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Research paper

Corroded pipeline failure analysis using artificial neural network scheme

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ABSTRACT

Corrosion defects occur very often on the internal and external surfaces of pipelines, which may result in a serious threat to the integrity of the pipelines. Numerous studies investigated failure behavior of corroded pipelines with single corrosion defects. However, few studies focus on interacting corrosion defects. Interacting defects are defined as defects with certain proximity that interact to reduce the overall strength of a pipeline. In the present study, the failure behavior of pipelines with interacting corrosion defects was studied using a finite element method, and then a solution was proposed to predict burst pressure using an artificial neural network. The solution was validated by experimental results in previous studies and compared with other existing assessment solutions to prove its applicability and efficiency.

1. Introduction

Pipelines comprise the main equipment for transporting gas and oil to downstream facilities. A network with more than 207,800 miles of liquid pipelines is spread over 300,000 miles of gas transmission pipelines and more than 2.1 million miles of gas distribution pipelines exist in the United States [1]. There are more than 840,000 km of transmission, gathering, and distribution pipelines in Canada [2]. However, harsh environments could lead to the occurrence and growth of corrosion defects, which are a main reason for pipelines failure accidents. For example, on September 23, 2008, a ruptured pipeline caused a fire because of external corrosion at a Pipeline Terminal in Pasadena, Texas in which a worker was killed and another injured with approximately 190,000 US gallons of product loss [3]. Therefore, there is a pressing need for improved integrity assessment of corroded pipelines to avoid large damages due to accidents.

Intensive studies focused on investigating the failure behavior of pipelines with single defects [4–10]. Additionally, several assessment methods examined the burst pressure of corroded pipelines and are widely practiced by industries. These include the ASME B31G method [11], the DNV RP-F101 method [12], and ABS method [13]. However, few studies focus on interacting defects, and existing assessment methods are considered conservative [14,15]. Specifically, these assessment methods calculate the failure pressure of pipelines with interacting defects using the overall length and the maximum depth, but the full thickness of the strip material between the defects is not considered. Therefore, these methods will likely to underestimate the failure pressure.

Interacting defects are defined as defects with certain proximity that interact to reduce the overall strength of a pipeline. The interaction tends to be negligibly small when the distance between defects increases and exceeds one limit value. Consequently, the burst pressure becomes identical to that of the isolated defect. Therefore, the interaction rule and a general solution to determine burst pressure are required to assess the limit pressure capacity of pipeline with interacting defects. The ASME B31G code recommends classification of defects as interacting defects if the longitudinal spacing (SL) and circumferential spacing (SC) between the defects satisfy the following conditions:

$$S_L \leq 3t \tag{1}$$

$$S_C \leq 3t \tag{2}$$

where t denotes the wall thickness of the pipeline.

The interaction rule of DNV RP-F101 is as follows:

$$S_L \leq 2\sqrt{D_e t} \tag{3}$$

$$S_C \leq \pi\sqrt{D_e t} \tag{4}$$

where De denotes external diameter.

Benjamin A.C. et al. conducted burst pressure tests with twelve tubes with single defects and interacting defects and proposed

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Nomenclature

D	external diameter of the pipe [mm]
d	depth of the corrosion defect [mm]
d/t	the ratio of defect depth to the pipeline thickness
E	Young's modulus [MPa]
L_0	length of the pipe [mm]
L	length of the corrosion defect [mm]
L/t	the ratio of defect length to the pipeline thickness
N_h	the number of neurons in the hidden layer
N_i and N_o	the number of inputs and outputs in ANN model
P_f	the failure pressure of a pipe with interacting defects [MPa]
P_0	the failure pressure of a pipe with single defects [MPa]
P_f/P_0	the ratio of the failure pressure of pipe with interacting defects to the failure pressure of a pipe with a single defect
R, r	radius of the rounded corner of corrosion defect [mm]
t	original wall thickness of the pipe [mm]
S_L	longitudinal spacing between defects [mm]
S_C	circumferential spacing between defects [mm]
$S_L/\sqrt{Dt}$	dimensionless longitudinal spacing
$S_C/\sqrt{Dt}$	dimensionless circumferential spacing
V_{ho} and W_{ih}	Synoptic weight
ν	Poisson's ratio
w	width of the corrosion defect [mm]
w/t	the ratio of defect width to the pipeline thickness
σ_u	true ultimate tensile stress [MPa]

a new method termed as the MTI (Mixed Type of Interaction Method) to predict the burst pressure of corroded pipelines [16]. Chen Y.F. et al. investigated the failure behavior of X80 pipelines with longitudinally and circumferentially aligned defects using finite element method and developed an assessment procedure to predict the failure pressure of pipelines with interacting defects based on regression equations proposed for pipelines with single defects [17]. However, these studies only considered equally shaped defects with different defect depths, longitudinal separation, and circumferential separation. They ignored the effect of defect length on the burst pressure of corroded pipelines.

In this study, the effect of defect length was considered while investigating the failure behavior and burst pressure of pipelines with interacting defects. First, a series of numerical models were created using API X80 pipelines that contained varied geometries of artificial defects and different separations between the defects. This was followed by comparing the numerical results with experimental results obtained by extant studies for validation purposes. Furthermore, extensive parametric studies were performed to determine the manner in which the defect length, depth, and interaction space influenced the burst pressure of corroded pipelines. More importantly, based on these efforts, an alternative assessment method for burst pressure of pipelines with interacting defects was implemented by using an artificial neural network (ANN). In 2007, Silva R.C.C. et al. presented interaction rules for pipelines with interacting defects using an ANN model and demonstrated the possibility of using the ANN method to determine the burst pressure [18]. However, the results of his study were not validated owing to the lack of an available experimental database. In addition, FEA models were created using shell elements instead of solid elements, which may provide less accurate results than those generated using solid models. First, use of shell elements cannot describe the exact geometrical characteristics, such as the rounded corners of the defects, which can reduce the effect of stress concentration, thereby influencing the estimation of the predicted failure pressure. Furthermore, when the corroded pipelines are subjected to internal pressure, the thickness of the corroded ligament is likely to be changed and von Mises stresses through the ligament are different. However, these phenomena cannot be adequately represented using the shell models. In the present study, the proposed ANN model was compared with the experimental results by Benjamin A.C. et al. and two existing assessment codes for validation. The findings revealed that the proposed model produced less conservative results to predict the burst pressure of pipelines with interacting defects.

Table 1
Mechanical properties of the API 5L X80 steel pipeline [19].

Material	D (mm)	t (mm)	E (GPa)	ν	σ_y (MPa)	σ_u (MPa)
API 5L X80	458.8	8.1	200	0.3	534.1	718.2

2. Verification of finite element analysis

2.1. Modeling of a corroded pipeline with interacting corrosion defects

Corroded pipe models are created using solid elements with two or more equal base defects on the external surface. The geometry of the base defect is described by several parameters including length L, depth d, width w, and fillet radius r and R as shown in Fig. 1. These base defects are located aligned or are in an arbitrary configuration. As shown in Fig. 2, longitudinal separation SL and circumferential separation SC are used to illustrate the spacing between defects.

2.2. Material properties

The material considered in this study corresponded to the API 5L X80 steel pipeline that is currently used in oil and gas transmissions. Material properties were defined based on previous experimental data obtained by De Andrade et al. [19]. The mechanical properties and dimensions of the API 5L X80 pipeline are illustrated in Table 1. Indicatively, σ_y and σ_u refer to the yield and the true ultimate tensile stresses, respectively. An ABAQUS program was used to perform the FE analyses, and the true stress–plastic strain curve—shown in Fig. 3 was input into the program as a piecewise linear representation. Additionally, a rate-independent plasticity model using the von Mises yield criterion and the isotropic hardening rule was adopted.

2.3. Boundary and loading conditions

With respect to corroded pipe models with longitudinal and circumferential aligned defects, only a quarter of a model that adequately implemented the symmetric boundary conditions was created to reduce computation time. As shown in Fig. 4(a), half of the wall was symmetrically restricted in the x-direction. In order to simulate plain strain conditions, both ends are restricted in the z-direction using symmetric boundary condition to restrain pipe from expanding or contracting axially, while the model was allowed to expand or contract radially. In addition, a node in the axial direction at the end farthest away from the defective area was fixed to avoid rigid motion of the model [20].

The full model was created for simulation purposes with respect to the FE models with defects in arbitrary locations. As

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