Journal of Solid and Fluid Mechanics (JSFM), 13(5): 1-4, 2024

Shahrood University of Technology

Journal of Solid and Fluid Mechanics (JSFM)

DOI: 10.22044/JSFM.2023.13373.3763

Manufacturing Engineering of Iran

Failure prediction in defective pipelines using finite element simulation of fluid-structure interaction and neural network method

M. Shirafkan[1], H. Afrasiab [2,*], A. Divsalar[3], A.M. Baghestani[4], M. Rahmati[5]

[1] MSc. Student, Mech. Eng., Babol Noshirvani University of Technology, Mazandaran, Iran
[2] Assoc. Prof., Mech. Eng., Babol Noshirvani University of Technology, Mazandaran, Iran
[3] Assist. Prof., Mat. Ind. Eng., Babol Noshirvani University of Technology, Mazandaran, Iran
[4] Assist. Prof., Mech. Eng., Babol Noshirvani University of Technology, Mazandaran, Iran
[5]Ph.D. Student, Mech. Eng., Babol Noshirvani University of Technology, Mazandaran, Iran
*Corresponding author: afrasiab@nit.ac.ir

Received: 07/15/2023 Revised: 10/15/2023 Accepted: 12/05/2023

Abstract

The occurrence of pipeline failures can lead to significant damage to the environment and natural resources, as well as high repair costs. In this study, the finite element simulation is employed to model the fluid-structure interaction between the fluid flow and the damaged pipe wall to investigate stress distribution and failure in damaged pipes. Given the time-consuming nature of this simulation, an artificial neural network is also used to predict the behavior of the damaged pipe. This neural network is trained using a recurrent backpropagation algorithm. To this end, the maximum stress in the damaged pipe is considered as the objective function and is calculated by the finite element method for different values of the flow velocity, size, distance, and depth of the defects. The design parameters are selected by Taguchi method to optimize the neural network structure and increase its accuracy. The results have suggested that combining the finite element and artificial neural network methods is an effective approach for failure prediction in defective pipelines.

Keywords: Defects of fluid transmission pipes, Fluid-structure interaction, Artificial natural network, Failure prediction

1. Introduction

Pipelines are one of the most common methods of fluid transportation worldwide. These pipelines transfer oil and gas to processing units, distilleries, refineries, or terminals for export. The occurrence of fractures in these pipelines entails significant human and financial losses, including environmental damage, depletion of natural resources, and high repair costs [1,2]. Hence, numerous studies have been conducted to examine the behavior of damaged pipelines. For example, Bruère et al. in 2019 investigated the behavior of corroded pipelines under a combination of internal pressure and axial compressive force using the finite element method [3]. Kong et al. In 2020 utilized experimental and finite element methods to study the performance of damaged and repaired pipes [4]. Gholami et al. in 2021 implemented an elastic-plastic strain-hardening homogeneous round pipe model for finite element modeling of defective steel pipes [5]. Sakonder and Paredes in 2023 employed a temperature-dependent failure criterion to study the mechanical response of a damaged steel pipe at different temperatures [6].

The condition of each pipe can be assessed through direct inspection or using methods such as electromagnetic testing, acoustic monitoring, or radar. However, due to the high costs associated with direct inspection and its impracticality in certain conditions, predicting failure through analytical methods and modeling is of particular importance. Additionally, a review of previous studies indicates a gap in systematic and comprehensive research where pipes have multiple localized damages adjacent to each other, and the combined effect of these damages leads to deterioration of the pipe's strength. Moreover, in most studies, the fluid pressure on the pipe wall is considered as a constant internal pressure, while in areas of pipelines such as bends or points where the pipe diameter changes, pressure variations exist.

This necessitates the analysis of fluid flow and accurate application of fluid pressure to the pipe wall through fluid-structure interaction analysis.

Considering the above-mentioned factors, in the current study, fluid-structure interaction simulation within the framework of the finite element method has been employed to accurately determine the pressure on critical points of the pipe. Additionally, instead of assuming a single damage on the pipe, side by side square-shaped damages have been assumed to study the behavior of the pipe for different scenarios where adjacent damages are present. Due to the time-consuming nature of finite element modeling, an artificial neural network model has been utilized to predict failure pressure. The neural network was trained using the results of finite element simulations. To obtain an optimal structure for the neural network and enhance its accuracy, the values of design parameters were determined using the Taguchi method.

2. Methodology

To investigate the effect of various variables on the maximum stress imposed on damaged pipes, the fluid passing through pipes with damage in bends has been examined. The choice of bends was due to the fact that they are subjected to the highest fluid pressure. To achieve fully developed flow and avoid negative pressure at the pipe's outlet, a long length has been selected for the pipe inlet [7,8]. The characteristics and material of the simulated pipelines are presented in Table (1).

Table 1. Material and Characteristics of the Pipelines

Material	polyethylene
Geometric Dimensions	Pipe diameter: 458.8 mm Pipe thickness: 8.1 mm Pipe bending curvature: 1.5 times larger than pipe diameter
Mechanical Properties	Density: 950 kg/m3 Elastic modulus: 1100 MPa Poison’s ratio: 0.42 Yield strength: 25 MPa Ultimate strength: 33 MPa

The flow through the pipe is assumed to be steady, incompressible, and fully developed. The term "damage" to the pipes refers to deformations caused by the impact of an external body in the external surface of the pipe. The damages have a square shape, and it is assumed that multiple damages are present side by side on the pipe. The dimensions of the damages (length, width, and depth) are chosen as proportions of the pipe's inner diameter, and by changing these proportions, the behavior of the pipe has been studied.

To determine the location of damage on the pipes, the most critical region in the bend was identified. Different values of fluid velocity were used in various simulations. The problem was modeled using ANSYS and Fluent software. A structured grid was used for problem meshing, and finer and denser elements were used in sensitive areas such as around the damage and bend regions. Additionally, to achieve a solution that is independent of the mesh, element convergence tests were performed. In the convergence test, the maximum von Mises stress for the solid part and the maximum pressure for the fluid part were used as convergence criteria. A sample of the meshing of damages on the pipe bend is shown in Figure (1).

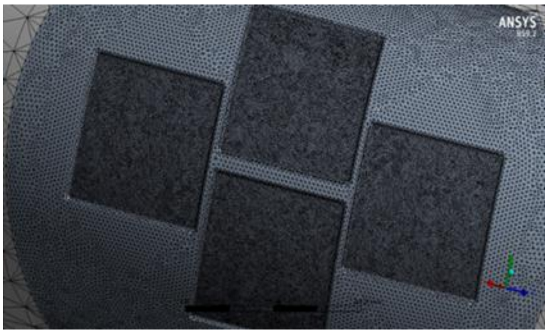

Figure 1. A sample of the meshing of damages on the pipe bend

2.1 Artificial Neural Network Modeling

In fluid-structure interaction problems, it is necessary to solve two separate domains for the fluid and solid mediums individually. After exchanging information such as fluid forces and solid displacements between the two domains, the fluid-structure coupling problem is solved. Therefore, performing this simulation is a time-consuming process. However, by training and utilizing a neural network, this time can be reduced to a few minutes. Hence, to reduce computational costs and time in this article, a neural network approach with the error backpropagation algorithm has been employed.

To form the artificial neural network, four influential factors, including fluid velocity, damage size and depth, and distance between damages have been chosen as input parameters, and the maximum stress imposed on the pipe has been selected as the output. In order to determine the optimal levels of the required parameters, Taguchi experimental design method is employed.

3. Results and discussion

To ensure the accuracy of the performed modeling, the pipe failure pressure obtained through finite element simulation has been compared with the experimental result presented in the reference [9]. For the geometry given in Table (1) and fluid velocity of 0.65 m/s, the failure pressure obtained by the finite element method was determined to be 17.85 MPa, which is slightly lower than the experimental value presented in the reference [9] (18.66 MPa) by about 4%. This small difference indicates the satisfactory accuracy of the modeling method used in the present study.

3.1 Finite Element Simulation Results

3.1.1 Effect of fluid velocity on the pipe stress

The stress distribution in different fluid velocities is illustrated in Figure (2). According to this figure, the highest stress occurs precisely in the middle of the four damages, where the interaction and interference between the damages are maximum. Moreover, with an increase in fluid velocity, the maximum stress exerted on the pipe also rises.

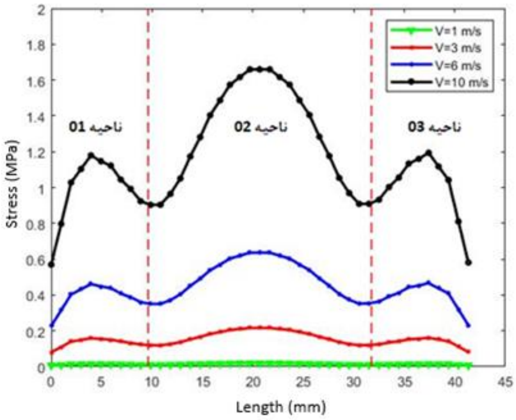

Figure 2. Comparison of stress variations at different fluid velocities.

3.1.2 Effect of damage size on the pipe stress

To investigate the effect of the damage size on the pipe stress, the side length of the damages was varied from one-fifteenth to one-third of the pipe diameter. It was observed that with an increase in the size of the damage, the maximum stress on the pipe increases.

3.1.3 Effect of damage depth on the pipe stress

Figure (3) shows the effect of damage depth on the maximum von Mises stress generated in the pipe. According to this figure, if the depth of the damage exceeds 7 mm, the maximum stress will significantly increase. This suggests a very high risk of pipe failure if it continues to be operated with deep damages. On the other hand, damages with large edges and shallow depth are not as hazardous.

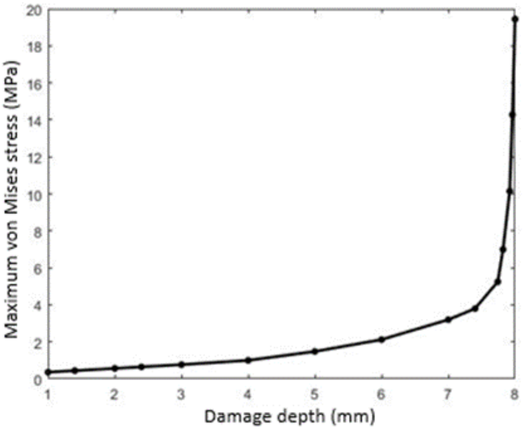

Figure 3. Effect of damage depth on the pipe maximum stress

3.1.4 Effect of distance between damages on the pipe stress

To examine the effect of the distance between damages on the stress generated in the pipe, the center-to-center distance between the damages was measured based on the length of the damage edge. The results showed that with increasing the distance between damages, their interaction decreases, and the magnitude of the pipe stress is reduced.

3.2 Results of the neural network

3.2.1 Effect of fluid velocity and damage size on the pipe stress

Figure (4) illustrates the effect of variations in fluid velocity and damages size on the stress imposed on the pipe, while keeping other parameters constant. Based on this figure, as the damages size increases, the stress rises in the pipe. Furthermore, with the increase of fluid velocity to its maximum value, the stress reaches its maximum level.

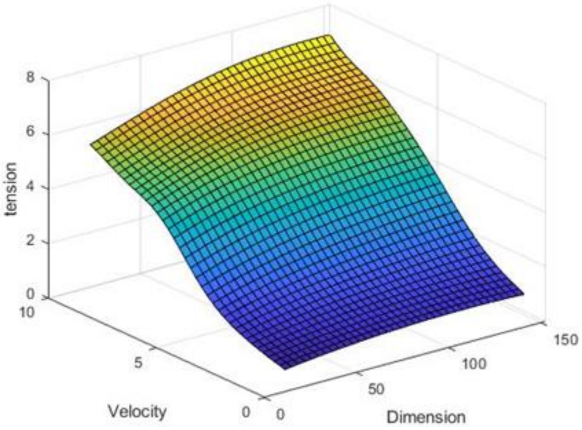

Figure 4. Effect of fluid velocity and damage size on the stress generated in the pipe.

3.2.2 Effect of fluid velocity and distance between damages on pipe stress

According to the results, as the fluid velocity increases, the interaction effect of damages increases. When the fluid reaches maximum velocities and the distance between damages decreases, the pipe stress increases.

3.2.3 Effect of fluid velocity and damages depth on the pipe stress

The results suggest that as the damage depth increases, the stress on the pipe also increases. The impact of the depth is so pronounced that at higher values, variations in fluid velocity have a minimal effect on the stress imposed on the pipe, becoming hardly noticeable.

3.2.4 Effect of size and distance of damages on the pipe stress

According to the results, the minimum stress occurs when the distance between the damages is large, and their size is at its minimum. With an increase in the size of damages, the stress also increases.

3.2.5 Effect of size and depth of damages on the pipe stress

The study indicates that increasing the depth of damage has a significant impact on increasing the stress imposed on the pipe, especially at greater depths, making the effect of changes in the size of damages on the stress imposed on the pipe difficult to observe.

3.2.6 Effect of the depth and distance between damages on the pipe stress

damage, the stress imposed on the pipe increases, and the importance of the distance between the damages is much less than the depth of the damage.

4. Conclusions

In this study, a combination of finite element modeling of fluid-structure interaction and artificial neural network method was employed to investigate stress in pipes with multiple damages. The results demonstrated that this combined approach is suitable for predicting failure in damaged pipes with fluid flow. According to the results, the risk of pipe failure increases with increase of fluid velocity, dimensions of the damage, depth of the damage, and decreasing distance between the damages. Additionally, it was observed that the depth of the damage has a much greater impact on the stress imposed on the pipe compared to the area of the damage. The interaction and synergistic effects of multiple damages, especially when they are close to each other, were found to be significantly more hazardous than a single damage. The comparison of results obtained from the neural network with finite element results indicates an acceptable agreement between the two methods. Given that the use of the neural network significantly reduces the analysis time, employing this method in combination with the finite element method is recommended for conducting accurate and efficient studies on failure in damaged pipes.

References

[1] Weng G, Ding J, Cao J, Hui Y (2023) Experiment and numerical simulation of stress detection for oil and gas pipelines based on magnetic stress coupling of pipeline steel. *Structures* 55:2478–2490.

[2] Woldesellasse H, Tesfamariam S (2023) Risk analysis of onshore oil and gas pipelines: Literature review and bibliometric analysis. *J Infrastruct Intell Resil* 100052.

[3] Bruère VM, Bouchonneau N, Motta RS, Afonso SMB, Willmersdorf RB, Lyra PRM, Torres JVS, de Andrade EQ, Cunha DJS (2019) Failure pressure prediction of corroded pipes under combined internal pressure and axial compressive force. *J Braz Soc Mech Sci Eng* 41:172.

[4] Kong D, Huang X, Xin M, Xian G (2020) Effects of defect dimensions and putty properties on the burst performances of steel pipes wrapped with CFRP composites. *Int J Press Vessels Pip* 186:104139.

[5] Gholami H, Shahrooi S, Shishesaz M (2021) A new approach for prediction of the remaining strength of pipeline with external defects. *Eng Fail Anal* 130:105754.

[6] Li Y, Sakonder C, Paredes M (2023) Plastic collapse analysis in multiaxially loaded defective pipe specimens at different temperatures. *J Pipeline Sci Eng* 3:100092.

[7] Alaei E, Afrasiab H, Dardel M (2020) Analytical and numerical fluid–structure interaction study of a microscale piezoelectric wind energy harvester. *Wind Energy* 23:1444–1460.

[8] Afrasiab H, Movahhedy MR, Assempour A (2011) Finite element and analytical fluid-structure interaction analysis of the pneumatically actuated diaphragm microvalves. *Acta Mech* 222:175.

[9] Benjamin AC, Freire JLF, Vieira RD, Diniz JLC, De Andrade EQ (2005) Burst Tests on Pipeline Containing Interacting Corrosion Defects. 24th Int. Conf. *Offshore Mech. Arct. Eng.* Vol. 3. ASMEDC, Halkidiki, Greece, pp 403–417