

Risk-based inspection planning for internal surface defected oil pipelines exposed to fatigue

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ABSTRACT

The pipelines should be inspected periodically to minimize the probability of failure. The timing of these periodic inspections can be determined by a risk assessment that considers the probability of failure of the pipeline and the potential undesirable effects of the chemical transferred. These are referred to as risk-based inspection methods in the literature. We evaluate pipelines with internal surface defects and under the effect of variable pressure in this study. Internal surface defects were considered production-related, and there is a lack of studies in the literature examining such kinds of defects. These defects generate the concentration of stress on the pipeline section. The reliability variation of the pipeline depends on some factors, namely, surface defect geometry, the pipe section geometry, and the mechanical properties of the pipe. Fatigue is accepted as the crucial damage mechanism. The cause of variable load is considered as the number of operations. As a result of the study, the probability of fatigue failure for pipelines with internal surface defects was evaluated. Then, a new approach was proposed for risk-based inspection planning of the pipelines. As a case study, the probability of fatigue failure on a fuel pipeline established between a refinery and an oil terminal operating in Turkey was calculated. Also, we tried to determine the most appropriate inspection time. The data used in the planning phase was collected from a measurement process performed on the pipeline using PIG (Pipe Inspection Gauge). Finite element analysis was used to calculate stress concentration factors. Finally, we used the Monte Carlo simulation method to obtain the probability of failure.

1. Introduction

Pressurized equipment such as tanks, pipelines, boilers, heat exchangers, etc., which operates in the chemical, oil, and natural gas industries, fatigue is caused integrity losses to occur because of defects arising from production or environmental mechanism. Because of this situation, the chemical process equipment released hazardous liquids or gases into the environment. This process is a threat to human health in the long term due to the harmful effects of the chemical. Additionally, these releases cause instantaneous undesirable results such as fire, flashing, or an explosion depending on the properties of the chemical, and this possibility threatens the life of laborers and people around. The loss of containment that occurs in pipelines will cause direct costs such as the repair of the pipeline, the operating cost of the waiting time during the repair period, and the replacement cost of wasted chemicals.

Additionally, it can also cause indirect costs such as compensations due to possible work accidents, the cost of cleaning activities to reduce

the negative effects on the environment, and punishments from authorities. The pipelines should be periodically inspected to prevent such undesirable situations. The inspectors perform nondestructive testing methods. The magnetic flux leakage (MFL) method is acceptable for pipelines. The inspection process can be conducted at fixed time intervals, or the frequency and the inspection can also be decided because of a risk assessment. In the literature, this approach is defined as a risk-based inspection method. The risk-based inspection method ensures that inspections are performed at a low cost and an acceptable risk level. The risk-based inspection method considers relative variables such as the physical and environmental conditions of the facility, the operating chemicals to which the equipment is exposed, and the frequency of using the equipment. Therefore, the method is applied specifically to the facility and is systematic.

Various suitable standards show how the method can apply in the literature. The well-known methods are the American Petroleum Institute's API 581 code of practice [1], Norway's accredited certification

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body Det Norske Veritas's DNV RP - G101 [2], and DNV GL of RP- C210 [3] standards. In these sources, how the risk-based inspection method should be applied for different types of equipment under various conditions of use has been systematically discussed and explained in some case studies. BS 7910 [4] is another appropriate guide that similar purposes prepared for evaluating whether the cracks formed on metallic structures are at an acceptable level. In the literature, the first application of the method goes back to the last decade using structural components with the definition of reliability-based periodic inspection planning. In these applications, the probability of failure is obtained for the structural parts, and inspection planning is conducted using these probabilities [5–8]. By the 2000s, the method began to be called risk-based inspection planning, with the possible consequences of damages, and the American Petroleum Institute published its first guide in this field [9]. In this manner, the applicability of the method on pressurized equipment has been demonstrated. In the same years, this approach was studied on oil pipelines [10]. Although risk-based inspection planning was initially conducted on structural components, some studies are used for large structural systems [11]. Applications of the method in the industry have also been conducted, and the risk-based inspection method has been used to evaluate the maintenance strategy in the process within a unit at a refinery [12]. Singh and Pokhrel [13] used fuzzy logic method to predict the microbiological corrosion rate in equipment such as pipes and pressure vessels made of carbon steel. In the estimation of reliability, they used the fuzzy membership function as the likelihood function. Luque and Straub [14] proposed an integrated risk-based inspection methodology for a structural system subject to fatigue for structural systems. Other studies in the literature focused on the fatigue damage in offshore platforms. Fatigue reliability is one of the most crucial design criteria for welded steel parts of offshore platforms. Due to repeated wave loading, fatigue cracks can start and grow in welded joints, which is significant to the integrity of these structures. Lotsberg et al. [15], used the fracture mechanics analysis method in the periodic inspection planning of offshore platforms. In the paper, probabilistic methods were used to estimate the growth in fatigue crack size in the structure over its service life. Results were validated with S–N data. The study was based on the DNV GL recommended practices. In another study, Lassen and Recho [16] conducted periodic inspection intervals of structural elements of offshore platforms using Monte Carlo simulation and the Markov chain model. From the literature survey, we understood that the risk-based inspection method is significant for structural components and pressurized equipment.

From the literature review, there are increasing number of studies noticed that examining the effects of pipeline defects on fatigue strength of the pipe sections. Corrosion is one of the most important failure mechanism that effect the fatigue strength of the pipeline. Cunha et al. [17], investigated the fatigue strength of the pipeline to different sized pitting corrosion under the effect of thermal stress. Mokhtari and Melchers [18] examined the relationship between stress concentration factor (SCF) and corrosion pit geometry. They indicated that complex shaped pits create greater SCF's than idealized geometries and idealized geometries of pits may overestimate the fatigue life. Dents are one of the most common defects on pipe wall. Shuai et al. [19], investigated pressurized pipe's mechanical behavior of dents and the stress concentration using experimental and finite element methods. Luo et al. [20], investigated dent leak in a gas pipeline in China. They concluded that fatigue failure occurred cause of stress concentration occurred on dented pipe section. There are also studies examining the effect of dents that occur because of the impact to the pipes corroded sections [21]. The effect of defects on welded joints in structures is also investigated [22]. There is an article examining the effect of welding defects on the fatigue strength of the socket welded pipes. The article in question includes both an experimental and numerical analysis [23]. Xu et al. [24], claimed that removing weld reinforcement increases the fatigue strength of welded joints. Another paper examines the effect of wall thinning on fatigue behavior of pipe elbows. They concluded that there is no

significant relation between local wall thinning and low cycle fatigue life of elbows [25]. The reliability of pressurized equipment is a concept directly related to the material used in the production of the equipment. For this reason, while the equipment is still in the design phase, the correct material selection should also be considered an issue that will affect the possibility of damage to the equipment. In the literature, there are also studies suggesting decision support systems for the most appropriate material selection for pressurized equipment according to the conditions used [26].

In the literature, studies are examining both the risk-based inspection method and the effect of defects on the fatigue strength of the pressurized pipes. In some studies conducted on the risk-based inspection method, it has been determined that the probability data to be used during the risk assessment are obtained from the databases created based on observation. Simultaneously, some studies used data obtained from the results of previous inspections. There are also current studies in which the fracture probabilities are determined stochastically. It has been observed that there is no study that takes into account the effect of production-induced internal surface defects on the fatigue life of pipes. Moreover, for risk-based inspection planning of pipelines, using the failure probability data obtained from fatigue analysis is considered a new approach in this field. The internal surface defects in the pipes were turned into ideal geometry, and stress concentration factors were obtained using the finite element analysis method. Fatigue-caused failure probabilities were obtained by considering the variations in geometric tolerances, mechanical properties, and internal pressure with the help of the Monte Carlo simulation method. A risk-based inspection planning is conducted by using the methods API 581 guideline. Periodic inspection planning of a real pipeline is carried out with the proposed approach.

2. Theoretical background

2.1. Risk based inspection

In the risk-based inspection method, the risk level is determined by evaluating the probability of failure, together with the possible consequences of failure. According to API 581, failure is defined as a loss of integrity or rupture of a pressurized component causing a leak from pressurized equipment to the environment. If damage accumulates in pressurized equipment during operation, the risk of failure increases. After some degree, if the operating risk tolerance is exceeded, a periodic inspection could be recommended to better understanding the damage level of the equipment. The point to be noted here is that the inspection does not reduce the risk. It only reduces the uncertainty. This situation allows better quantification of existing damage to equipment [1]. The magnitude of the risk is calculated in the simplest terms as shown below:

$$Risk(t) = H(t)xC \quad (1)$$

In Eq. (1), “H (t)” is the probability of failure, which will be expressed as the probability of fracture in the remainder of the study. “C” is the magnitude of the consequences. Although the effect of the consequences varies depending on the facility conditions, the magnitude of the consequences can be obtained using methods listed in API 581 and DNV -RP-G101 or similar code of practices.

Within API 581, fatigue-caused damages are considered only for pipelines. In particular, frequently repeated operations, variable pressures from reciprocating pumps or compressors, bending loads caused by insufficient support of pipe bodies, vibrations caused by frequently operating relief valves, or unpredictable loads on pipelines have been shown as the main causes of fatigue damage in pipelines. Similarly, the DNV-RP-G101 application guide defines welded joints, forks, or points where pipelines connect with pressure vessels as hot spots for fatigue damage. Hot spots are defined as points where the stress concentration factor is high. Since the stress value at these points exceeds the nominal stress, the cracks that occur due to the variable load at these hot spots. Surface defects in pipes caused by corrosion, erosion, and impact are

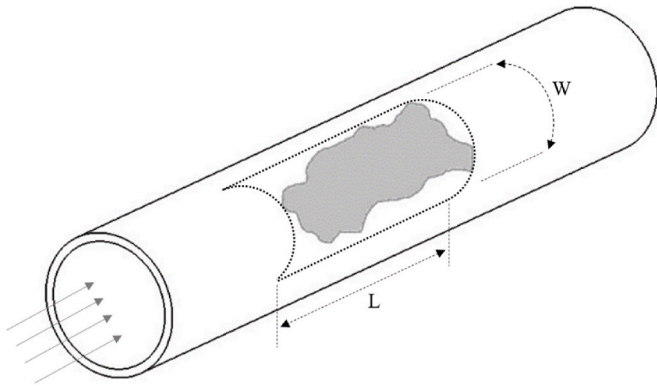


Fig. 1. Pressurized pipe inner surface defect shape.

also hot spots when considering the effect of fatigue. Additionally, surface defects of various sizes and shapes occur during rolling in the production of seamless steel pipes [27,28]. Although those defects are like corrosion pits or patches, they should not be confused with each other as the formation mechanism originates from the pipe manufacturing processes [27]. In this study, the internal surface defects, which are considered to occur during the production of the pipe, were accepted as hot spots in terms of fatigue strength. In Fig. 1, the possible surface defect on the pressurized pipe inner surface is shown as a representation.

2.2. Pipeline inspection by magnetic flux leakage (MFL) method

It is preferred that inspections in pipelines be conducted using nondestructive testing methods without shutting down the line for operation. For this purpose, the most used nondestructive testing methods are ultrasonic examination, eddy current, and magnetic flux

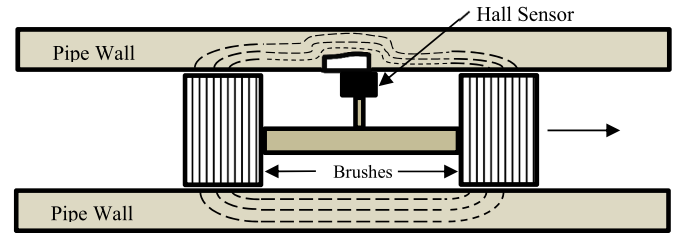


Fig. 2. Surface defect detection by magnetic flux leakage method.

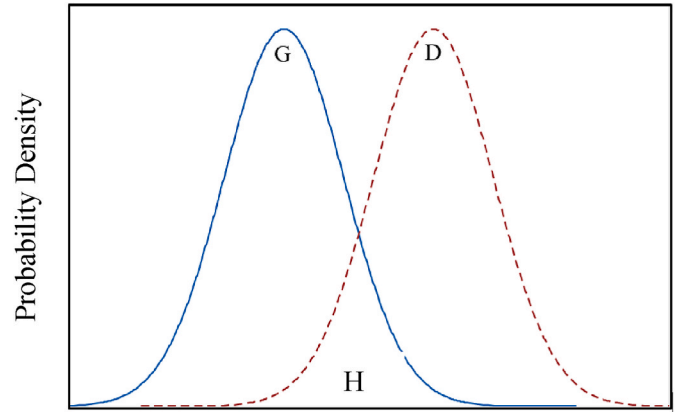


Fig. 3. Probability density functions for stress and strength random variables.

method to predict the reliability of a product is affected by the random factors that occur from production or which it may be exposed during use. In this method, the reliability “ $R(t)$ ” is defined as the probability that the strength value will exceed the stress value. The fracture occurs when stress equals or exceeds strength.

$$R(t) = \text{Probability}[\text{Strength} > \text{Stress}] = \text{Probability}[D > G] = \text{Probability}[D - G > 0] \quad (2)$$

leakage [29]. We preferred that the inspections of pipelines that travel long distances underground made from the inner surface of the pipeline. The pipeline inspection gauges (PIG) are devices that enable pipeline inspection in line with nondestructive testing methods [30]. PIGs move using the kinetic energy of the product in the pipeline [31]. PIGs are used to clean the pipeline or prevent mixing the products when transferred. Those, which inspect with the magnetic flux leakage method are called MFL - PIG. Through the brushes on the MFL-PIGs, a flux is created on the ferromagnetic pipe. This flux encounters resistance in the area where the pipe is defective and creates deviations while passing over the pipe. These deviations are recorded using Hall sensors on the MFL-PIG to determine the location, size, and approximate geometry of the possible defect on the inner and outer surfaces of the pipe. In this way, axial and circumferential measurements can be done on the pipe [32]. Fig. 2 shows how the measurement is made with the magnetic flux leakage method.

2.3. Estimation of fracture probability

It is necessary of estimating the probability of fracture for the pipeline to determine the risk level. For this purpose, we used a probabilistic design approach [33]. This approach is suitable for a reliable design by determining the effective parameter affecting the reliability and defining the stress-strength distributions [34]. In this study, we applied a

In Eq. (2), “ D ” is the random strength variable and “ G ” is the random stress variable. The probability that the boundary value function obtained from the difference in the distributions of the aforementioned variables is greater than zero gives the reliability of the design. In Fig. 3, probability density functions are presented graphically. The probability of fracture “ $H(t)$ ” in this study is obtained from Eq. (3) shown below.

$$H(t) = 1 - R(t) \quad (3)$$

Different approaches used to obtain reliability are available in the literature. A significant portion of these approaches has focused on estimating the boundary value function [35–38]. In this study, the Monte Carlo simulation method was used to estimate the fracture probability.

2.4. Monte Carlo simulation

Monte Carlo simulation is an approach that uses random sampling. It uses statistical modeling to predict the results of mathematical functions and simulate the processes of complex systems. It was introduced during the Second World War to develop nuclear weapons. Monte Carlo simulation is a frequently used scientific tool for solving problems that are difficult to solve analytically or take a long time, costly, and

impractical for experiments [39,40]. If more random data are generated in the estimation of the functions that define the problems, the closer the result will be. The use of excessive data will prolong the computation time.

The variables in the problem are defined as probability density functions and placed in the simulation (Fig. 3). It is accepted that the variables in the problem examined in this study show a normal distribution. The probability density function of the normal distribution is presented below.

$$f(x) = \frac{1}{\sigma_{st}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma_{st}}\right)^2} \quad (4)$$

where “ x ” is the random variable, “ σ_{st} ” is the standard deviation of the distribution and “ μ ” is the mean value of the distribution. Random numbers in the range (0–1) are needed to obtain probability density functions of normal distributions in the simulation. Although the variables defined in the problem are inherently random, it is unlikely that computers will be able to create random numbers by own. However, there are algorithms in the literature that can generate pseudo-random numbers, and they are called random number generators. One of the oldest and known is the linear conjugate generator. In this method, provided that the n th random number is “ z_n ”, the next random number “ z_{n+1} ” can be obtained as seen in Eq. (5) [40]. “ a ”, “ c ” and “ m ” in the equation are constants that are decided to generate random results.

$$z_{n+1} = (az_n + c) \bmod m \quad (5)$$

If “ X ” is a continuous random variable and “ F ” is the distribution function of this variable, the distribution of the random variable “ X ” can be obtained by the transformation in Eq. (6) is made for the random number Z (0,1).

$$F^{-1}(z) = X \quad (6)$$

In this study, we obtained the normal distributions of the variables for the problem using the “Normal Distribution” function of the MINITAB software. Some variables in the problem constitute the normal distribution function of stress, and some of them constitute the normal distribution of strength. If Eq. (2) and Eq. (3) are solved using the data in these distributions obtained, the probability of fracture for the problem can be obtained.

2.5. Calculation of stress concentration factor with finite element analysis

With the effect of internal pressure in the pipelines, normal stress occurs in the circumferential direction on the wall of the pipe. This stress state is also called “membrane stress.” Stress in the axial direction theoretically occurs when the flow in the pipe is restricted for any reason. We did not consider this condition in the study. We neglected the stress in the radial direction. Surface defects, which have been examined in this study, will increase the stress value in the pipe section. Therefore, the maximum normal stress in the circumferential direction in the wall of the defective pipe can be calculated using Eq. (7).

$$\sigma^h = \frac{PD}{2t} SCF_h \quad (7)$$

where, “ σ^h (MPa)” normal stress in the circumferential direction, “ P (MPa)” internal pressure, “ D (mm)” pipe diameter, “ t (mm)” wall thickness, and “ SCF_h ” is the stress concentration factor at the circumferential direction. The stress concentration factor can be obtained using the finite element analysis method. Although the surface defects in the pipe are not regular, the surface defect geometry is acceptable (Fig. 4) to simplify the finite element analysis models to reduce the computation time. Where, “ t ” wall thickness, “ L ” defect length, “ W ” defect width, “ R ” and “ r ” edge radius, “ d ” maximum depth of the groove, and “ h ” are the difference between basement radius and groove depth as shown in

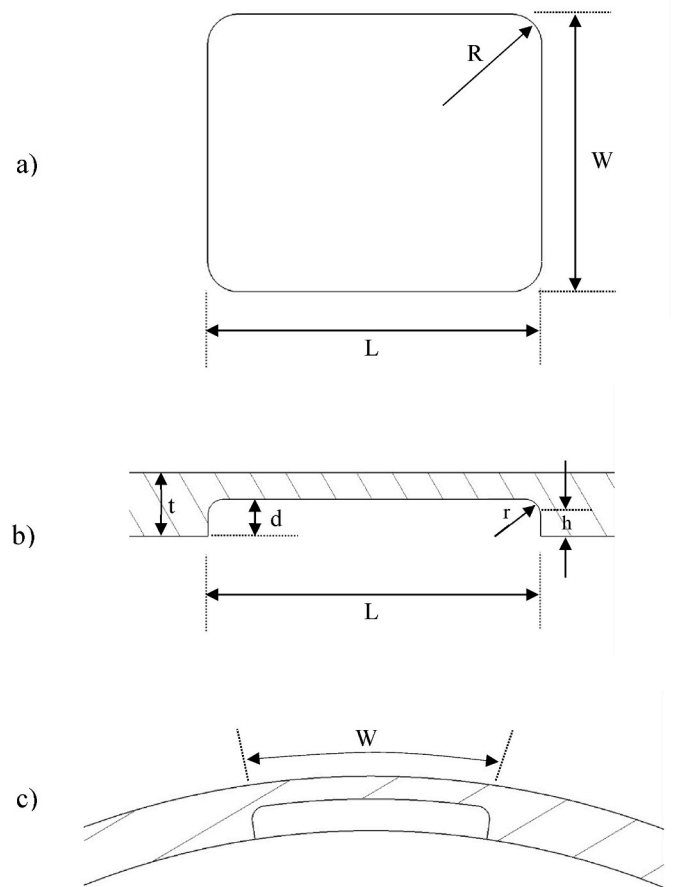


Fig. 4. Milling Feature on Internal Surface of Pipe a) Top View, b) Side View, c) Section View.

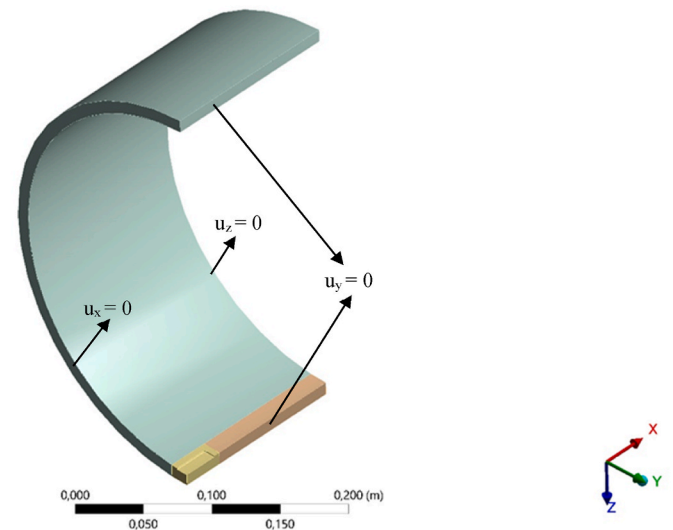


Fig. 5. Geometry of the problem and boundary conditions.

Fig. 4.

A solid model has been prepared for the inner surface defect, whose geometrical features are shown. The pipe length is determined as 150 mm to the boundary conditions don't affect the stress value in the defective region. Since the problem is symmetrical, the solid model pipe

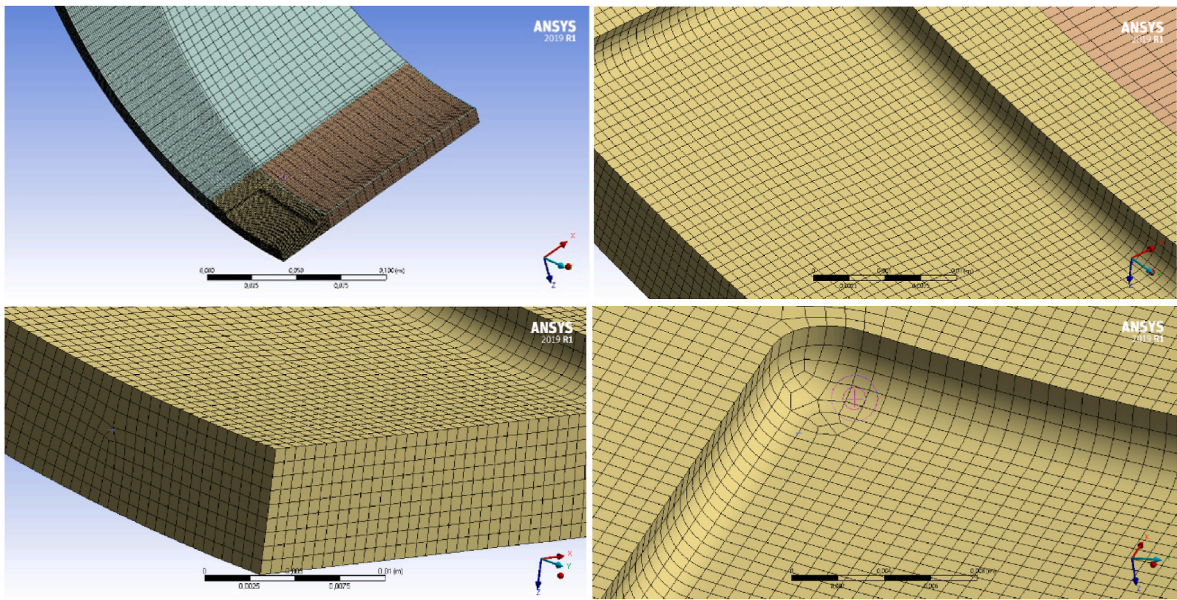


Fig. 6. Mesh study.

Table 1
Geometric properties of the models and calculated stress concentrations.

	d/t	d (mm)	r (mm)	h (mm)	L (mm)	W (mm)	R (mm)	P (MPa)	SCF _h
1	0.1	1.031	0.8248	0.2062	60	20	1.6496	8.2	2.50
2	0.2	2.062	1.6496	0.4124	90	30	3.2992	8.2	2.67
3	0.3	3.093	2.4744	0.6186	120	40	4.9488	8.2	2.86
4	0.4	4.124	3.2992	0.8248	150	50	6.5984	8.2	3.11
5	0.5	5.155	4.124	1.031	180	60	8.248	8.2	3.45

is prepared as a quarter of its actual size to reduce the analysis time. The geometry of the defective model and the boundary conditions of the problem are available in Fig. 5.

A convergence study was conducted to decide on the mesh size. The mesh size was determined to be smaller than the rest of the model to obtain more precise results for the defective region. Hexagonal solid elements are mainly used in the model. Twelve elements were used throughout the wall thickness for the defective region. The Mesh size of the defective region is 0.8 mm. The mesh size in the rest of the model

was determined as 5 mm to reduce the computation time. Fig. 6 shows the details of the mesh in the defective region.

Finite element analyzes for internal surface defects, whose properties are given in Table 1 were performed in ANSYS software. We assigned the inner surface boundary condition of the pipe considering the specific pressure value (see Fig. 5 and Table 1). Thus, the maximum normal stress values in the circumferential direction were recorded for the defective regions. Fig. 7 shows the stress distribution of the defective region of the 1st-row analysis.

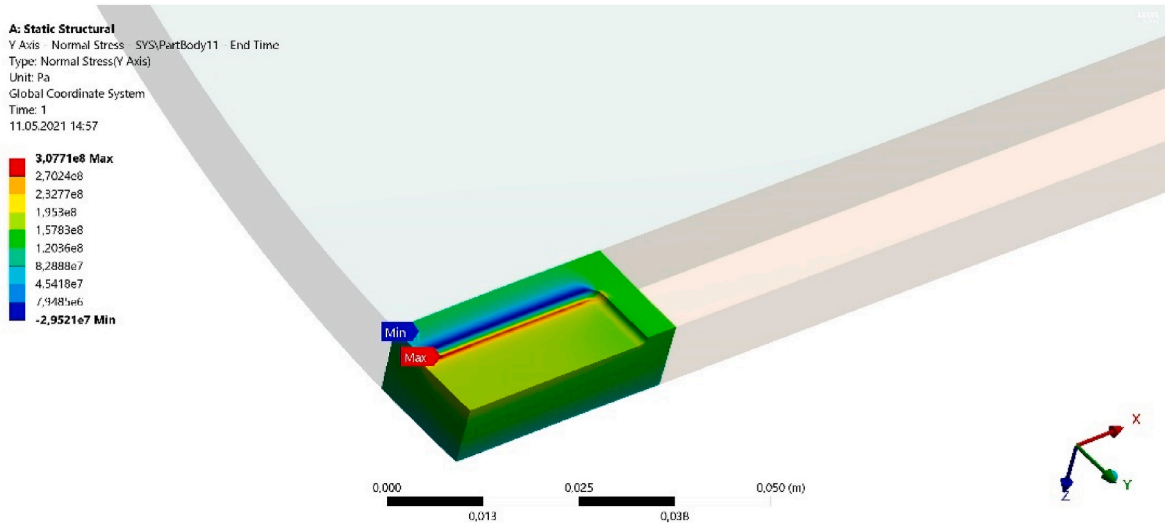


Fig. 7. Analysis results.

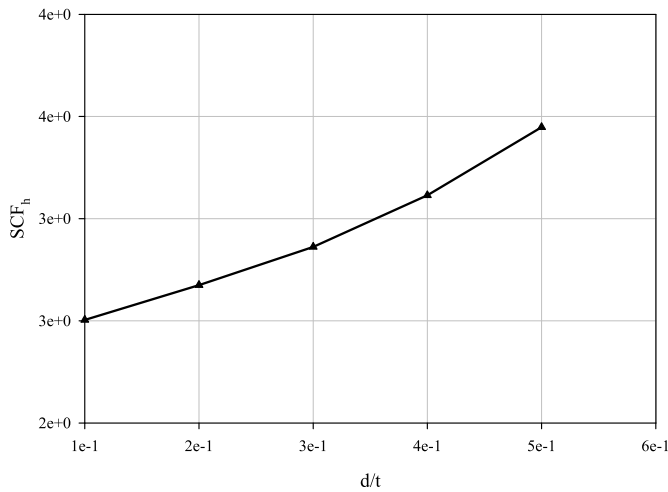


Fig. 8. Circumferential stress concentration factor for defected pipe.

We prepared a perfect model with the same diameter and wall thickness to obtain the stress value in the non-defective parts of the pipe, using finite element analysis. Thus, the normal stress value in the circumferential direction was determined. Stress concentration factors given in Table 1 were obtained by proportioning the stress value of the defective region to the stress value of the non-defective region.

In the graph in Fig. 8, it is seen that the stress concentration factor increases depending on the “d/t”.

2.6. Prediction of stress concentration factor

With the finite element analysis method, SCF_h can be obtained for the different values of each variable in Fig. 4. However, since finite element analysis will take a long time, we developed a design of an experimental model consisting of surrogate models for different values of each geometric variable to obtain an equation that can predict SCF_h. We developed a Taguchi's Design of Experiment [41] model with four variables and three levels consisting of nine experimental runs (Tables 2 and 3).

We used the linear regression formula of MINITAB software to create an equation between the variables in Table 2 and SCF_h. The resulting relation is shown in Eq. (8).

$$SCF_h = 1.450 + 5.161\left(\frac{d}{t}\right) - 1.211\left(\frac{r}{t}\right) - 2.711\left(\frac{R}{t}\right) + 0.543\left(\frac{L}{W}\right) \quad (8)$$

It is seen from the model summary presented in Table 4 that the obtained equation represents the surrogate models to an acceptable extent, and the predictive ability of the equation is also reasonable. Eq. (8) is used to obtain the stress concentration factors for the defective regions.

To test the consistency of the equation, the SCF_h results obtained using the finite element analysis were compared with obtained from equation (Table 5). The results show that acceptable consistency.

Table 2
Taguchi design of experiment L₉ (3⁴).

	d/t	r/t	R/t	L/W
1	0.1	0.1	0.1	0.6
2	0.1	0.2	0.2	1.2
3	0.1	0.3	0.3	1.8
4	0.3	0.1	0.2	1.8
5	0.3	0.2	0.3	0.6
6	0.3	0.3	0.1	1.2
7	0.5	0.1	0.3	1.2
8	0.5	0.2	0.1	1.8
9	0.5	0.3	0.2	0.6

3. Inspection planning

We present how to perform inspection planning in a pipeline with the proposed method in Fig. 9 as a flowchart. First, it is necessary to determine the geometric and mechanical properties of the pipeline to be inspected and their tolerance values. The inclusion of tolerance ranges in the calculations ensures that the uncertainty from the pipe production is considered in the fracture probability calculations. Tolerance ranges can be obtained from the steel pipe manufacturer or various standards. Then, possible surface defects must be identified. These defects may be occurred by the manufacturing processes of the pipe, erosion, or corrosion. If an inspection is conducted before planning, the size and geometry of the surface defects should be obtained using the data taken from the inspection process. If not, estimation should be made for possible defects using previous inspections on other pipelines or experience in the industry. Since this uncertainty will disappear after the first inspection, the planning for the next inspections will be conducted more effectively. The number and geometry of these defects on the pipe surface also create uncertainty for the problem; a tolerance range should also be defined for the geometric variables shown in Fig. 4. Thus, within the scope of this study, by using Eq. (8) an SCF_h distribution for surface defects can be obtained. Although the SCF_h distribution is significant to obtain the maximum stress distribution on the pipe, possible changes in the pipe's internal pressure are another variable that affects the stress. For this reason, it is appropriate to consider the line-operating pressure and to define a mean and standard deviation for this variable. We used Eq. (4) to obtain the normal distributions of variables within the scope of this study. Number of operations will perform on the pipeline in a certain period should be evaluated since fatigue is a problem. For each variable in the problem, distributions should be generated with the computer by considering the mean and standard deviation values, and a multivariate Monte Carlo simulation should be performed using these distributions. The simulation must be performed based on the number of cycles to consider the effect of fatigue. After fracture probability is obtained depending on the number of cycles, the risk can be determined using Eq. (1). Since the probability of fracture is time-dependent, the risk will also be time-dependent. The inspection should be conducted when the magnitude of the risk exceeds the acceptable level.

4. Inspection planning for the pipeline in an oil terminal

4.1. Determining stress and fatigue strength distributions

As a case study, inspection planning of a pipeline, most of which is underground, between refinery and oil terminals in Turkey was conducted on a risk-based with the method proposed in this study. The application was conducted on the 775 m long section of the pipeline under the responsibility of the terminal. A photograph from the area where the pipeline emerges from the ground is in Fig. 10.

Diesel transfer is conducted regularly between the refinery and oil terminal via the pipeline. The mechanical and geometric properties of the pipeline are available in Table 6.

We examined the inspection at the end of the 10th year following the installation of the pipeline. As most of the pipeline is underground, the inspection was conducted using MFL-PIG. (Fig. 11). A total of 31 surface defects of different sizes and geometries were detected on the pipeline. Because of the expert evaluation, it was concluded that the surface defects in the pipeline were not formed on the basis of corrosion or erosion. But that the defects were formed during the manufacturing processes of the pipes. For the deepest of these surface imperfections, a 28% loss in thickness was detected. Although these surface defects do not constitute an obstacle to the operation of the pipe under current conditions, the probability of long-term damage increases as the fatigue strength decrease depending on the number of operations.

Although the detected surface defects are not as regular as are shown in Fig. 4, the data processed after the inspection is aligned with Fig. 4.

Table 3Geometric properties of surrogate models and calculated SCF_h.

	D (mm)	t (mm)	d (mm)	r (mm)	h (mm)	L (mm)	W (mm)	R (mm)	SCF _h
1	329.9	10.31	1.031	1.031	0	54	90	1.031	1.97
2	329.9	10.31	1.031	2.062	0	54	45	2.062	1.86
3	329.9	10.31	1.031	3.093	0	54	30	3.093	1.83
4	329.9	10.31	3.093	1.031	2.062	54	30	2.062	3.16
5	329.9	10.31	3.093	2.062	1.031	54	90	3.093	2.29
6	329.9	10.31	3.093	3.093	0	54	45	1.031	2.82
7	329.9	10.31	5.155	1.031	4.124	54	45	3.093	3.72
8	329.9	10.31	5.155	2.062	3.093	54	30	1.031	4.68
9	329.9	10.31	5.155	3.093	2.062	54	90	2.062	3.46

Table 4

Model summary.

Std. Dev.	R-sq	R-sq(adj)	R-sq(pred)
0.163391	98.61%	97.21%	91.94%

Table 5

Comparison of finite element analysis results and regression equation results.

SCF _h (FEA)	SCF _h (Eq. (8))	% Error
1.97	1.90	3.6
1.86	1.83	1.6
1.83	1.77	3.3
3.16	3.31	4.7
2.29	2.27	0.9
2.82	3.02	7.1
3.72	3.75	0.8
4.68	4.49	4.1
3.46	3.45	0.3
	Mean Error	2.9

The results of the inspection do not produce precise information about the surface radii. The geometrical properties of 31 surface defects detected are given in Table 7.

The knowledge in Table 7 constitutes suitable data for the SCF_h equation obtained from Eq. (8). However, in reality, the geometries of those defects are not exactly compatible with Fig. 4, and the surface radii create another uncertainty. Since the study claims to calculate a damage probability, it would be appropriate to expand the data source in the problem and evaluate all possibilities. For this reason, the calculation of SCF_h for the problem, the mean and standard deviation values of the results of the inspection of the L/W and d/t variables presented in Table 7 was used directly. For the r/t and R/t variables, a more comprehensive mean and standard deviation estimation were made. By estimating the r/t and R/t variables a participatory SCF_h data source was created. The data used in calculating the distributions of those variables are presented in Table 8.

Although the allowable operating pressure for the pipeline is 11 (MPa), the operating pressure applied at the terminal where the inspection planning is conducted is well below the allowable operating pressure. Therefore, the actual operating pressure is assumed to be 7.5 (MPa), approximately half of the design pressure. Eq. (7) gives the maximum normal stress in the circumferential direction depending on the pressure in the pipeline. 500,000 data with a normal distribution are created with the software for each independent variable in Table 8. Histograms of the variables affecting SCF_h are presented in Fig. 12.

The pressure rises from zero to operating conditions during each operation in the pipeline and returns to zero when finishing the operation. This condition creates a variable loading in the pipeline. We accepted that an average of 5 operations per week is performed in the terminal. The number of operations on the pipeline is considered in fatigue analysis while calculating the number of cycles. The circumferential stress amplitude and the average stress for the pipeline were calculated using Eq. (9).

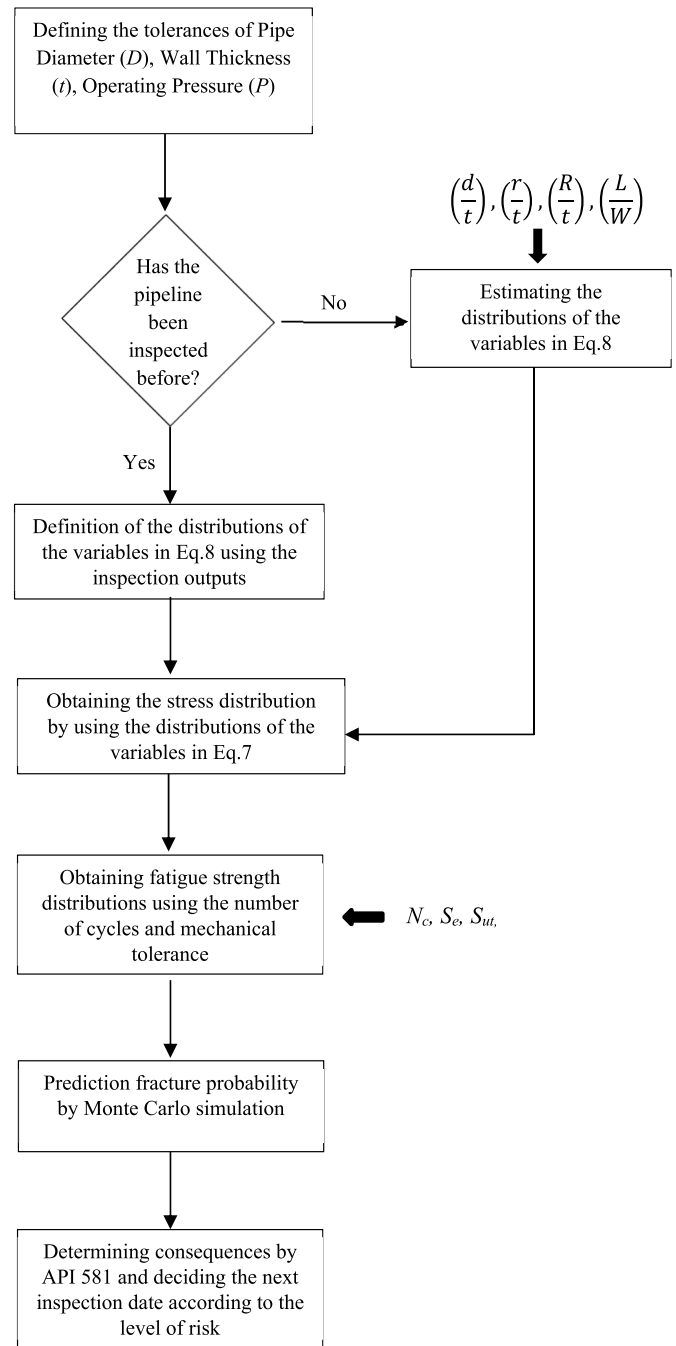
**Fig. 9.** Flowchart of the proposed method.



Fig. 10. Pipeline with inspection planning.

Table 6

Geometric and mechanical properties of the pipeline.

Material	API 5L Grade B
Yield Strength (MPa)	241
Tensile Strength (MPa)	413
Young modulus (GPa)	206
Diameter (mm)	323.9
Wall Thickness (mm)	10.31
Design Pressure (MPa)*	15.3
Maximum Allowable Pressure (MPa)**	11

* Design pressure obtained by $P = \frac{2S_{yt}}{D}$. The operating pressure can be up to 0.72 times the design pressure [42].



Fig. 11. MFL-PIG used during inspection.

Table 7

Internal surface defects detected from inspection.

	L (mm)	W (mm)	d (mm)	L/W	d/t
1	27	24	2.06	1.13	0.20
2	58	70	0.62	0.83	0.06
3	48	47	1.86	1.02	0.18
4	76	91	1.13	0.84	0.11
5	74	89	0.52	0.83	0.05
6	69	43	1.34	1.60	0.13
7	63	49	0.62	1.29	0.06
8	86	64	0.52	1.34	0.05
9	75	40	0.52	1.88	0.05
10	65	49	0.52	1.33	0.05
11	52	43	0.62	1.21	0.06
12	38	42	1.13	0.90	0.11
13	37	50	1.44	0.74	0.14
14	39	36	0.52	1.08	0.05
15	42	38	2.89	1.11	0.28
16	33	32	1.44	1.03	0.14
17	37	41	1.03	0.90	0.10
18	48	43	0.72	1.12	0.07
19	34	36	1.75	0.94	0.17
20	24	26	0.82	0.92	0.08
21	18	18	0.52	1.00	0.05
22	39	59	1.65	0.66	0.16
23	39	38	1.96	1.03	0.19
24	38	26	0.62	1.46	0.06
25	54	56	1.96	0.96	0.19
26	18	18	0.72	1.00	0.07
27	63	37	0.93	1.70	0.09
28	63	59	0.52	1.07	0.05
29	58	45	1.13	1.29	0.11
30	49	60	1.13	0.82	0.11
31	63	55	1.55	1.15	0.15
Mean				1.10	0.11
Std. Dev.				0.28	0.06

Table 8

Variables affecting stress distribution.

Variable	Mean	Standard Deviation
Wall thickness t (mm)	10.31	0.43 ^a
Diameter D (mm)	323.9	0.83 ^a
L/W	1.10	0.28
d/t	0.11	0.06
r/t	0.2	0.033
R/t	0.2	0.033
Pressure P (MPa)	7.5	0.25 ^b

^a Standard deviations of normal distributions created according to tolerances in the DNV GL-ST-F101 directive.

^b Possible pressure deviation is taken as 1.1 times the operating pressure [43].

$$\sigma_a^h = \sigma_m^h = \frac{\sigma^h}{2} \quad (9)$$

The S–N curve of the pipeline, whose mechanical properties are given in Table 6, is presented in Fig. 14 to be used in fatigue analysis. The endurance limit “Se” for the S–N curve was obtained using Eq. (10). Studies show that the standard deviation of the endurance limit is below 8% [44]. In this study, it was accepted as 5%. Therefore, the S–N curve was created following this tolerance.

$$S_e = 0.5k_a S_{ut} k_b k_c \quad (10)$$

In the equation, “ S_{ut} ” represents the tensile strength of the material, “ k_a ” represents the surface factor of the material, “ k_b ” represents the dimension factor of the material and “ k_c ” represents the load factor of the problem. In the calculation of the endurance limit, the surface factor is “0.76”, the load factor is “0.85”, and the dimension factor is accepted as “1” since normal stress occurs in the pipe. Fatigue strength for the low cycle ($N_c \leq 10^3$) is taken as approximately 0.9 times the material tensile strength [45].

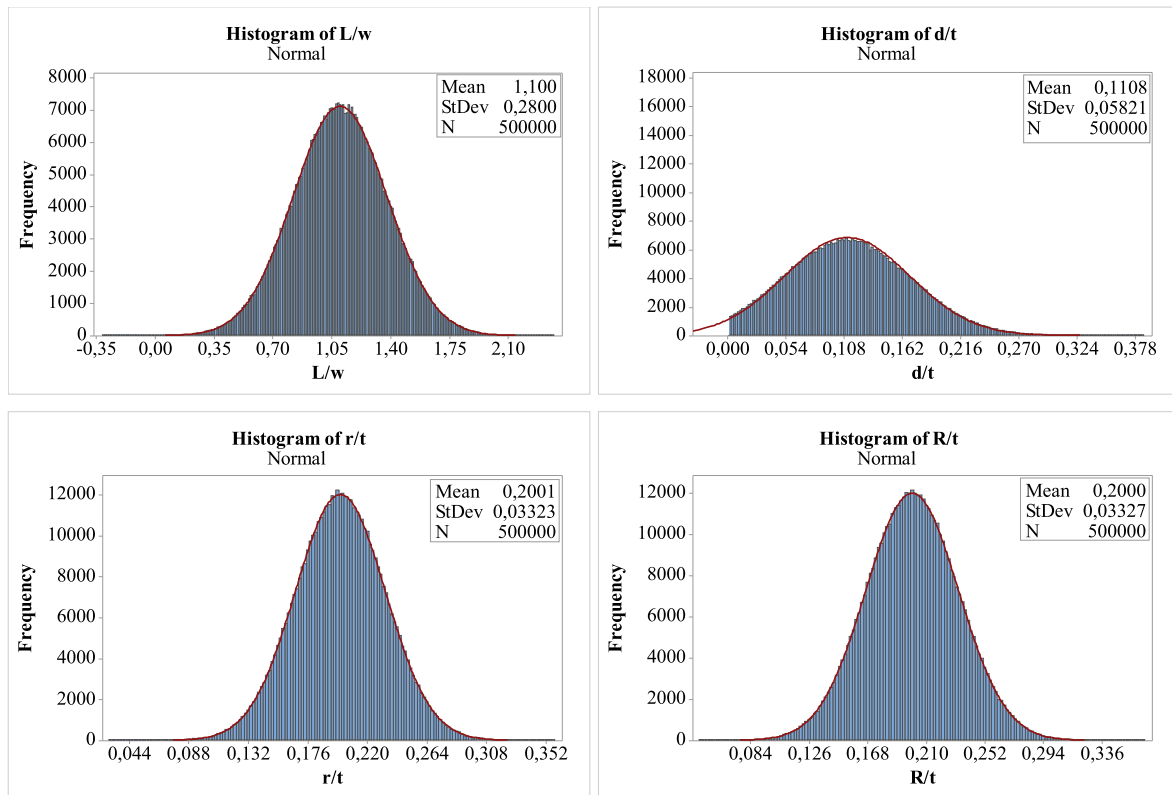


Fig. 12. Histograms of Variables. The stress normal distribution obtained from the Monte Carlo simulation performed for different values of each independent variable in Eq. (7) is presented in Fig. 13.

4.2. Prediction of fracture probability

“D” strength and “G” stress distribution curves should be evaluated together to estimate the probability of fracture. The example is presented in Fig. 3. For the pipe problem that has surface defects considered in this study, the stress distribution was obtained under the influence of multiple variables and is presented in Fig. 13. In the fatigue analysis phase of the problem, the equivalent stress amplitude distribution should be calculated for the solution since both the medium stress and the stress amplitude existed, as shown in Eq. (9). Modified Goodman approach, one of the fatigue damage criteria, was used in the analysis, and the equivalent stress amplitude distribution was obtained using Eq. (11) [46].

$$\sigma_{a\ eq}^h = \sigma_a^h \left(\frac{S_{ut}}{S_{ut} - \sigma_m^h} \right) \quad (11)$$

Fatigue strength distributions vary depending on the number of cycles and thus time. However, using the S–N curve obtained in Fig. 14, fatigue strength distributions corresponding to the desired number of cycles can be obtained.

In Fig. 15, the equivalent stress distribution in the circumferential direction for the pipe with surface defects and the fatigue strength distributions that vary depending on the number of cycles is compared. The probability of fracture is obtained from the intersection of the two distributions. As shown in Fig. 15, as the number of cycles increases, the fatigue strength distribution approaches the stress distribution, and therefore the probability of cumulative damage increases.

To obtain the probability of fracture, depending on the number of cycles, Eq. (2) and Eq. (3) need to be solved repeatedly for different cycle numbers. The results of the Monte Carlo simulation performed which has 500.000 data are presented in Table 9. When Table 9 is examined, it is seen that the probability of fracture due to fatigue increases with time.

5. Application results

With the case study, the most appropriate inspection time is decided for the API 5L Grade B steel pipeline, which the properties presented in Table 6. For planning, we used a risk-based inspection method. In this method, the risk can be calculated using Eq. (1). The probability of fracture in the equation is calculated based on time under the effect of fatigue for the pipeline with surface defects considered in this study and is presented in Fig. 16. The consequence “C,” another variable needed in the calculation of the risk, was obtained using the API 581 code of practice. According to API 581, the effect related to fracture varies considering the properties of the chemicals in the pipeline and operating conditions. The consequence analysis section of the code of practice includes information about the fire, toxic release, explosion, etc., that occur due to chemicals. It can be used to calculate the possible effects of consequences based on area or cost [1]. Since there are only flammable chemicals in the terminal where the case study occurred, the effect of a possible fire has been considered.

It provides ease of application by making API 581 Eq. (1) a risk matrix (Fig. 17). While the columns correspond to the consequences of the fracture, the rows of the matrix correspond to the probabilities of fracture. In the matrix, the green represents low risk, yellow medium risk, orange medium-high risk, and red high risk.

Table 10 shows which risk levels correspond to the size of the area affected by a possible fire according to API 581.

Diesel is transferred in the pipeline, and we assumed that a hole of approximately 102 mm formed on the pipe because of a fracture. The effect of the fire is calculated as 650 m² according to API 581 [1]. This result corresponds to C-level risk according to Table 10. So, the risk level that the terminal can tolerate considering the risk matrix (Fig. 17). The maximum acceptable probability of fracture corresponding to this level is determined from the matrix. Finally, the inspection time corresponding to the maximum acceptable fracture probability can be

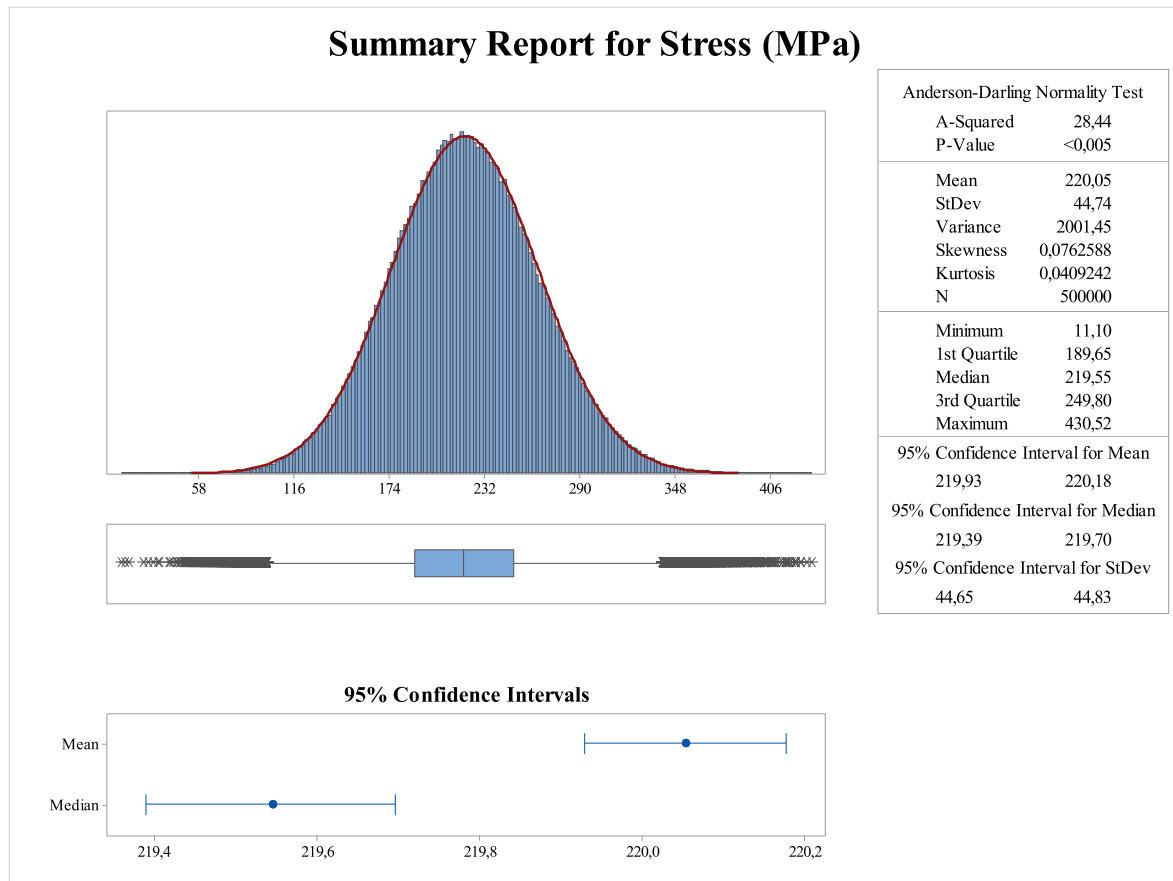


Fig. 13. Simulation result for stress.

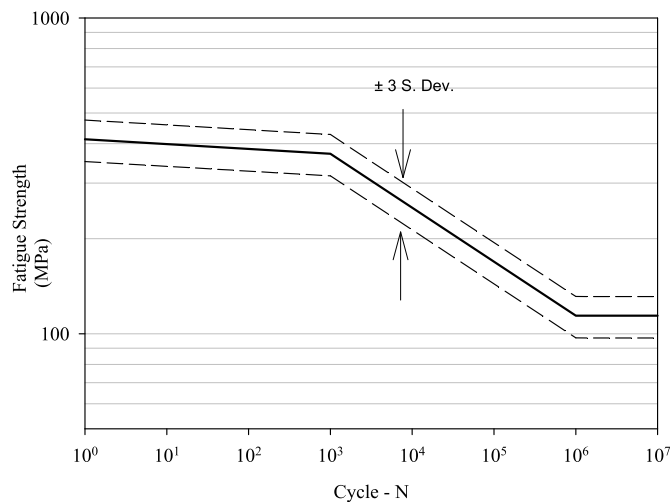


Fig. 14. S-N curve for pipe body.

determined using the graph in Fig. 16. At the end, the most appropriate inspection times according to the risk levels are presented in Table 11.

Pipelines with internal surface defects due to production were evaluated within the scope of this study. Fatigue is considered the main damage mechanism. It has been accepted that fatigue is caused by pipe internal pressure variations. In this study, corrosion effects that will develop on the pipeline over time and dents that may occur due to external effects are excluded from the evaluation. The S-N curve, which is used to estimate the fatigue strength, is calculated theoretically. Since the data obtained as a result of the inspection do not include crack size,

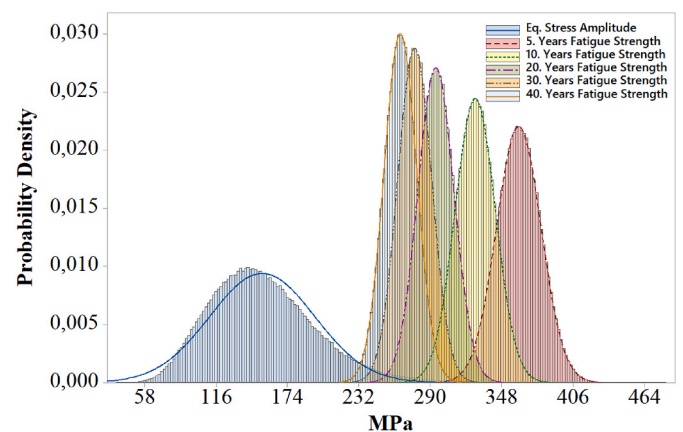


Fig. 15. Equivalent stress amplitude - fatigue strength probability density plots.

Table 9

Fracture probability based on the number of cycles.

Year	Number of Cycle (N_c)	Probability of Fracture
1	240	2.52E-04
5	1200	4.78E-04
10	2400	1.81E-03
15	3600	3.67E-03
20	4800	5.87E-03
25	6000	8.28E-03
30	7200	1.09E-02
35	8400	1.38E-02
40	9600	1.66E-02

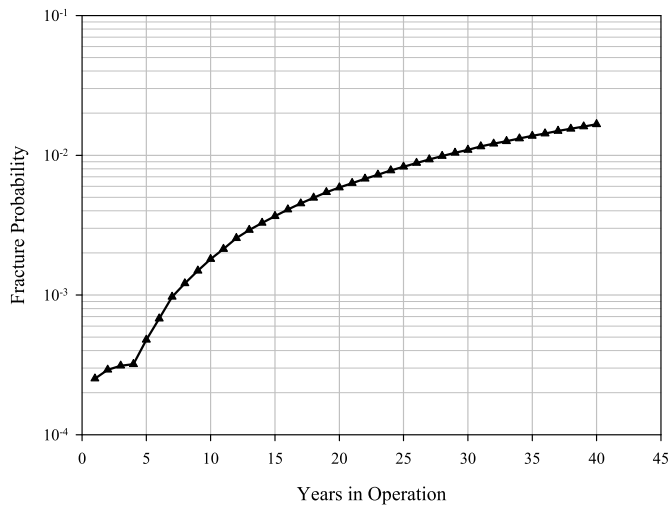


Fig. 16. Change of Fracture Probability with Time (The number of cycles in 1 year is accepted as “ $N = 240$ ”).

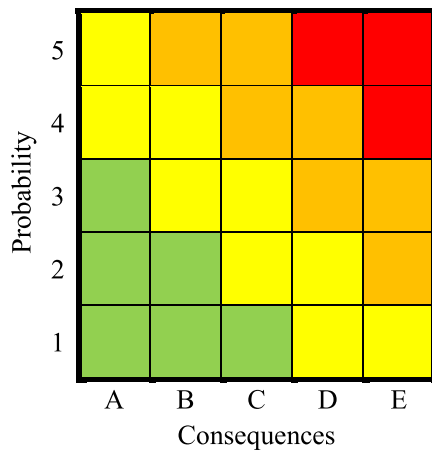


Fig. 17. Api 581 risk matrix [1].

Table 10

Risk levels according to the size of area affected by fire [1].

Level	Affected Area C (m^2)
A	$C \leq 10$
B	$10 < C \leq 100$
C	$100 < C \leq 1,000$
D	$1,000 < C \leq 10,000$
E	$C > 10,000$

Table 11

Fracture probability levels according to API 581 and inspection time for case study.

Level	Fracture Probability $H(t)$	Inspection Time	Risk Level
1	$H(t) \leq 3.0 \cdot 10^{-5}$	-	Low Risk
2	$3.0 \cdot 10^{-5} < H(t) \leq 3.0 \cdot 10^{-4}$	Ins. Year < 5	Medium Risk
3	$3.0 \cdot 10^{-4} < H(t) \leq 3.0 \cdot 10^{-3}$	$5 < \text{Ins. Year} \leq 10$	Medium Risk
4	$3.0 \cdot 10^{-3} < H(t) \leq 3.0 \cdot 10^{-2}$	$10 < \text{Ins. Year} \leq 40$	Medium - High Risk
5	$H(t) > 3.0 \cdot 10^{-2}$	Ins. Year > 40	Medium - High Risk

fatigue life is not able to be estimated using the fracture mechanics approach. Since the defect geometry has been optimized for ease of finite element analysis, the probabilistic solution has been carried out by including the possible different values of the variables that make up the ideal defect geometry.

The fracture probability graph obtained for the sample pipeline is presented in Fig. 16. The graph constitutes important data for determining the periodic inspection time. Facilities can decide their inspection periods for pipelines by determining their acceptable risk levels with the method proposed in this study.

6. Conclusions

Within the scope of this study, the probability of fatigue failure for inner surface defected pipes was estimated over time due to variable internal pressure. It is assumed that the inner surface defects in the pipes are due to milling stage of production. Any past fracture data have not been used in the estimation of the probability of fracture. It was calculated completely stochastic based on multiple variables. Variable internal pressure, mechanical properties of the pipe, geometric parameters of surface defects and the pipe, were taken into consideration in the calculations as random variables affecting the reliability. The stress concentration factor for the surface defected regions was obtained by the finite element method. The Monte Carlo simulation method is used for probability calculations within the study. The fracture probability data obtained from simulations are used for risk-based inspection planning. As a result of this paper, a new practice is introduced for inspection planning of pipelines that include the fabrication related inner surface defects. The case study is conducted on a pipeline established between a refinery and an oil terminal in Turkey. The consequences of possible damage were calculated according to API 581, and a new risk-based inspection date was proposed for the pipeline. As a result of the case study, the probability of fracture is obtained by considering the working conditions of the terminal and all mechanical and geometrical properties of the pipeline section. A risk-based inspection planning specific to the pipeline which is considered in the case study has been provided. Thus, increases the reliability of the risk-based inspection planning method. If there is no maintenance or renewal because of the inspection, noted that the probability of fracture does not decrease, but the uncertainty in the current situation decreases. For this reason, it would be appropriate to use the information obtained during the inspection to determine the next inspection date. Additionally, the fracture probabilities obtained for the pipeline evaluated within the scope of the study are theoretical, and the inspection intervals forced within the scope of national or international standards and relevant legislation for inspections should not be ignored.

Author contributions

Levent Sözen: Conceptualization, Methodology, Writing - original draft, Software application. Mustafa Yurdakul: Conceptualization, Methodology, Supervision, Writing - original draft. Yusuf Tansel İç: Methodology, Validation, Visualization, Writing - original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Symbols

<i>C</i>	Magnitude of Consequences
<i>D</i>	Diameter
<i>d</i>	Depth of Groove
<i>H(t)</i>	Failure Probability
<i>h</i>	Difference Between Base Radius and The Groove Depth
<i>k_a</i>	Surface Factor
<i>k_b</i>	Dimension Factor
<i>k_c</i>	Load Factor
<i>L</i>	Defect Length
<i>N</i>	Number of Monte Carlo Simulation Data
<i>N_c</i>	Number of Cycle
<i>P</i>	Pressure
<i>R</i>	Inner Radius of Defect
<i>r</i>	Basement Radius of Defect
<i>W</i>	Defect Width
<i>R(t)</i>	Reliability
<i>S_e</i>	Endurance Limit
<i>S_f</i>	Fatigue Strength
<i>S_{ut}</i>	Tensile Strength
<i>S_y</i>	Yield Strength
<i>SCF_h</i>	Stress Concentration Factor at Circumferential Direction
<i>t</i>	Wall Thickness
<i>z_n</i>	Random Number
<i>μ</i>	Mean of Distribution
<i>σ_h</i>	Stress at Circumferential Direction
<i>σ_a^h</i>	Stress Amplitude at Circumferential Direction
<i>σ_m^h</i>	Mean Stress at Circumferential Direction
<i>σ_{eq}^h</i>	Equivalent Stress Amplitude
<i>σ_{st}</i>	Standard Deviation of Distribution

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