Numerical investigation of corroded middle-high strength pipeline subjected to combined internal pressure and axial compressive loading

Linlin Lu1 | Lecai Liang2

1Tianjin Research Institute for Water Transportation Engineering, M.O.T., Beijing, China
2Tianjin Port Petrochemicals Terminal Co., Ltd., Beijing, China

Abstract
Buried oil and gas pipelines may face the threat of geological disasters such as landslides, faults, and floods. However, long-term buried oil and gas pipelines often have corrosion defects, which bring greater challenges to the safe operation of pipelines. In this study, via the finite element analysis method validated by the testing results, the blasting pressure of a middle-high strength pipeline with corrosion defects under an axial compressive load, the distribution of the von Mises stress on the pipeline surface, and the local buckling behavior of the pipeline were studied. In the analysis of the influencing factors, the axially compressive load, the size of the corrosion defects, and the characteristics of the pipeline material were studied. Based on 437 sample points, an artificial neural network was adopted to predict the burst pressure of a pipeline with corrosion defects. By comparing the prediction results with the numerical simulation results, the accuracy verification of the prediction model was conducted. When the axially compressive load increases to a certain value, the burst pressure of a pipeline with corrosion defects will begin to decrease rapidly as the axial compressive load increases. The larger the size of the corrosion defect, the smaller the burst pressure of the pipeline. The depth and length of the corrosion defect have a significant influence on the blasting pressure. The lower the steel grade of the pipeline, the smaller the $Y/T$ ratio, and the lower the bursting pressure of the pipeline. Both the axial compressive load and the size of the corrosion defect affect the failure mode of the pipeline. When the corrosion defect's size is small and the axial compressive load is small, the pipeline material fails. When the corrosion defect's size is large enough, and the axial compressive load is large enough, the pipeline is prone to structural instability. An increase in the axial compressive load and the decrease in the corrosion defect's size cause the local stress concentration of the corrosion defects to become more significant. When the axial compressive load on the pipeline is small, the increase in the axial compressive load does not affect the bursting pressure of the pipeline, but it greatly increases the degree of the local buckling of the pipeline.
1 | INTRODUCTION

Buried oil and gas pipelines suffer from volumetric defects due to the corrosive external environment. Corrosion defects are one of the important causes of pipeline accidents. Furthermore, oil and gas pipelines are often subjected to complex loads during service, which further accelerate the failure of corroded pipelines. It is of great significance to determine how to effectively evaluate the remaining strength of pipelines with corrosion defects to ensure the safe operation of pipelines.

The existing standards provide methods for evaluating the remaining strength of corroded pipelines. The ASME B31G, API 579, and SY/T6151 standards for evaluating corroded pipelines consider the internal pressure.1-3 Based on this, the DNV-RP-F101 standard evaluates the failure pressure of the pipeline under the complex loading of axial stress and internal pressure.4 In addition, the British Standards Association’s standard BS-79010 and the Canadian Standards Association’s standard CSA-Z184-M86 also carry out corresponding evaluations on the remaining strength of corroded pipelines.5,6

Many researchers have recently investigated the failure behavior and strength influencing factors of corroded pipelines using full-scale laboratory testing and finite element (FE) analyses. Hopkins et al proposed the plastic limit criterion method to determine the failure of corroded pipelines. It is believed that when the equivalent stress in the corrosion area of the pipeline exceeds the yield strength of the pipeline, the pipeline will fail.7 Benjamin et al8 performed a series of burst tests and finite element analysis on multipoint group corrosion and complex shape corrosion pipelines, and they proposed a new method for evaluating the remaining strength of multipoint corrosion and complex shape corrosion pipelines. Silva et al used the nonlinear finite element method combined with the artificial neural network method to study the interaction between the corrosion defects. They demonstrated that the artificial neural network method can be used to predict the ultimate burst pressure of multipoint corrosion pipelines.9 Kim et al10 performed a burst test on the X65 pipeline with rectangular axial corrosion and studied the failure mechanism and the variation in the limit internal pressure load of the pipeline. Freire et al11 developed a failure mechanism for pipelines with complex shape corrosion defects based on burst pressure tests conducted on corroded pipelines. Shuai et al quantitatively determined the effects of the length, width, and depth of corrosion defects on the pipeline failure pressure. A formula for calculating the failure pressure of pipelines with corrosion defects was proposed.12 Han et al13 adopted the finite element method to study the effect of corrosion defect width on the ultimate internal pressure bearing capacity of the pipeline. Cai et al considered the material and geometric nonlinearity and used the finite element method to numerically calculate the internal pressure limit of a pipeline with corrosion defects. They also analyzed the influence of the corrosion parameters and corrosion location on the failure pressure of the pipeline.14 Chen et al15 analyzed the effects of the corrosion parameters and location on the ultimate blasting pressure of pipelines with corrosion defects. In addition, they evaluated the influence of the corrosion parameters on the failure pressure through numerical simulation. The remaining strength evaluation results for corroded pipelines obtained using the standard methods are often too conservative. Previous studies have rarely involved failure behavior analysis of corroded pipelines under combined loads. The research on the factors influencing the burst pressure of pipelines with corrosion defects is not comprehensive enough. The method for predicting the ultimate blasting pressure of corroded pipelines under an axial compressive load cannot be obtained accurately.

In this study, based on a validated accurate numerical simulation model, we used the arc length method to calculate the burst pressure of a pipeline with corrosion defects under an axial compressive load. In addition, we quantitatively analyzed the effects of the length, width, and depth of the corrosion defect and the pipeline material on the ultimate blasting pressure. The blasting pressure prediction model of a pipeline with corrosion defects was obtained using the artificial neural network method. The accuracy of the model meets the engineering requirements. The results of this study provide a theoretical reference for the safety evaluation of corroded pipelines.

2 | FINITE ELEMENT MODEL FOR CORRODED PIPES UNDER COMBINED INTERNAL PRESSURE AND AXIAL LOADING

2.1 | FE model

Finite element analyses (FEA) were conducted to simulate the full-scale compression tests on the corroded pipelines. The commercial finite element software ABAQUS16 was
used to conduct the FEA. The outer diameter of the pipeline was 813 mm, and the wall thickness was 12.5 mm. In order to avoid the influence of boundary effect on the strain capacity, the length of the pipeline was set as $5D$, which can be obtained from the research results in the relevant literature.\textsuperscript{17} The pipeline was modeled using three-dimensional hybrid eight-node solid elements and reduced integration (C3D8RH) to avoid the influence of excessive mesh deformation on the accuracy of calculation results. Due to the symmetry conditions in the circumferential and longitudinal directions, as shown in Figure 1, only half of the pipeline was modeled. Symmetry boundary conditions were applied to the 1/2 model. The $0.25D$ part of the end of the pipeline and the reference point (RP) was constrained as a rigid body, and the RP was used to impose the axial compressive load, so that the longitudinal compression strain occurred in the corrosion defect area of the pipeline.

As shown in Figure 2, in order to avoid the unreasonable numerical result caused by excessive stress concentration in the corrosion defect area, a corrosion defect with a smooth edge was applied on the outer surface of the pipeline. The element was refined adequately to obtain converged (mesh independent) solutions. Along with the longitudinal direction, small elements were used at/near the defect. The element size gradually increased away from the corrosion defects for computational efficiency. The smallest element size in the longitudinal direction was 5.0 mm. Along the circumferential and thickness directions, the sizes of the elements were kept uniform. The element sizes in the circumferential and thickness directions were 5.0 and 4.0 mm, respectively. The model was divided into 47,532 elements.

Based on their shapes and sizes, the corrosion defects were broadly grouped as general corrosions, grooves (longitudinal and circumferential), and pits. The dimensions of the corrosion defects include longitudinal length ($L_c$), circumferential width ($W_c$), and depth ($d_c$), as shown in Figure 3. When $L_c$ is equal to $W_c$, it is classified as general corrosion. When $L_c$ is greater than $W_c$, it is classified as a longitudinal groove. When $L_c$ is less than $W_c$, it is classified as a circumferential groove. In this study, a pipeline with a longitudinal groove was investigated.

Nondimensional defect sizes are used in the assessment of corrosion defects using many methods. For example, in the ASME B31G standard,\textsuperscript{1} to assess the burst pressure of corroded pipelines, the longitudinal length and depth of the corrosion defects are normalized using $\sqrt{D/t}$ and $t$, respectively.

### 2.2 Loading conditions

Buried pipelines with defects may be subjected to the axial force of the soil before operation. In this study, the load in the FEA was applied in two steps. In the first step, a monotonically increasing axially compressive load was applied to the end of the pipeline. In the second step, an internal pressure was applied to the internal surface of the pipeline model, and the internal pressure was increased until the maximum pressure was reached (ie, the burst pressure), while the displacement and rotation at the end of the pipeline were fixed.
2.3 Material model

Similar to the Ramberg-Osgood equation, the equation given in standard CSA Z662 defines the relationship between the engineering stress \( \sigma_{\text{eng}} \) and the engineering strain \( \varepsilon_{\text{eng}} \) as

\[
\varepsilon_{\text{eng}} = \frac{\sigma_{\text{eng}}}{E} + \left( 0.005 - \frac{\sigma_y}{E} \right) \left( \frac{\sigma_{\text{eng}}}{\sigma_y} \right)^n,
\]

where \( \sigma_y \) is the YS at 0.5% strain; and \( n \) is the strain hardening exponent of the CSA equation. The fitting equation for the correlation was developed as follows:

\[
n = \frac{3.14}{1 - \frac{Y}{T}},
\]

where \( Y \) is the YS (MPa) and \( T \) is the ultimate stress (MPa).

The above equation is for the engineering stress-strain curves of the pipeline materials, and the true stress-strain curves of the pipeline materials can be calculated using the following equations:

\[
\sigma = \sigma_{\text{eng}} \left( 1 + \varepsilon_{\text{eng}} \right),
\]

\[
\varepsilon = \ln \left( 1 + \varepsilon_{\text{eng}} \right),
\]

Three typical middle to high strength pipeline steels were considered in this study, that is, X65, X70, and X80. The true stress-strain curves of these three pipeline materials are shown in Figure 4. Table 1 lists the material properties of the pipeline steel types. The value of the \( Y/T \) ratio is within the reasonable range of the standard. The YS is defined as yield stress, and the UST is defined as ultimate stress.

3 FAILURE ANALYSIS OF A CORRODED PIPELINE SUBJECTED TO INTERNAL PRESSURE AND AN AXIAL COMPRRESSIVE LOAD

3.1 Failure criteria

The burst pressure of the corroded pipeline can be obtained from the FEA. The pipeline parameters and the geometries of corrosion defects are presented in Table 2. Nondimensional defect sizes are used in the assessment of corrosion defects in many methods. For example, in standard ASME B31G, to assess the burst pressure of a corroded pipeline, the longitudinal length and depth of the corrosion defects are normalized using \( \sqrt{Dt} \) and \( t \), respectively. The pipeline contains a longitudinal groove with a circumferential width of \( \sqrt{Dt} \) and an axial length of \( 2.0 \sqrt{Dt} \). The depth of the corrosion defect is \( 0.2 t \).

In this study, the maximum load criterion was selected to identify the burst failure behavior, which has been proven by previous studies. In the FEA, the burst event was defined as the event that occurs when the maximum pressure is reached. The static Riks analysis method was used to determine the maximum pressure. The relationship between the arc length and load proportionality factor (LPF) is shown in Figure 5. The parameters of the finite element model are shown in Table 2. The internal pressure of the pipeline gradually increases and unloads after reaching the peak. The peak value of the LPF can be used to calculate the burst pressure. The calculation method is shown in Equation 5.

\[
P_{\text{burst}} = P \lambda,
\]

where \( P_{\text{burst}} \) is the burst pressure of the pipeline (MPa); \( P \) is the internal pressure of the pipeline applied in the second step of the finite element model (MPa); and \( \lambda \) is the LPF when the von Mises stress reaches the peak value.
3.2 Comparison of the FEA and experimental results

The existing documented test results were used to verify the accuracy of our finite element model. Twelve burst tests have been performed in the DNV Joint Industry Project, and 9 were with longitudinal corrosion defects and 3 with circumferential corrosion defects. The pipes were loaded with combined internal pressure and external loads, except for 2 tests with internal pressure only. The external loads considered were bending moment and axial compressive force. In this study, the finite element model is adopted to simulate 4 burst tests of corroded pipeline subjected to the interaction of internal pressure and axial compression force. The steel grade of the pipeline used in the test was X52. The yield strength of this material is 380 MPa, and its tensile strength is 514 MPa. The pipeline diameter is 324 mm, the wall thickness is 10.3 mm, and the defects were external corrosion axial defects. The finite element method was used to calculate the burst pressure of the pipeline subjected to axial stress. The relationship between the arc length stress and the LPF is shown in Figure 6, and the burst pressure results are presented in Table 3.

As can be seen from Table 3, the average error of the finite element simulation results is 11.33%, and the burst pressure calculated using the finite element method is close to the pipeline burst pressure test data, which verifies the accuracy of the established finite element model.

3.3 Failure mode analysis of corroded pipeline subjected to axial compressive loading

3.3.1 Failure mode of a corroded pipeline

The parameters used to study the effect of an axial compressive load are listed in Table 2. The effect of an axial compressive load on the burst failure of a corroded pipeline is shown in Figure 7. When the axial compressive load is less than \(-1.0 \times 10^4\) kN, the burst pressure of the corroded pipeline is almost constant. When the axial compressive load is greater than \(-1.0 \times 10^4\) kN, the burst pressure of the corroded pipeline decreases significantly as the axial compressive load increases.

The effect of axial compressive loading on the von Mises stress of the corroded pipeline when the internal pressure of the pipeline is unloaded was obtained. As can be seen from Figure 7, when compressive loads less than \(-10,000\) kN, the burst pressure of the pipeline without an axial compressive load and the burst pressure of the pipeline with an axial compressive load are almost equal. When a corrosion defect pipeline is subjected to internal pressure, the pipeline undergoes elastic deformation first until it reaches the tensile strength, and then, local instability

| Specimen ID | Axially compressive load \((\times 10^4\text{kN})\) | \(d_c\) (mm) | \(L_c\) (mm) | \(W_c\) (mm) | Experimental burst pressure (MPa) | FEM Burst pressure (MPa) | Relative Error (%) |
|-------------|---------------------------------|-------------|-------------|-------------|--------------------------------|------------------------|-------------------|
| 1           | 2.60                            | 3.09        | 162         | 30.9        | 28.60                          | 30.28                  | 5.87              |
| 2           | 3.00                            | 3.09        | 162         | 30.9        | 28.70                          | 30.32                  | 5.33              |
| 3           | 3.04                            | 5.15        | 243         | 30.9        | 18.60                          | 21.60                  | 16.13             |
| 4           | 2.10                            | 7.21        | 243         | 30.9        | 12.30                          | 14.51                  | 17.97             |
occurs. If the axially compressive load exceeds 10,000 kN, the pipeline is prone to structural instability, which can explain why the burst pressure starts decreasing after the critical axial load of −10,000 kN. However, as can be seen from Figure 8, the stress concentration phenomenon of the pipeline subjected to the axial compressive load is more significant, and the degree of local wrinkles is more significant. When the axial force on the pipeline is small, the failure mode of the pipeline is structural instability. The axial compressive load affects the local stress state of the pipeline, thereby accelerating the yield of the pipeline and reducing the ultimate bearing capacity of the pipeline.

As can be seen from Figure 8, the smaller the axial compressive load, and the greater the burst pressure of the pipeline subjected to the axial compression, the more significant the stress concentration phenomenon. However, the burst pressure and the von Mises stress of the pipeline subjected to the above two working conditions are much lower, and the degree of the local folding is higher than that of the pipeline not subjected to axial compressive loading. This shows that the failure mode of the pipeline subjected to a higher axial compressive load is different from that of the pipeline subjected to a lower axial compressive load, and its failure mode is structural instability.

3.3.2 | Discussion

The von Mises stress contour of the pipeline not subjected to axial compressive loading is shown in Figure 9. The internal pressure of the pipeline is 17.73 MPa. The von Mises stress on the surface of the pipeline increases as the internal pressure of the pipeline increases, and the stress concentration occurs on the surface in the pipeline corrosion defects area, as shown in Figure 11A. As the internal pressure of the pipeline continues to increase, the von Mises stress at the edge of the pipeline corrosion defect reaches a peak value, as shown in Figure 11B.

The von Mises stress contour for the corroded pipeline subjected to a $-1.3 \times 10^4$ kN axial compressive load is shown in Figure 10. The internal pressure of the pipeline is 9.79 MPa. As the internal pressure increases, the local von Mises stress on the pipeline corrosion defects gradually increases to the

![Figure 7](image-url)  
**FIGURE 7** Effect of axial compressive loading on the burst pressure of a corroded pipeline

![Figure 8](image-url)  
**FIGURE 8** Effect of axial compressive loading on the von Mises stress contour of a corroded pipeline

![Figure 9](image-url)  
**FIGURE 9** Von Mises stress contour for the corroded pipeline under 0.0 kN axial compressive load and 17.73 MPa internal pressure load. (A) Stress concentration occurs; (B) the von Mises stress at the edge of the pipeline corrosion defect reaches a peak value; (C) and pipeline failure occurs.
peak value. Moreover, it was found that an outward wrinkle forms at the corrosion defect and grows under the influences of the axial compressive load and the internal pressure.

The von Mises stress contour for the corroded pipeline under a 0.0 kN axial compressive load is shown in Figure 11A. The von Mises stress contour for the corroded pipeline under a $-1.3 \times 10^4$ kN axial compressive load is shown in Figure 11B. The internal pressure bearing capacity of the corroded pipeline subjected to a 0.0 kN axial compressive load is much greater than that of the corroded pipeline subjected to a $-1.3 \times 10^4$ kN axial compressive load, and the expansion of the corroded pipeline subjected to a 0.0 kN axial compressive load is more significant.

4 | PARAMETRIC ANALYSIS ON BURST PRESSURE OF PIPE

4.1 | Parameter range in the investigation

The pipeline parameters and corrosion defect geometries used in the FEA are listed in Table 4. The analyses were divided into 4 groups. Groups 1-4 investigated depth, length, and width of the corrosion defect and the material properties. In all of the analyses, the outer diameter of the pipeline was kept constant ($D = 813$ mm), and the wall thickness was $t = 12.5$ mm.

4.2 | Effect of corrosion defect size on burst pressure

4.2.1 | Effect of corrosion depth on the burst pressure of the corroded pipeline

As shown in Figure 12, when the axial compressive loading of the pipeline is constant, the burst pressure of the pipeline increases as the depth of the corrosion defects increases. The effect of the axial compressive load on the blasting pressure of the pipeline varies with the depth of the corrosion defects. When the depth of the corrosion defect is larger, a smaller axial compressive load causes the burst pressure of the pipeline to decrease significantly. Therefore, the deeper the corrosion defect, the more significantly the burst pressure of the pipeline is affected by the axial compressive load. The reason for this is that the deeper the corrosion defect, the more significant the local stress concentration on the pipeline corrosion defect, so a smaller axial load can cause the pipeline to fail.

The von Mises stress of the pipeline can directly reflect the local stress concentration phenomenon of corrosion defects, which should be concerned when studying the strength of the pipeline. Figure 13 shows the effect of the corrosion defect's depth on the von Mises stress of a corroded pipeline when the internal pressure of the pipeline is unloaded. The depth of the corrosion defects and the axial compressive load affect the failure mode of the corroded pipeline. When the axial compressive load is less than or equal to $-1.1 \times 10^5$ kN, for pipelines with corrosion defect depths of $d_c/t = 0.1$, the bursting pressure of the pipeline is not very different, but the von Mises stress on the surface of the pipeline increases as the axial compressive load on the pipeline increases. With this increase, the local buckling of the pipeline occurs, and
TABLE 4  Pipeline parameters and corrosion defect geometries

| Group | Axially compressive load \((\times10^4\text{kN})\) | \(d_c/t\) | \(L_c/\sqrt{Dt}\) | \(W_c/\sqrt{Dt}\) | Material |
|-------|--------------------------------|----------|----------------|----------------|----------|
| 1     | \(-1.3 \sim 0.0\)          | 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4 | 2.0          | 1.0            | X65      |
| 2     | \(-1.3 \sim 0.0\)          | 0.2      | 1.2, 1.5, 1.8, 2.3, 2.5, 3.0 | 1.0            | X65      |
| 3     | \(-1.3 \sim 0.0\)          | 0.2      | 2.0          | 0.3, 0.5, 0.8, 1.2, 1.5, 1.8 | X65      |
| 4     | \(-1.3 \sim 0.0\)          | 0.2      | 2.0          | 1.0            | X70, X80 |

**FIGURE 12** Effect of corrosion defect depth on the burst pressure of the corroded pipeline. (A) The pipeline under the lower axial compressive load; and (B) the pipeline under the higher axial compressive load.

**FIGURE 13** Effect of corrosion defect depth on the von Mises stress contour of the corroded pipeline under the 0.0 kN, \(-0.5 \times 10^4\) kN, \(-1.1 \times 10^4\) kN and \(-1.3 \times 10^4\) kN axial compressive loads and 0 MPa internal pressure load.
the pipeline material fails. When the axial compressive load is greater than $-1.1 \times 10^4$ kN, the von Mises stress on the surface of the pipeline is small, and the pipeline is structurally unstable. Even when the axial compressive load is small, for a pipeline with a defect depth of $d_c/t = 0.4$, the burst pressure of the pipeline decreases, the von Mises stress on the surface of the pipeline will gradually decrease, and the structure of the pipeline becomes unstable. Even when the axial compressive load is small, as the axial compressive load increases, the burst pressure of the pipeline and the von Mises stress on the surface of the pipeline decrease, and the structure of the pipeline becomes unstable.

### 4.2.2 Effect of corrosion length on the burst pressure of a corroded pipeline

As shown in Figure 14, the axial length of the corrosion defect has a significant influence on the burst pressure of the corroded pipeline. When the axial compressive load on the pipeline is constant, the longer the length of the corrosion defect, the smaller the burst pressure of the pipeline. Moreover, when the length of the corrosion defect is longer, a smaller axial compressive load can significantly decrease the burst pressure of the pipeline.

Figure 15 shows the effect of corrosion defect length on the von Mises stress of the corroded pipeline when the internal pressure of the pipeline is unloaded. When the axial compressive load is constant, the longer the corrosion defects, the more pronounced the local wrinkle phenomenon. Similar to the effect of the depth of the corrosion defects, the length of the corrosion defects also affects the von Mises stress on the pipeline's surface, the degree of local wrinkling of the pipeline, and the failure mode of the pipeline. When the corrosion defect is short and the axial compressive load is small, an increase in the load increases the von Mises stress on the surface of the pipeline, the local buckling phenomenon of the pipeline gradually becomes significant, and the pipeline material fails. As the axial compressive load increases, the von Mises stress on the surface of the pipeline gradually decreases, but the degree of the local folding weakens, and the pipeline usually suffers from structural instability. When the length of the corrosion defect is long, a pipeline subjected to an axial compressive load is prone to structural instability.

### 4.2.3 Effect of corrosion width on the burst pressure of a corroded pipeline

As shown in Figure 16, the width of the corrosion defects has little effect on the burst pressure of the pipeline. When the axial compressive load is high, the wider the corrosion defects, the lower the burst pressure of the pipeline. When the axial compressive load is low, the width of the corrosion defects has little effect on the burst pressure of the pipeline. The effect of corrosion defect width on the von Mises stress of the corroded pipeline is shown in Figure 17. When the internal pressure of the pipeline is unloaded, and the same axial compressive load is applied, the smaller the width of the corrosion defect, the more significant the local wrinkling of the pipeline. The wider the corrosion defects, the more sensitive the von Mises stress and the local folds in the pipeline are to axial compressive loading. When the width of the corrosion defect and the axially compressive load are small, the pipeline material fails. When the width of the corrosion defect is wide enough, or the axially compressive load on the pipeline is large enough, the pipeline is prone to structural instability.

![Figure 14](image_url)  
**Figure 14** Effect of corrosion defect length on the burst pressure of the corroded pipeline. (A) The pipeline under the lower axial compressive load; and (B) the pipeline under the higher axial compressive load.
Three types of pipeline materials were investigated in the FEA. The material parameters are shown in Table 4, and the true stress-strain curves of the pipeline materials are shown in Figure 4. Figure 18 shows that the burst pressure increases as the $Y/T$ ratio increases. The X80 pipeline material has the highest tensile strength and ultimate bearing capacity. This is because when a corrosion defect pipeline is subjected to internal pressure, the pipeline undergoes elastic deformation first. When the equivalent stress at the defect area reaches the yield strength of the pipeline, the pipeline deforms plastically until it reaches the tensile strength, and then, local instability occurs.

Figure 19 shows the effect of the material properties on the von Mises stress of a corroded pipeline when the internal pressure of the pipeline is unloaded. For the same
axial force, the local von Mises stress of the corrosion defects of the X80 pipeline is greater than that of the X70 pipeline. The von Mises stress distributions of the pipelines subjected to 0.0 kN and $-1.1 \times 10^4$ kN of axial compression are not very different. However, the local folding phenomenon is more significant in the latter. When the axial force is $-1.3 \times 10^4$ kN ~ 0.0 kN, the burst pressure of the X80 pipeline is almost equal, but the greater the axial compression load, the more significant the local wrinkling of the pipeline.

5 | AN ARTIFICIAL NEURAL NETWORK BASED BURST PRESSURE PREDICTION METHOD FOR CORRODED STEEL PIPELINES

5.1 | Burst pressure prediction model based on an artificial neural network

Artificial neural network is an effective machine learning regression analysis model, which composed of many simple processing units, and its function depends on the structure of the network, the connection strength, and the processing methods of each unit. Artificial neural network is suitable for big data processing. The model can be divided into an input layer, one or more hidden layers, and an output layer.

Artificial neural network (ANN) technology is used in the simulation, abstraction, and simplification of brain function, and it has the functions of learning, association, memory, and a highly nonlinear prediction ability. It has been widely used in burst pressure prediction of oil and gas pipelines. In this study, ANN technology is used to predict the burst pressure of corroded steel pipelines. The burst pressure of the pipeline can be predicted based on the corrosion defect parameters and the axial force, by adopting the ANN technology. Meanwhile, the ANN method is efficient and the prediction result is reliable.

The ANN toolbox in MATLAB was used to build the ANN. In this study, the transfer function between the input layer and the hidden layer was set to be "logsig", while
the transfer functions between the hidden layer and the output layer were set to be “purelin”. By comparing several kinds of ANN structures with different numbers of neurons and hidden layers, a neural network suitable for failure pressure prediction was obtained. We determined that 2 hidden layers with 6 neurons are the best choice for the presented problem. The structure of the ANN with 2 hidden layers with 6 neurons is illustrated in Figure 20.

5.2 Prediction model validation

There are 437 sample points in the training database, and their parameter values are listed in groups 1-4 in Table 4. A comparison of the FEM results and the training results is shown in Figure 21. The total elapsed time of this model is 10.11 s, and the relative error between the training results and FEM results is less than 20%. Most of the relative errors are less than 10%. Therefore, the ANN-based burst pressure prediction method for corroded X65 steel pipelines is accurate.
6  CONCLUSION

In this study, a finite element model of a corroded pipeline subjected to an axial compressive load was established, the burst pressure of the pipeline was calculated, the results were compared with experimental data from the literature, and the reliability of the finite element model was verified. The average error of the finite element simulation results is 11.33%. The effects of the axial compressive load, the corrosion defect size, and the pipeline material properties on the burst pressure of corroded pipelines were studied.

When the size of the corrosion defect and the axial compressive load is small, the burst pressure of the pipeline does not significantly change with the axial compressive load, and the pipeline material fails. When the size of the corrosion defect is large enough, or the axial compressive load of the pipeline is large enough, the burst pressure of the pipeline decreases significantly as the axial compressive load increases, and the pipeline is prone to structural instability.

The larger the corrosion defect size, the lower the pipeline's burst pressure. Compared with the effects of the depth and length of the corrosion defects, the width of the corrosion defects has less effect on the burst pressure of the pipeline. When the axial compressive load is small, the width of the corrosion defect has little effect on the burst pressure of the pipeline.

The lower the steel grade of the pipeline, the smaller the $Y/T$ ratio, and the smaller the burst pressure of the pipeline. Compared with the X65 pipeline and the X70 pipeline, the X80 pipeline has a higher $Y/T$ ratio and has the highest burst pressure, and when the X80 pipeline is subjected to an axial compressive load of $-1.3 \times 10^4$ kN $\sim 0.0$ kN, the burst pressure does not significantly change. Therefore, the use of high strength steel pipelines can effectively ensure the safety of pipeline operations.

In addition, the burst pressure analysis results of the pipelines with corrosion defects subjected to axial compressive loading show the following.

The greater the axial compressive load, the more obvious the stress concentration phenomenon in the pipeline corrosion defect area. The smaller the pipeline corrosion defect size, the more significant the stress concentration phenomenon in the pipeline corrosion defect area.

The smaller the depth and width of the corrosion defect, the more significant the local wrinkling of the pipeline. As the length of the corrosion defect increases, the more likely the plastic deformation pipeline will occur.

Based on 437 sample points in the training database, an artificial neural network prediction model was developed. A comparison of the FEM results and the training results shows that the ANN model is accurate, and the relative error between the training results and the FEM results is less than 20%.

ACKNOWLEDGMENTS

This paper is supported and funded by programs with Fundamental Research Funds for the Central Public Welfare Research Institutes (Grant no.TKS 20200316, TKS 20200320, TKS 190108).

ORCID

Lecai Liang  https://orcid.org/0000-0003-0542-9941

REFERENCES

1. ASME B31G–2009, Manual for determining the remaining strength of corroded pipelines.
2. API 579–2000, Recommended practice for fitness for service.
3. SY/T 6151–2009, Assessment of corroded steel pipelines.
4. DNV RP-F101–1999, Recommended practice RP-F101 corroded pipelines.
5. BS-7910, Guidance on the method for assessing the acceptability of flaws in metallic structure[S]. British Standard, Britain, 2005.
6. CAN/CSA-Z184-M86, Gas pipeline system[S]. Canadian Standard Association, Canada, 1996.
7. Hopkins P, Jones DG. A study of the behavior of long and complex shape corroded in transmission pipelines. Proceedings of the 11th International Conference of Mechanic and Arctic Engineering, Calgary, Canada, June 7-11, 1992[C]. Calgary: ASME, 1992.
8. Benjamin AC, Freire JLF, Vieira RD, et al. Burst tests on pipeline containing interacting corrosion defects[C]. The 24th International Conference on Offshore Mechanics and Arctic Engineering, Halkidiki, Greece, 2005:1-15.
9. Silva RCC, Guerreiro JNC, Loula AFD. A study of pipeline interacting corrosion defects using the FEM and neutral networks. Adv Eng Mater. 2007:38:868-875.
10. Kim W, Kim Y, Choi J. Full scale burst test and finite element analysis on corroded gas pipeline[C]. The 4th International Pipeline Conference, Calgary, Alberta, Canada: 2002:1-8.
11. Freire JLF, Vieira RD, Castro JTP, et al. Part 3- Burst tests of pipeline with extensive longitudinal metal loss. Exp Tech. 2006:30:68-65.
12. Jian S, Chun’e Z, Fulai C. Prediction of failure pressure in corroded pipelines based on non-linear finite element analysis. Acta Petrolei Sinica. 2008;29(6):933-937.
13. Liang hao H. Limit load analysis for local wall-thinning pipeline under internal pressure. Press Vessel Technol. 1998;12(4):1-44-48-86.
14. Wenjun C, Guoming C, Dongming P. Nonlinear analysis on remaining strength of corroded pipeline. J China Univ Petr. 1999;23(1):79-81+9-10.
15. Yanfei C. Study on failure mechanism and ultimate load capacity of corroded submarine pipeline. Dalian: Dalian University of Technology; 2009.
16. ABAQUS/Standard User’s Manual (ver 6.13). Providence, RI: Dassault Systèmes Simulia Corp.; 2013.
17. Fatemi A, Kenny S, Sen M, et al. Parameters affecting the buckling and post-buckling behaviour of high strength pipelines. ASME International Conference on Ocean; 2009.

18. Yongyi W, Ming L, Yaxin S. Second generation models for strain-based design [R]. U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration, PRCI Report PR-ABD-1-Project 2; 2011.

19. Canadian Standards Association. Oil and Gas Pipeline Systems[S]. Rexdale, ON; 2015.

20. General Administration of Quality Supervision, Inspection and Quarantine of the People’s Republic of China, GB/T9711-2017. Petroleum and Natural Gas Industries-Steel Pipeline for Pipeline Transportation Systems. Beijing: China Quality Inspection Press; 2017.

21. Liu M, Zhou HG, Wang B, Wang YY. Strain-Based Design and Assessment in Critical Areas of Pipeline Systems with Realistic Anomalie. Center for Reliable Energy Systems; 2017.

22. Bjornoy OH, Sigurdsson G, Cramer EH. Remaining strength of corroded pipelines, DNV test results[C]. 10th International Offshore and Polar Engineering Conference; 2000:189-194.

23. Liu X, Xia M, Bolati D, et al. An ANN-based failure pressure prediction method for buried high-strength pipelines with stray current corrosion defect. Energy Sci Eng. 2019;8(8):248-259.

How to cite this article: LU L, LIANG L. Numerical investigation of corroded middle-high strength pipeline subjected to combined internal pressure and axial compressive loading. Energy Sci Eng. 2021;9:798–811. https://doi.org/10.1002/ese3.830