simulation are used to train an artificial neural network as alternative way for forecasting the failure pressure in easy steps. Also the results were used for regression analysis to obtain a formula that can predict the failure pressure for the studied defects.

2. Finite Element Modeling (FEM)

2.1 Pipe geometry

The implementation of present work was based on finite element analyses of X52 pipeline with diameter (D: 700 mm), wall thickness (t: 9 mm), pipe length (L: 1400 mm) and welding defect depths for the first defect (lack of penetration) (d= 0 mm to 4 mm) and for the undercut defect the depths ranged from (.4 to 1.5 mm). The study also includes the welding flaw length (L) that ranged from 0 to 1285.539 mm. It was assumed that the welding flaws have regular shape that equally affected the internal pipe wall thickness in a circumferential orientation, as presented in Figure 1.

![Pipe geometry](image)

(a) Pipe geometry

![Cross section of Weld joint design](image)

(b) Cross section of Weld joint design.

**Figure 1.** Simulation of X52 grade steel pipe

The present study included 60 models that were drawn by the AutoCAD software and the defects were represented in each drawing according to the depth and length specified for each defect.

2.2 Welding process

The method used to weld the tube in the present study is the shield metal arc welding (SMAW) method according to the specified welding procedure specification. The filler metal was E6010 for the root pass
with current range between 75-100 A, E7010 for the hot pass with current range between 100-120A and E7018 for the filling and cap pass with current range between 90-110A.

2.3 Material properties

Table 1 show the mechanical properties of the simulated pipes used for Finite Element Modeling (FEM) were adapted from Chen et al. [7] and submitted to the ANSYS in the Engineering Data Table1.

| Steel grade                  | API 5L X52 |
|------------------------------|------------|
| Yield stress                 | 381MPa     |
| SMYS (specified min. yield stress) | 358MPa    |
| Ultimate tensile strength    | 556MPa     |
| Fracture toughness           | 86.6MPa·m1/2|
| Weld metal tensile stress    | 600MPa     |
| Weld metal yield stress      | 400MPa     |
| Heat affected zone tensile stress | 500MPA    |
| Heat affected zone yield stress | 360MPa    |

2.4 simulations of welding defects

The first case study is incomplete penetration defect which was represented by decreasing the thickness of the welding area from the inner side of the welding groove at different depths and different lengths and assuming the defect form is regular as shown in figure 2. The second case study is the undercut defect which occurs due to the high current and other reasons during the welding process; this defect is represented by an external parabolic groove between the welding area and the Heat Affected Zone (HAZ) with different depths and different lengths also.

2.5 Meshing

The FEM constructed for the first incomplete penetration defect geometry with depth of 1mm and length of 10 mm is revealed in Figure 3. The model in the figure was generated with number of nodes equal to of 69396 and 34030 triangular elements that were refined automatically at the welding defect location. The element size for the mesh was from 2 mm at the defect location to 71mm at the base metal surface of the model. The further pipes were modeled with a variable number of nodes and elements, with sufficient refinement prepared at the welding defects.
2.6 Validation of Finite Element Model

The results of the FEM analysis were confirmed by comparing with the results of the practical tests and numerical results published in literature. The data in table 2 shows that the maximum error percentage is 2% which give us the guide to follow the same steps for mesh quality and the other analysis procedure in simulation new models with different defect geometries.

| Pipe | Practical Burst Pressure [MPa] | Predicted pressure (FEM) [MPa] | Error % |
|------|-------------------------------|--------------------------------|---------|
| Validation with Chen et al[7]. for practical Burst test of X52pipe with defect | 5.5 | 5.503 | 0.054 |
| Validation with Qazi[16]. Experimental Burst Test of API 5L X-70 without defects | 25 | 24.5 | 2 |
| Validation with Li et al[17]. for API 5L X80 grade with 3mm bore defect (numerical study) | 12 | 12.001 | 0.0083 |
Also FEM results were compared with the engineering standards and empirical equations listed below:

| Failure pressure method | Mathematical expression |
|-------------------------|-------------------------|
| Kastner [18]            | \[ p = \frac{\pi[\pi - \beta(1-\eta)]}{\pi\eta + 2(1-\eta)\sin\beta} \] \[ (1) \] |
| Schulze [19]            | \[ p = 1 - \frac{\beta(1-\eta) + 2\sin^{-1}(1-\eta)\sin\frac{\beta}{2}}{\pi} \] \[ (2) \] |
| Yeoma et al [3]         | \[ P_f = 0.9\sigma_u \frac{2t}{D} (1 - \frac{d}{t} (1 - \exp(-0.224 \frac{L}{(R(t-d))^{1/2}}))) \] \[ (3) \] |
| FITNET FFS [20]         | \[ P_f = \frac{2}{D-t} \sigma_u t (5^{(65/\sigma_y)}) \left( \frac{1 - \frac{d}{t}}{1 - \frac{d}{t} Q^{-1}} \right) \text{ Where } Q = \left( 1 + 0.8 \frac{L}{(Dt)^{1/2}} \right)^{1/2} \] \[ (4) \] |
| Ossai et al [21]        | \[ P_f = \frac{1.8}{D} \sigma_u \left( \frac{1 - \frac{d}{t}}{1 - \frac{d}{t} Q^{-1}} \right) \text{ Where } Q = \left( 1 + 0.805 \frac{L}{(Dt)^{1/2}} \right)^{1/2} \] \[ (5) \] |
| Cosham et al [22]       | \[ P_f = \frac{2(\sigma_y + 68.95)t}{D} \left( \frac{1 - 0.85 \frac{d}{t}}{1 - 0.85 \frac{d}{t} M^{-1}} \right) \] \[ (6) \] |
|                        | \[ M1 = \left( 1 + 0.6275 \left( \frac{L}{(Dt)^{1/2}} \right) - 0.003375 \left( \frac{L}{(Dt)^{1/2}} \right)^2 \right)^{1/2} \text{ For } \frac{L}{(Dt)^{1/2}} \leq 50 \] |
|                        | \[ M1 = 0.032 \frac{L}{(Dt)^{1/2}} + 3.3 \text{ For } \frac{L}{(Dt)^{1/2}} \geq 50 \] |
| ASME B31G-2009 [23]     | \[ P_f = \frac{2(1.1\sigma_y + 68.95)t}{D} \left( \frac{1 - 0.85 \frac{d}{t}}{1 - 0.85 \frac{d}{t} M^{-1}} \right) \] \[ (7) \] |
|                        | \[ M1 = \left( 1 + 0.6275 \left( \frac{L}{(Dt)^{1/2}} \right) - 0.003375 \left( \frac{L}{(Dt)^{1/2}} \right)^2 \right)^{1/2} \text{ For } \frac{L}{(Dt)^{1/2}} \leq 50 \] |
|                        | \[ M1 = 0.032 \frac{L}{(Dt)^{1/2}} + 3.3 \text{ For } \frac{L}{(Dt)^{1/2}} \geq 50 \] |
3- Results and Discussion

3.1 Case Study (1): API 5L X52 Pipe with Lack of penetration defect (LOP)

The input parameters are the incomplete penetration depth and length which represented as a ratio to the pipe wall thickness. The defect depth ratio is (d/t) and the defect length ratio is (L/t). The defect width is the same for all the simulated geometries which approximately equal to 2.5mm at the welding root and increased slightly with increasing in the defect depth due to the bevel angle of the joint design. For this case three defect depth ratios are considered which are 0.111, 0.277 and 0.444 also ten defect length ratios for each defect depth ratio which are 1.111, 2.777, 5.555, 11.111, 21.921, 47, 61, 71.41, 95.22, 119.03, and 142.83

From the stress analysis it’s clear that the defects caused an increasing of the stress concentration at the defect where the maximum Von Mises stress occurs. Figure 4 shows the contours of von Mises equivalent stress distribution around the incomplete penetration defect.

![Figure 4](image)

**Figure 4.** Von Mises equivalent stress distribution around the defect for d/t=0.444 and L/t=1.111

The burst pressure is decreased by 9.8% - 46.2% when the defect ratios (d/t=0.111- 0.444 and L/t=1.1111- 119.03 ) as compared with the free defect pipe.

By assuming a linear relationship between the rupture pressure and the rupture pressure elements d/t, L/t and P for LOP defect , a multi linear regression study of the rupture pressures calculated with FEM produced the relationship shown in Equation (8)

\[
P_f = \frac{(0.948\sigma_f t)}{R} - 16.566\frac{d}{t} - 0.009\frac{L}{t} \quad \ldots\ldots(8)
\]
Figure (5) illustrates comparison between the present results with the obtained equation, theoretical equations and industry design codes. Table 4 shows the average error between FEM with the empirical equations and corrosion equations obtained from design codes.

Table 4. Average error with assessment equations

| Assessment method         | Average Error |
|---------------------------|---------------|
| Kastner[18]               | 5.195%        |
| Schulze et al[19]         | 4.47%         |
| FITNET FFS[20]            | 12.29%        |
| Yeoma et al[3]            | 10.83%        |
| Ossai et al [21]          | 12.27%        |
| Cosham et al[22]          | 7.51%         |
| ASMEB31G-2009[23]         | 13.4%         |
| LOP equation              | 1.54%         |

(a) d/t=0.111

(b) d/t=0.277
Figure (5) failure pressure variation with $L/t$ for a) $d/t=0.111$, b) $d/t=0.277$ and c) $d/t=0.444$

Figure (6) effect of $d/t$ on the rupture pressure for a given values of $L/t$

(c) $d/t=0.444$
From figure (5) it's clear that the failure pressure of the pipe decreased as the defect depth and length increased. Also it's clear that the equations that were compared with the results of numerical analysis have given results close to and somewhat acceptable. It is noted that the LOP equation gives more accurate results than the other assessment equations, while Schulze et al[19] equation was the closest to the results of numerical analysis and then the formula of Kastner[18] and Cosham et al[22] equation where it gave results close. The ASME B31G -2009[23] equation and Ossai et al [21], FITNET FFS [20] equation were slightly higher than the rest of the equations when the length of the defect is short. When the length increases, the results converge to the results of FEM with almost the same error. The average error percentage between FEM and the assessment methods mentioned in this study is illustrated in table3. Figures (6and7) show the variation of burst pressure with different values of d/t and L/t. It's clear from this figure that for a given values of d/t the defect length ratio L/t has a significant influence on the failure pressure while for a given values of L/t the defect depth ratio d/t affects slightly on the burst pressure, this due to the effect of the surface area of the defect which increased with the increasing the length of the defect. It's very important to avoid the long defects in the welding joints. These observations agreed with the design codes which assess the incomplete welding defect according to its length. In API1104standard [15], the maximum acceptable length of incomplete penetration is 25mm. For L/t=2.78 which corresponding to LOP (lack of penetration) length =25 and d/t=0.2777 the burst pressure has decreased by 12.31% which explained why the API standard rejects the LOP defects if its length was greater than 25mm. For the current pipe dimensions if the length of this defect was equal to 25mm then the maximum allowable operating pressure should not exceed 7.54MPa if the safety factor is 1.5.

3.2 Case Study (2): API 5L X52 Pipe with external undercut defect (EU).

The input variables are the same for the case study (1) which are the undercut depth and length which represented as a ratio to the pipe wall thickness. For this case three defect depth ratio are considered which are 0.044, 0.088 and 0.166 also ten defect length ratio for each defect depth ratios which are 1.111, 2.777, 5.555, 11.111, 21.921, 47, 61, 71.41, 95.22, 119.03, 142.83. From the stress analysis it’s clear that the defects caused an increasing of the stress concentration at the defect where the maximum Von Mises stress occurs due to the metal loss at that location. Figure 8 shows the geometry of the defect and the contours of von Mises equivalent stress distribution around the external undercut defect.
It’s clear that the flaw length has significant effect on the failure pressure than the flaw depth. The manners of failure pressure according to the length and depth of the flaw is revealed in Figure 8. From regression analysis of results calculated with FEM for external undercut defect produced the relationship presented in Equation (2)

\[
P = \frac{D}{\sigma_f} \times (7.824 - (4.075\frac{d}{t}) - (0.009205\frac{L}{t}))
\]

.....(9)

Fig. 11 reveals a comparison between the FEA with equation 2 and the assessment equations—Yeoma et al [3], Schulze et al[19], Kastner [18], FITNET FFS[20], Ossai et al[21], Cosham et al [22], ASMEB31G[23]. To determine the suitable assessment for the pipe line with welding defects.

Figure 8. Undercut defect geometry and von Mises equivalent stress distribution around the defect
Figure 9. Failure pressure variation with $L/t$ for (a) $d/t=0.044$, (b) $d/t=0.088$ and (c) $d/t=0.166$

Figure 10. (a) effect $d/t$ on the failure pressure for a given values of $L/t$, (b) effect $L/t$ on the failure pressure for a given values of $d/t$
It’s clear from figure 11 that the pipes that having LOP defect have a lower burst pressure than that which having EU defect for the same defect dimensions and it can be said that the LOP defect is slightly more dangerous than EU.

3.3 Artificial Neural Network

An artificial neural network (ANN) is used for prediction of the failure pressure. The FEM data are used to train and test the ANN model, input parameters include of (d/t and L/t) while, failure pressure (Pf) is the output parameter. The ANN model consist 20 as training data and 10 samples are used for testing. The optimal structure of this neural network model is (2-7-1) as shown in the figure (12). The correlation coefficient is 0.993, 0.996, 0.990 and 0. Training, validation, test and all samples training respectively. The FEM and the predicted ANN results of testing dataset are compared as shown in figures13, 14. It can be seen that the maximum error between FEM and the predicted ANN results is equal to 3.4% for LOP defect and 1.58% for EU defect.
Figure 12. Construction of ANN with three layers.

Figure 13. Comparison between FEM predicting, NN predicting and LOP equation for LOP defect
4- Conclusions

In this research, the failure pressure was predicted via FEM with two types of welding defects which are lack of penetration and external undercut defects with various depths and lengths. The following conclusions were reached from this study.

1- Good agreement between finite element analysis and experimental burst tests where the comparing between them indicated more accurate predictions with maximum error of 2%

2- From the comparison with the assessment equations; it's observed that the LOP equation and undercut equation that have yielded from the present study was very accurate with average error percentage of 1.5% and 2.17% respectively and it can be used in engineering field to give accurate predictions for the studied pipe.

3- The corrosion assessment equations by design codes gave higher average percentage error which indicates that the assessment corrosion equations are not accurate to assess welding defects.

4- The lack of penetration defect (internal defect) is slightly more dangerous than the external undercut defect. So it's very important to discover this defect and control the operating pressure of the pipe in service for safe operation if the defect was not repaired before interring to the service.

5- The API standard rejects the lack of penetration defect if its length exceeded 25 mm while this limitation can be accepted when the operational pressure on which the pipe works is controlled. This can avoid the repair the defect, which takes time, effort and cost from the owner.

6- The ANN model was used to predict the burst pressures of pipelines with welding flaws. The observations showed that the ANN model could predict the burst pressure with a relative error lower that 4%. This showed that the ANN model can be used as another easy solution for burst pressure assessment of API 5L X52 pipelines with LOP and EU flaws.

Figure 14. Comparison between FEM predicting, NN predicting and EU equation for EU defect
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