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A dynamic condition assessment model of aging subsea pipelines subject to corrosion-fatigue degradation

Ziyue Han [a], Xinhong Li [b,*], Renren Zhang [b], Ming Yang [c], Mohamed El Amine Ben Seghier [d]

[a] School of Mechanical and Electrical Engineering, Xi'an University of Architecture and Technology, No.13 Yanta Road, Xi'an 710055, China
[b] School of Resources Engineering, Xi'an University of Architecture and Technology, No.13 Yanta Road, Xi'an 710055, China
[c] Safety and Security Science Section, Faculty of Technology, Policy, and Management, Delft University of Technology, The Netherlands
[d] Department of Built Environment, Oslo Metropolitan University (OsloMet), Oslo, Norway

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ABSTRACT

Extension of operating lifetime of aging subsea pipelines is of great interest to oil and gas sectors. Corrosion and fatigue are the main causations of the condition degradation of subsea pipelines. A dynamic probabilistic condition assessment model based on continuous dynamic Bayesian network (DBN) is developed to support the life extension decision-making of aging subsea pipeline subjected to the corrosion-fatigue degradation. The methodology is built based on equivalent initial flaw size (EIFS) concept and a time-dependent prediction model implemented using DBN. The complex corrosion-fatigue degradation process is simplified by EIFS concept, and the crack propagation due to corrosion-fatigue is modelled using fracture mechanics model and DBN. A limit state function (LSF) is used to express the failure condition of subsea pipeline due to crack propagation. The dynamic reliability of subsea pipeline is estimated using Monte Carlo (MC) method with the probability distributions of the predicted crack sizes at different time slices. The estimated reliability is compared with the acceptable threshold to decide whether any measures are required to extend the life of subsea pipeline. The methodology is tested by a case study, and it is observed that it can be a useful tool to support life extension decision-making of aging subsea pipelines.

1. Introduction

Many subsea pipelines around the world are approaching or have already gone beyond their design life. It is reported that more than 50% of offshore pipelines in Gulf of Mexico, Norwegian Continental Shelf, and United Kingdom Continental Shelf have exceeded their design life (Dehghani and Aslani, 2019). Due to management flaw, irrational design, and harsh environments, aging subsea pipelines are subjected to seriously structural damages, e.g., corrosion pits and fatigue cracks. In practice, the corrosion pit on pipeline may develop into the fatigue crack under the cycling loading of current and wave. Corrosion-fatigue degradation is a general failure mode of subsea pipeline, which may threaten the safety of subsea pipelines and cause serious environment pollution (Aljaroudi et al., 2014). Thus, it is of great significance to estimate the corrosion-fatigue condition of aging subsea pipeline, and it is helpful for deciding whether any maintenance activities are required to extend the life of subsea pipelines (Yang et al., 2022).

The condition degradation of pipeline was investigated in recent years, including mechanism analysis (Wasim and Djukic, 2022; Yazdi et al., 2021), probabilistic prediction (Amaya-Gómez et al., 2019; Yuan et al., 2021; Wang et al., 2021), experimental analysis (Davaripour et al., 2021). Goswami and Hoeppner (1995) considered the effect of electrochemical processes on pit formation to develop a conceptual seven-stage degradation process. Shekari et al. (2017) predicted pitting growth behavior to maintain equipment safety in offshore environments, including pitting initiation time, density, and maximum depth. Li et al. (2021) developed an intelligent model to predict corrosion degradation of subsea pipeline integrating three data-driven methods. Cai et al. (2021) solved the limitation of degradation modelling caused by missing monitoring data with re-prediction methodology based on DBN and Wiener process. Cheng and Chen (2017) built a novel crack growth model to capture the effects of environmental parameters for crack propagation. Although some theoretical and physical models were available for corrosion and fatigue degradation of steel structure, the coupling effect of corrosion and fatigue was seldom reported. With the advancement of experimental verification on corrosion-fatigue

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* Corresponding author.
E-mail addresses: safety_lxh@163.com, lixinhong@xauat.edu.cn (X. Li).

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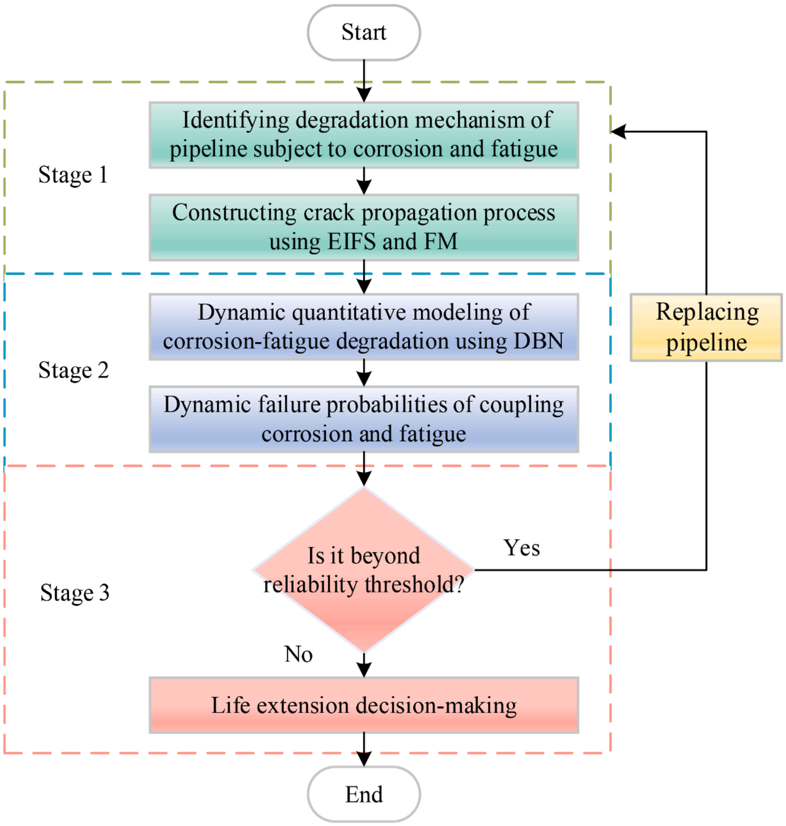

Fig. 1. The framework of the proposed methodology.

mechanisms, linear superposition models have increasing limitations in describing degradation of corrosion and fatigue (Ryan and Mehmanparast, 2023). The transition of degradation state from pitting corrosion to short crack growth is difficult to describe using an integral model. The concept of EIFS can simplify the modeling of corrosion-fatigue degradation for life prediction (Sun et al., 2019a; Zhao et al., 2018). However, previous studies on modeling of corrosion-fatigue degradation did not include specific pitting corrosion sizes (Cai et al., 2019; Kovalov et al., 2019).

Currently, considerable efforts were made on life prediction and management of subsea pipelines, including remaining useful life prediction (Shafiee and Animah, 2022), structural integrity assessment (Shabani et al., 2019) and reliability assessment (Pourahmadi and Saybani, 2022). Animah and Shafiee (2018) integrated the condition assessment and remaining useful life estimation to establish a life extension decision-making framework for offshore pipelines. Hafez (2021) investigated the performance of dent depth in failure mode and analyzed local stress and strain concentration of subsea pipeline. Zhu et al. (2021) developed an operation condition determination methodology based on failure and repair monitoring data for pipeline life extension. Chakraborty and Tesfamariam (2021) represented a time-dependent reliability analysis to compute the incremental failure probability and mean crossing rates of multiple-defects pipeline. Wang et al. (2022) developed a Monte Carlo and DBN based reliability analysis approach to evaluate the failure probability of subsea wellhead connector during service life. The degradation-based reliability is a useful index to measure the life condition of subsea pipelines, which can estimate the dynamic evolution of pipeline structure condition. Hence, two important issues remained to be addressed for predicting reliability degradation and life extension decision-making of aging subsea pipeline. How to model the transition from pitting corrosion to short crack growth of aging subsea pipeline subject to corrosion-fatigue degradation. How to estimate the failure probability of subsea pipeline during crack propagation due to corrosion-fatigue degradation.

The purpose of this paper is to present a dynamic corrosion-fatigue condition assessment model to support the life extension decision-making of aging subsea pipelines. The methodology simplifies the transition from pitting corrosion to short-crack growth, which is equivalent to a part of long crack propagation. Thus, the corrosion-fatigue degradation of subsea pipelines can be treated as a whole of long crack growth using EIFS concept and fracture mechanic model. To consider the uncertainties in crack propagation, DBN is used to model and predict the crack propagation following certain of probability distribution at different time slices. The limit state function of pipeline failure and MC method are utilized to estimate the reliability condition which is used as the index to implement life extension decision-making of aging subsea pipelines.

The rest of the paper is organized as follows: Section 2 presents the proposed methodology for corrosion-fatigue condition assessment, which is illustrated in Section 3 using a case study. Section 4 gives the conclusion of this paper.

2. Methodology

Fig. 1 presents the methodology for corrosion-fatigue condition assessment and life extension decision-making of aging subsea pipelines. It includes three steps:

- Modeling of corrosion-fatigue degradation.
- Dynamic crack propagation prediction.
- Condition assessment and life extension decision-making.

2.1. Modeling of corrosion-fatigue degradation

In the first stage of methodology, the information of aging subsea

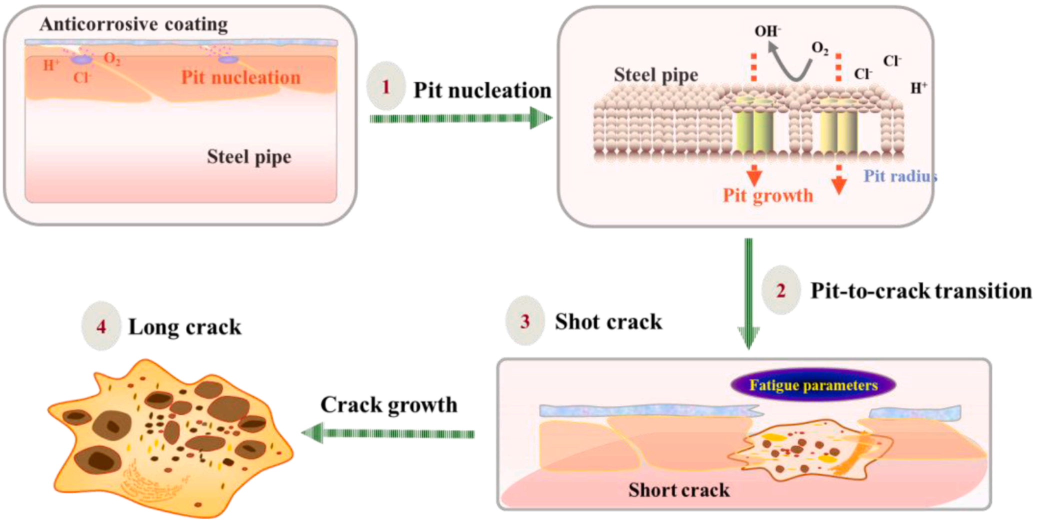

Fig. 2. Corrosion-fatigue degradation.

pipeline from design to operation is collected. The data includes pipeline service life, material properties, accident reports, environmental loading, and historical inspection and maintenance, expected service time, et al. These data are used to analyze the condition of pipeline with corrosion pit and fatigue cracks. This stage is the basis for establishing corrosion-fatigue condition assessment model of subsea pipeline. Determining the physics of corrosion-fatigue degradation phenomena is critical for assessing the structural condition of subsea pipeline. The seven-stage model is classic degradation process to describe the times and transition stages of the pit and crack growth (Goswami and Hoeppner, 1995). In the past decades, this model has been continuously improved and updated (Miller and Goswami, 2007; Shi and Mahadevan, 2003; Bastidas et al., 2009; Arzaghi et al., 2018). However, modeling corrosion-fatigue degradation is a challenging task since it is difficult to describe the transition from pit to crack transition. This study adopts the seven-stage model as the basis to simplify and analyze the corrosion-fatigue degradation process in four stages, as shown in Fig. 2. The improved degradation process includes pitting nucleation, pit-to-crack transition, short crack, and long crack. Specifically, the pit-to-crack transition is a complex process, and the precise model for capturing the transition was not available. The transition from corrosion pit to the short crack growth depends on the grain size, grain orientation, and initial flaw shape, which brings enormous uncertainties for modeling corrosion-fatigue (Zhang et al., 2021). Nevertheless, it can be addressed with the presence of EIFS concept. EIFS represents the equivalent quality of the original corrosion pits on the pipeline (Xue et al., 2021). The present study combines EIFS with the improved corrosion-fatigue process to develop a simplified degradation of subsea pipelines.

Step 1: Modeling of corrosion pitting to short crack

During the early stages of crack growth, the growth rate is mainly controlled by corrosion action (Xu et al., 2021). Although there is a large amount of anti-corrosion coating on the weld, the steel still contacts the seawater to create the corrosive conditions and further corrode the bare metal (Chen et al., 2015). Also, preexisting flaws such as original defects or dents caused by third-party interference may act as initiating sites for the corrosion. When corrosion pitting grows to a critical size, a fatigue crack will nucleate from corrosion pitting. The surface crack ultimately transits into a through (or through-thickness) crack causing pipeline failure (Harlow and Wei, 1994). The influence of environment on the transition from corrosion pitting to short-crack growth is complicated (Cheng and Chen, 2017). Some random process models were adopted to present the pit nucleation process to simplify the complex electrochemical effects (Shi and Mahadevan, 2001).

The essence of EIFS is the equivalent quality of the original crack in the pipeline. It is a hypothetical crack existing before the starting of fatigue crack. Several methods were available to estimate EIFS, e.g., reverse extrapolation method, Kitagawa-Takahashi diagram method, and time to crack initiation method (Xue et al., 2021). This paper develops a novel methodology to assess EIFS considering the corrosion pitting depth and the fatigue crack growth threshold based on Kitagawa-Takahashi diagram method. In this methodology, the fatigue limit estimation formula proposed by El Haddad et al. (1979), is employed to estimate EIFS with the fatigue crack growth threshold (ΔK_{th}), the geometric coefficient (Y) and the relevant fatigue limit ($\Delta\sigma_f$), as shown below:

$$a_{EIFS} = \frac{1}{\pi}\left(\frac{\Delta K_{th}}{\Delta\sigma_f Y}\right)^2 \tag{1}$$

where, ΔK_{th} can be obtained by damage tolerance design approach. Y is a geometric coefficient which takes 1.2 in this study. $\Delta\sigma_f$ can be described with corrosion degree ρ_m, as expressed below:

$$\Delta\sigma_f = \frac{\Delta\sigma_0}{\frac{200.26}{65.17e^{\frac{-\rho_m}{7.51}}+135.11}} \tag{2}$$

where, $\Delta\sigma_0$ is the fatigue limit of specimens without the initial crack.

The corrosion degree is generally reflected by corrosion pitting depth d, shown as following:

$$\rho_m = 1 - \left(1 - \frac{2(d-0.687)}{6.598}\right)^2 \tag{3}$$

Finally, the quantitative relationship among EIFS, ΔK_{th} and d can be expressed as:

$$a_{EIFS} = \frac{1}{\pi}\left(\frac{\Delta K_{th}}{0.75 \times 1.2} \times \frac{200.26}{65.17e^{\frac{1-\left(1-\frac{2(d-0.687)}{6.598}\right)^2}{7.51}} + 135.11}\right)^2 \tag{4}$$

The fracture mechanics model is used to predict the crack propagation of subsea pipeline subjected to corrosion and fatigue after obtaining a_{EIFS}.

Step 2: Long crack growth

The long crack growth of subsea pipeline under cycling loadings can

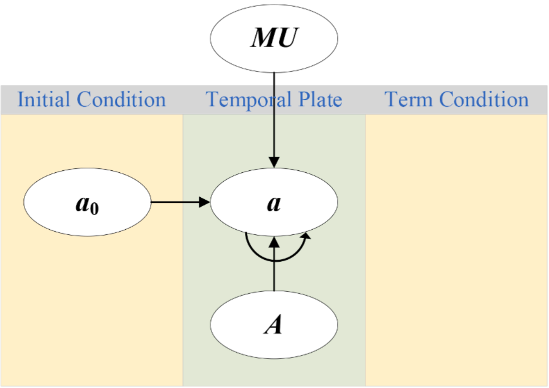

Fig. 3. A simplified DBN model.

Table 1
The distributions of crack propagation parameters.

Parameters	Description	Distribution types	Mean	Standard deviation
m	Material parameter	Constant	3	–
C	Material parameter	Constant	2.17×10^{-13}	–
B	Geometry parameter	Constant	0.66	–
N	Load cycle	Constant	3×10^{6} /year	–

be predicted using fracture mechanic model. The problem of crack growth prediction using fracture mechanics model is that the reliable initial flaw/crack size is difficult to obtain. Paris and Erdogan (1963) first proposed the law of fatigue crack growth based on fracture mechanics. It assumes that any structure component has initial cracks and ignores the fatigue crack initiation life, which means that the long crack propagation process is equivalent to the entire fatigue failure process (Sun et al., 2019b). The Paris law is represented as Eq. (5), which presents the relationship between crack growth rate and stress intensity factor range (Rao et al., 2020).

$$\frac{da}{dN} = C(\Delta K)^{m}, \Delta K > \Delta K_{th} \tag{5}$$

where, N is the number of load cycles, m and C are material parameters specifically obtained of short and long cracks resulting in two same growth rates from the equation (Rao et al., 2020). The da/dN is the crack growth rate, and ΔK is the stress intensity factor range, which can be expressed empirically as:

$$\Delta K = \Delta\sigma Y\sqrt{\pi a} \tag{6}$$

where, $\boldsymbol{\Delta\sigma}$ is the far-field stress amplitude.

However, if the geometric coefficient Y is assumed to be independent with crack depth a and the stress amplitude $\boldsymbol{\Delta\sigma}$ follows the Weibull distribution, the crack depth should be expressed as:

$$a = \left(a_0^{\frac{2-m}{2}} + CNA^{m}\Gamma\left(1+\frac{m}{B}\right)Y^{m}\pi^{\frac{m}{2}}\left(1-\frac{m}{2}\right)\right)^{\frac{2}{2-m}}, m \neq 2 \tag{7}$$

where, a_0 is the initial crack size; A is the Weibull distribution scale parameter; B is Weibull distribution shape parameter; γ is Gamma function used to calculate the expected value of Weibull distribution. The stress amplitude $\boldsymbol{\Delta\sigma}$ is described by Weibull distribution and can be

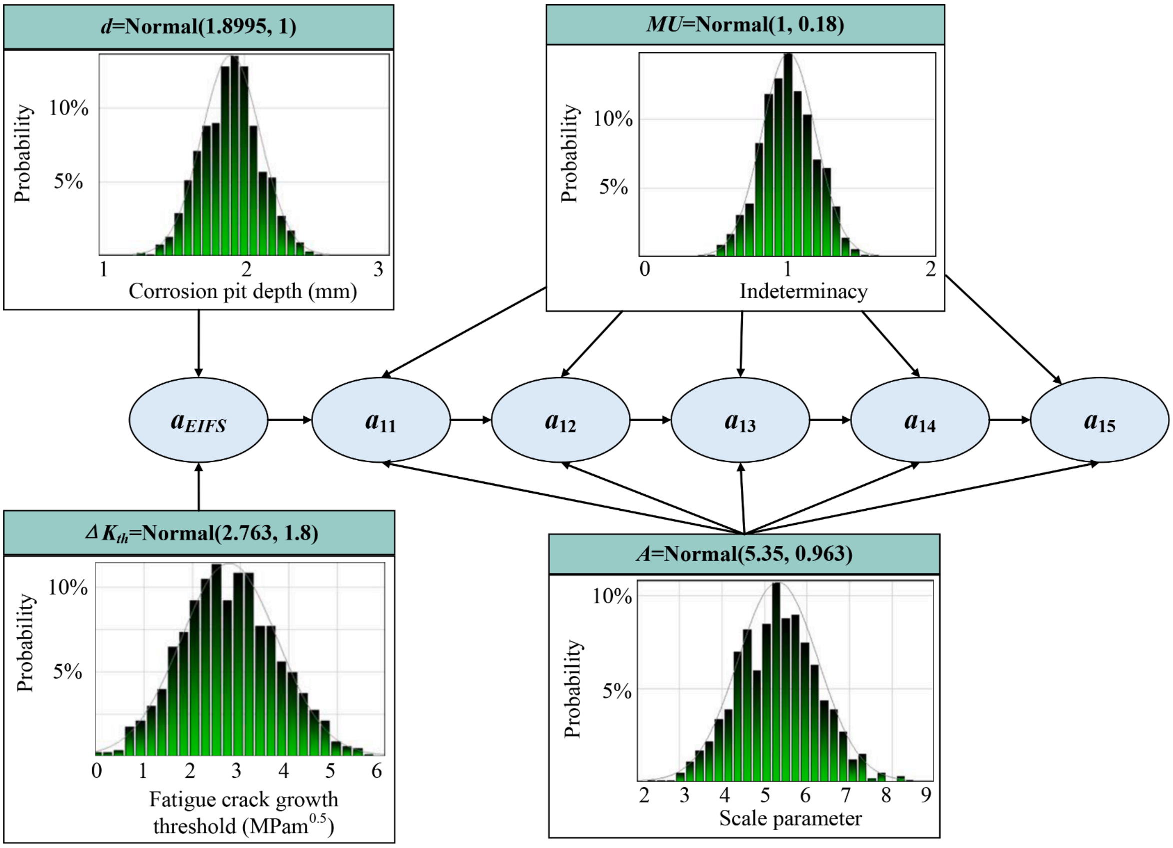

Fig. 4. DBN model of corrosion-fatigue degradation of subsea pipeline.

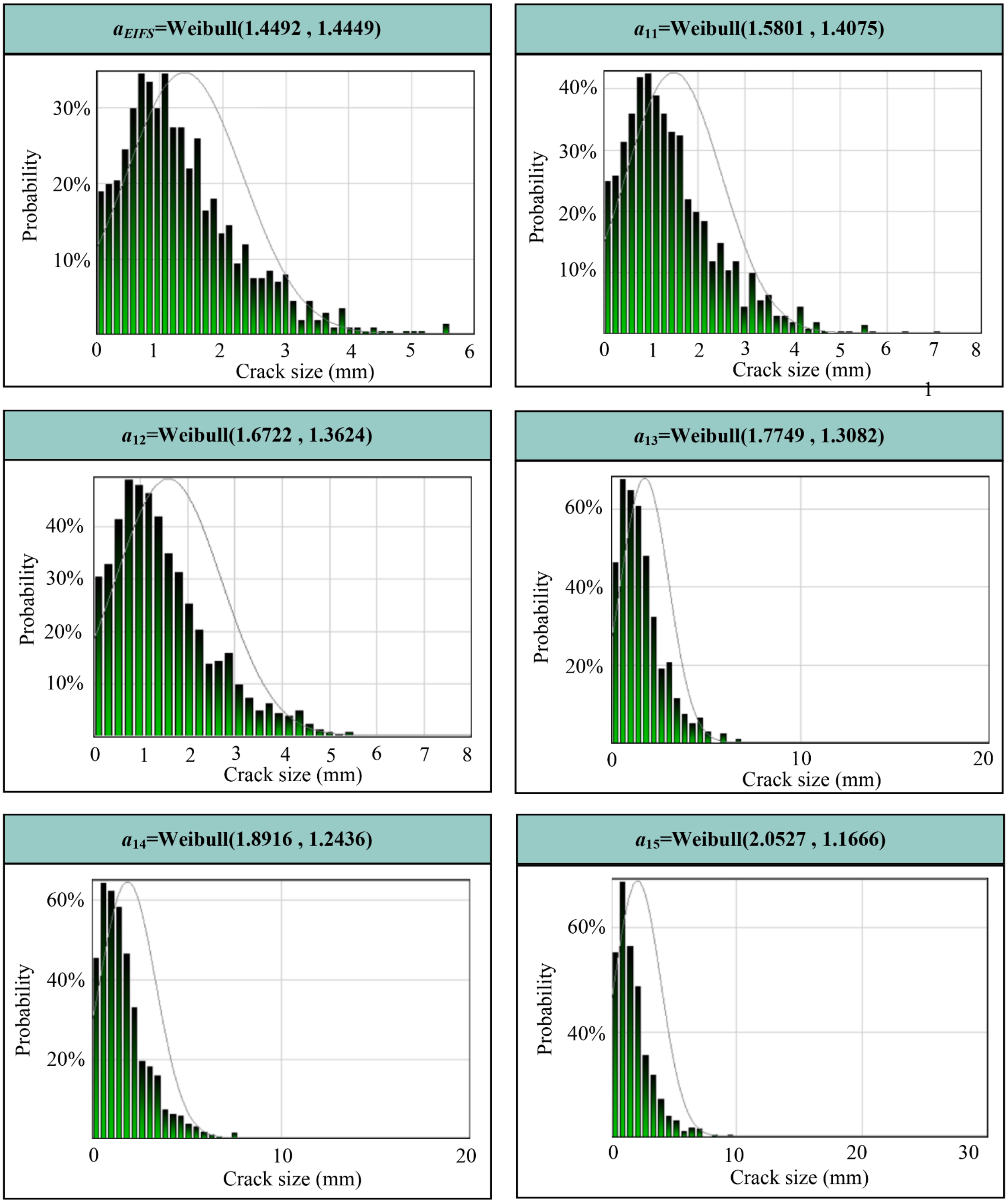

Fig. 5. Probability distribution of crack sizes at different time slices.

expressed as:

$$F(\Delta\sigma) = 1 - \exp\left[-\left(\frac{\Delta\sigma}{A}\right)^{B}\right], \Delta\sigma > 0 \tag{8}$$

Crack A is a function of other parameters. To express the uncertainty of the parameters in Paris formula, these parameters need to be regarded as vectors that make up the random variable X. The random variable X is described by a probability distribution. The failure criterion is defined as crack propagation through the entire material thickness. At this point, the crack propagation model is established, and the failure probability can be determined using the functional relationship of all variables.

2.2. *Dynamic crack propagation prediction*

Fracture mechanics model describes a determinative relationship for crack propagation. In practice, there are some uncertainties in crack propagation process. Thus, dynamic crack propagation is predicted using fracture mechanics model implemented with DBN model. BN is a probabilistic network which is widely used for quantitative reasoning under uncertainty. It is a representation of information in graphical form in which the logical relationships between variables in terms of conditional probabilities. Considering the conditional dependencies of variables and chain rules, the joint probability distribution $P(U)$ of a set of variables $U = A\ (A_1, A_2, A_3, \ldots, A_n)$ in BN can be described as Eq. (9) (Li et al., 2018).

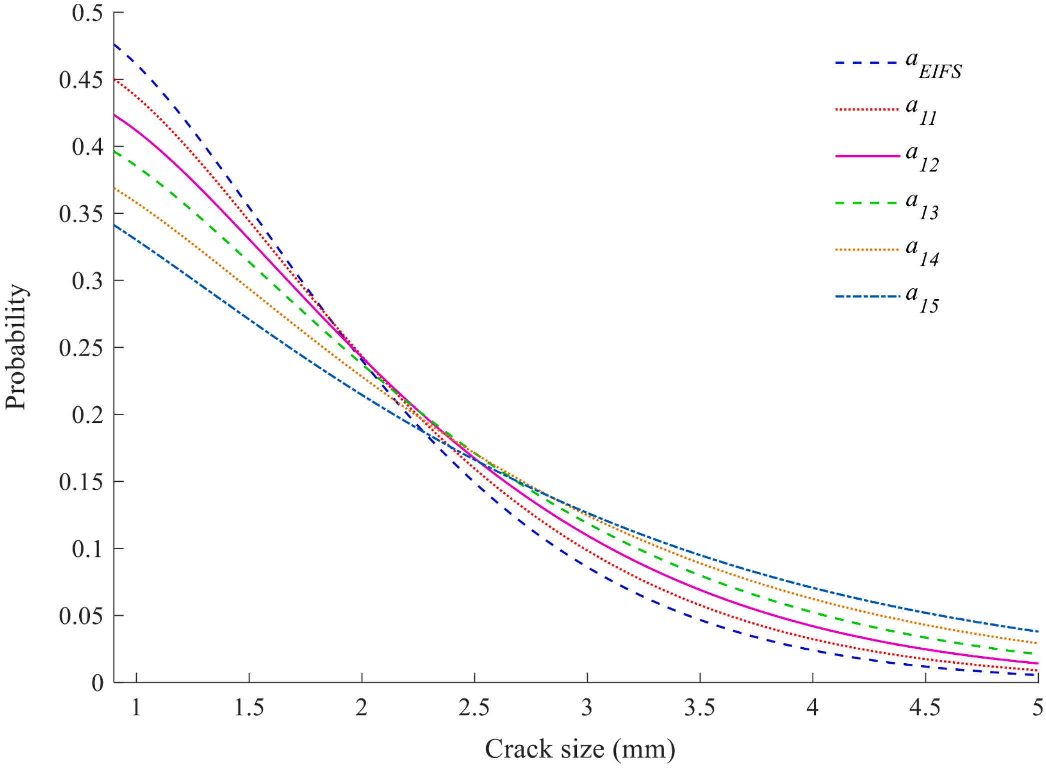

Fig. 6. Probability of crack size in different years.

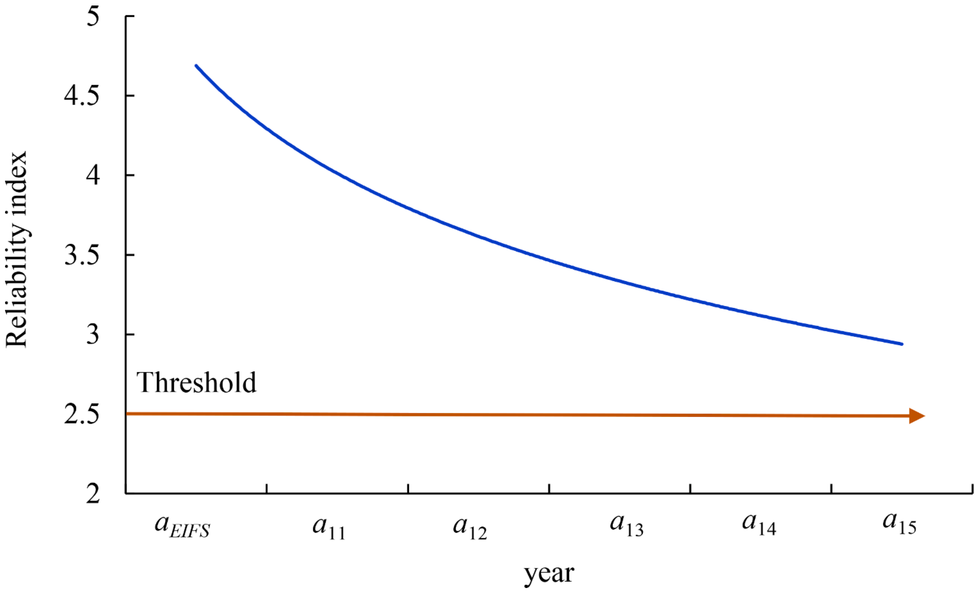

Fig. 7. Reliability degradation of subsea pipeline.

$$P(U) = \prod_{i=1}^{n} P(A_i|Pa(A_i)) \tag{9}$$

The state of system can be updated when new information becomes available. Applying Bayes' theorem, the initial beliefs can be updated when new evidence is observed, as shown in shown in Eq. (10).

$$P(A_i|E) = \frac{P(A_i, E)}{P(E)} = \frac{P(A_i, E)}{\sum P(A_i, E)} \tag{10}$$

where, E is new evidence; $\mathrm{P}(X_i|E)$ is the posterior probability; $P(E)$ is the probability of new evidence E.

DBN is an extension of BN, which adds the time dimension and can capture the dependence relationship along the time dimension. DBN can be interpreted as a generalization of Markov process models, and it was widely used for modeling of system deterioration over time. The joint probability density of a DBN for time $t = 1$ to N can be expressed as Eq. (11).

$$P(U_{1:N}) = \prod_{t=1}^{N} \prod_{i=1}^{n} P\left(U_{i,t} \,/\, Pa\left(U_{i,t}\right)\right) \tag{11}$$

For a DBN model, it is critical to determine the network structure including network variables (nodes) and the dependence among these variables (directed arcs) described using conditional probability table. The variable in DBN can be discrete or continuous. A simplified DBN model with continuous nodes is shown in Fig. 3. This model represents variable a as a function of variables A, $a0$ and MU. The conditional probability table (CPT) is transformed into the mathematical functions representing the relationship between these nodes (Yazdi et al., 2021).

Continuous DBN is used to establish corrosion-fatigue degradation model of subsea pipeline, which requires determining the parametric models that describe the crack growth of pipeline. This study integrates fracture mechanics model into DBN to predict crack propagation. It should be noted that all nodes are presented in the form of function nodes. It can make the model more realistic and explicit by selecting appropriate parameter distributions and functional relationships between these nodes (Parhizkar et al., 2021). The equivalent initial flaw size (a_0) is considered as the initial crack condition, and the probability distributions of crack sizes at difference time slices are estimated using DBN. The developed model can consider the uncertainties in crack propagation. The obtained crack size at different years follows a certain of probability distribution, not a crisp value.

2.3. *Life extension decision-making of subsea pipelines*

The corrosion-fatigue condition is reflected by the reliability for subsea pipelines. Life extension decision-making can be based on the reliability of subsea pipeline. The condition of pipeline is measured by the relationship between the actual crack depth and the permissible maximum crack depth. A limit state function is used to represent pipeline condition, as shown in Eq. (12).

$$Z = D - D_{(t)} \tag{12}$$

where, D is the permissible maximum crack depth which is 85% wall thickness, and $D_{(t)}$ is the actual crack size which follows a probability distribution obtained from DBN; Z represents the performance function of subsea pipeline, and $Z<0$ means that the pipeline is in failure state while $Z>0$ means that the pipeline is in reliable state.

Monte Carlo (MC) simulation is a mathematical technique used for estimating the possible outcomes of an uncertain event. This technique is usually used to get the approximate solution to a problem that has a specific probability model. The reliability of pipeline is estimated by simulating the actual process and random degradation behavior of pipeline in a computer model, which is based on repeating random sampling. MC simulation is often used to solve LSF when the probability density functions of the parameters in LSF are determined. In Eq. (12), the actual crack size at different time slices follows a certain probability distribution, and this is estimated through DBN model. Based on the probability distribution of actual cracks size and LSF shown in Eq. (12), the failure is estimated by counting the number of $Z<0$. The failure of subsea pipeline is treated as the ratio between the number of $Z<0$ and the total simulation number, as shown in Eq. (13).

$$P_f = \frac{N_f}{N} \tag{13}$$

where, P_f is the failure probability of subsea pipeline, N_f is the number of $Z<0$ while N is the total simulation number.

To facilitate the expression, the failure probability obtained using Eq. (13) is usually transferred into a reliability index β, as shown in Eq. (14).

$$\beta = -\Phi^{-1}\left(P_f\right) \tag{14}$$

where, Φ^{-1} is the inverse function of standard normal distribution function.

After getting the reliability index of pipeline, life extension strategies can be implemented based on the acceptable reliability level which depends on actual production requirement of oil and sector. When the reliability of pipeline is below the acceptable threshold, it indicates that any maintenance activities should be adopted to improve the performance of subsea pipelines and extend their service life.

3. Case study

A subsea pipeline in Cheng Dao Oilfield is used for illustrative purposes. The total length of this pipeline is about 8 km, which is used to transport crude oil from production platform to the onshore terminal. The pipeline material is X56 steel. The pipeline diameter is 323 mm, and the wall thickness is 11.1 mm. The service time of the pipeline is 10 years, which is reaching its design life. The external corrosion protection adopts a combination of anti-corrosive coating and sacrificial anode. The buried depth of this pipeline is 1.5 m. Due to the long service time, this pipeline is subjected to serious corrosion and some sections of this pipeline are unburied.

3.1. *Corrosion-fatigue degradation modeling of subsea pipeline*

As discussed in Section 2.1, EIFS and fracture mechanics model are used to describe corrosion-fatigue degradation of subsea pipeline, which is integrated into DBN model to predict the crack propagation. Specifically, the function relationship in Eq. (7) is transferred into a DBN. The variables in the equation are used as the network nodes, which are discretized based on their probability density functions.

The detection interval of 1 year is utilized in the model. The variables a_{EIFS} to a_{15} represent the crack size in time axis as $T = 10$ to 15 years. The variable a_{EIFS} represents the equivalent crack size of corrosion pitting and short crack, which depends on the fatigue crack growth threshold and corrosion pitting depth, following as $\Delta K_{th} \sim N$ (2.763, 1.8) and $d \sim N$ (1.8995, 1), respectively (Irwin and de Wit, 1983). Variable A is the scale parameter of Weibull distribution, which follows normal distribution with mean of 5.35 and standard deviation of 0.963, that is, $A \sim N$ (5.35, 0.9632). The shape parameter B of Weibull distribution is constant which is taken as 0.66 in this study. Material parameters C and m are constants ($C = 2.17 \times 10^{-13}$ and $m = 3$). Load cycle N is set as $3 \times 10^6/$ year. The related statistical parameters of variables used in the formulas are summarized in Table 1. As mentioned in Section 2.1, the geometric coefficient Y is assumed as a constant, $Y = 1.2$ (Qu et al., 2008). Thus, Eq. (7) can be further simplified as:

$$a = \left(a_0^{-\frac{1}{2}} - 2 \times 10^6 \times 5.8809 \times 10^{(-11)} \times MU \cdot A^3 \right)^{-2} \tag{15}$$

As illustrated in Fig. 4, the crack propagation model contained the process of a_{EIFS} period and the long crack growth. The integral propagation process is presented by a number of time slices (each representing one year). In the DBN model, variables MU and A follow the normal distribution. The crack size is discretized, and the crack in $i + 1$ interval is a constant multiple of i interval. At the same time, the sum of cracks at all intervals is equal to the wall thickness of pipeline (set as 11 mm).

3.2. *Crack propagation prediction using DBN*

Fig. 5 presents the time-dependent probability distribution of crack sizes. As illustrated in Fig. 5, the corresponding EIFS is assigned as 0.9675 mm with the observed pitting corrosion depth of 1.8995 mm, following as $a_{EIFS} \sim W$ (1.4492, 1.4449). a_{EIFS} is the initial crack including the corrosion pitting and short crack process. Therefore, compared with the observation corrosion depth, a_{EIFS} is smaller and conformed to the actual engineering situation. Moreover, it can be found that the scale parameters of probability distribution of crack size gradually increase, while the shape parameters gradually decrease. The failure time range of pipeline will become more concentrated with the increase of service life, and the failure time points will appear more frequently. In the sixth year, the crack will be growing at a high rate to larger size. At the end of design life, the extent of damage and failure probability has increased significantly. Subsea pipeline is exceptionally close to a failed event approximately 2 years later if repairs are not performed. The probability variation of the crack size of 1.27–3.16 mm gradually is becoming smooth and steady over time. In contrast, the large crack size is rising quickly at a_{13} and a_{14}.

It can be seen from Fig. 6 that the probability of small size crack size decreases gradually. The exponential distribution expression is selected and the initial value is defined. Collecting the calculated data base, the parameters are estimated, and the optimized degree of fitting and correlation coefficient are calculated. The curve fitting equation shows that the probability variation of crack size in different years conforms to the exponential distribution. It seems that the probability of crack size of 2.25–2.5 mm nearly varies without changes. When the crack growth rate is high, the hydrogen supply in the crack tip region is insufficient, resulting in a gradual recovery of the fracture resistance of the material. The change of the critical crack size with time is small. When the crack growth rate is high, the hydrogen supply in the crack tip region is insufficient. The fracture resistance of the material is gradually recovering, which is the main reason for the smaller change in critical crack size (Cheng and Chen, 2017). Compared to the small-size crack, the curve slopes in the larger-sizes crack are smoother. It means that the growth of larger sizes cracks is synchronous to small sizes cracks. In the small sizes crack propagation stage, the crack propagation is mainly affected by the microstructure and the corrosive environment. With the effect of stress concentration, the later period crack can spread rapidly until failure, which is the main reason for the coexistence phenomenon of the large sizes crack. Therefore, the cycle loading contributes more in crack propagation compared to the corrosion environment.

3.3. *Condition assessment and life extension decision-making*

Fig. 7 presents the dynamic reliability of aging subsea pipelines. The design life of this pipeline is 15 years, and the threshold of acceptable reliability index is 2.5 required by . It can be seen from Fig. 7 that the reliability of subsea pipeline is above the acceptable reliability level. The service life of pipeline can still be extended for about 1–2 years when it reaches its design life, and more service time is required in the engineering practice. The aging subsea pipeline had high reliability in the middle service period. Metal structures in seawater will develop a passivation layer on their surface to resist further crack propagation. However, the combined action of chloride and salt deposits provides a favorable environment for the flourishing activities of microorganisms, which accelerates the formation of metal cracks. Therefore, Cl^- ions can damage the layer and promote further corrosion and crack development although OH^-ions in seawater favor the formation of a passivation layer to avoid the formation of cracks. After microcracks are initiated, the decreasing trend of reliability is accelerated. The pipeline will enter the rapid degradation period of the 12th year. Although subsea pipelines are protected with coatings to inhibit corrosion and stress corrosion cracking, regular inspection and maintenance activities are required after ten years of operation to ensure that the corrosion protection system function well. The outcomes of the methodology can effectively support the life management of aging subsea pipelines and help to implement safety-related decision-making.

4. Conclusions

This study presented a corrosion-fatigue condition assessment approach to support life extension decision-making of aging subsea pipelines. The methodology simplified the complex corrosion-fatigue degradation process into the long crack propagation, which is implemented with EIFS and fracture mechanics model. Besides, this methodology considers the uncertainty in crack propagation, and a continuous DBN model is developed to predict the crack sizes following certain of probability distribution at different time slices. MC method is used to estimate the dynamic reliability of aging subsea pipeline during the rest of the design life, which is used as the index to perform life extension decision-making.

A case study of an aging subsea pipeline operating in China is used to test the availability and accuracy of the methodology. Corrosion-fatigue conditions are modelled and the dynamic reliability during the remaining design life is assessed. The crack propagation includes EIFS based on corrosion pitting depth and modeling long crack growth. The failure probability is calculated using MC and limit state function of pipeline fatigue failure. The estimated reliability index is used to optimize life management decision-making of aging subsea pipeline. The advantage of this approach is that the transition from corrosion pitting to short crack growth is simplified as the EIFS that is a part of long crack propagation. This approach is capable of qualitatively representing a crack propagation process and describing the failure probability over the lifetime of different crack sizes.

The observations of methodology application show that it can help to predict the reliability degradation and perform life extension decision-making of aging subsea pipelines. The limitation is that this approach cannot well consider the effect of installation and maintenance activities on the reliability of subsea pipelines. Although it can be reflected the use of proper stress intensity factor range ΔK which is difficult to be determined. In the future work, the necessary experiments will be conducted to further improve the accuracy of the model.

CRediT authorship contribution statement

Ziyue Han: Writing – original draft, Methodology. **Xinhong Li:** Methodology, Writing – original draft. **Renren Zhang:** Visualization. **Ming Yang:** Writing – review & editing. **Mohamed El Amine Ben Seghier:** Writing – review & editing.

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

Data will be made available on request.

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References

Aljaroudi, A., Thodi, P., Akinturk, A., Khan, F., Paulin, M., 2014. Application of probabilistic methods for predicting the remaining life of offshore pipelines. In: Proceedings of the International Pipeline Conference, p. 46131.

Amaya-Gómez, R., Riascos-Ochoa, J., Munoz, F., Bastidas-Arteaga, E., Schoefs, F., Sánchez-Silva, M., 2019. Modeling of pipeline corrosion degradation mechanism with a Lévy Process based on ILI (In-Line) inspections. Int. J. Press. Vessel. Pip. 172, 261–271.

Animah, I., Shafiee, M., 2018. Condition assessment, remaining useful life prediction and life extension decision making for offshore oil and gas assets. J. Loss Prev. Process Ind. 53, 17–28.

Arzaghi, E., Abbassi, R., Garaniya, V., Binns, J., Chin, C., Khakzad, N., Reniers, G., 2018. Developing a dynamic model for pitting and corrosion-fatigue damage of subsea pipelines. Ocean Eng. 150, 391–396.

Bastidas-Arteaga, E., Bressolette, P., Chateauneuf, A., Sánchez-Silva, M., 2009. Probabilistic lifetime assessment of RC structures under coupled corrosion–fatigue deterioration processes. Struct. Saf. 31 (1), 84–96.

Cai, B., Fan, H., Shao, X., Liu, Y., Liu, G., Liu, Z., Ji, R., 2021. Remaining useful life re-prediction methodology based on Wiener process: subsea Christmas tree system as a case study. Comput. Ind. Eng. 151, 106983.

Cai, B., Shao, X., Liu, Y., Kong, X., Wang, H., Xu, H., Ge, W., 2019. Remaining useful life estimation of structure systems under the influence of multiple causes: subsea pipelines as a case study. IEEE Trans. Ind. Electron. 67 (7), 5737–5747.

Cheng, A., Chen, N.Z., 2017. Corrosion fatigue crack growth modelling for subsea pipeline steels. Ocean Eng. 142, 10–19.

Chen, Y., Zhang, H., Zhang, J., Liu, X., Li, X., Zhou, J., 2015. Failure assessment of X80 pipeline with interacting corrosion defects. Eng. Fail. Anal. 47, 67–76.

Chakraborty, S., Tesfamariam, S., 2021. Subset simulation based approach for space-time-dependent system reliability analysis of corroding pipelines. Struct. Saf. 90, 102073.

Davaripour, F., Quinton, B.W., Pike, K., 2021. Effect of damage progression on the plastic capacity of a subsea pipeline. Ocean Eng. 234, 109118.

Dehghani, A., Aslani, F., 2019. A review on defects in steel offshore structures and developed strengthening techniques. Structures 20, 635–657.

El Haddad, M.H., Topper, T.H., Smith, K.N., 1979. Prediction of non propagating cracks. Eng. Fract. Mech. 11 (3), 573–584.

Goswami, T.K., Hoeppner, D.W., 1995. Pitting corrosion fatigue of structural materials. ASME-Publ. 47, 129–140. -AD.

Hafez, K.M., 2021. The role of a plain dent on the failure mode of a crude oil pipeline. Eng. Fail. Anal. 122, 105291.

Harlow, D.G., Wei, R.P., 1994. Probability approach for prediction of corrosion and corrosion fatigue life. AIAA J. 32 (10), 2073–2079.

Irwin, G.R., de Wit, R., 1983. A summary of fracture mechanics concepts. J. Test. Eval. 11 (1), 56–65.

Kovalov, D., Fekete, B., Engelhardt, G.R., Macdonald, D.D., 2019. Prediction of corrosion fatigue crack growth rate in alloys. Part II: effect of electrochemical potential, NaCl concentration, and temperature on crack propagation in AA2024-T351. Corros. Sci. 152, 130–139.

Li, X., Chen, G., Jiang, S., He, R., Xu, C., Zhu, H., 2018. Developing a dynamic model for risk analysis under uncertainty: case of third-party damage on subsea pipelines. J. Loss Prev. Process Ind. 54, 289–302.

Li, X., Zhang, L., Khan, F., Han, Z., 2021. A data-driven corrosion prediction model to support digitization of subsea operations. Process Saf. Environ. Prot. 153, 413–421.

Miller, D.L., Goswami, T., 2007. A review of locking compression plate biomechanics and their advantages as internal fixators in fracture healing. Clin. Biomech. 22 (10), 1049–1062.

Paris, P., Erdogan, F., 1963. A critical analysis of crack propagation laws. J. Basic Eng. 85 (4), 528.

Parhizkar, T., Utne, I.B., Vinnem, J.E., Mosleh, A., 2021. Dynamic probabilistic risk assessment of decision-making in emergencies for complex systems, case study: dynamic positioning drilling unit. Ocean Eng. 237, 109653.

Pourahmadi, M., Saybani, M., 2022. Reliability analysis with corrosion defects in submarine pipeline case study: oil pipeline in Ab-khark Island. Ocean Eng. 249, 110885.

Qu, X., Ma, T., Cui, H., Zhang, J., Wang, C., 2008. Statistical research of material coefficient in Paris Law. In: Proceedings of the Chinese Society of Theoretical and Applied Mechanics.

Rao, M., Yang, X., Wei, D., Chen, Y., Meng, L., Zuo, M.J., 2020. Structure fatigue crack length estimation and prediction using ultrasonic wave data based on ensemble linear regression and Paris's Law. Int. J. Progn. Health Manag. 11 (2), 1–14.

Ryan, H., Mehmanparast, A., 2023. Development of a new approach for corrosion-fatigue analysis of offshore steel structures. Mech. Mater. 176, 104526.

Shi, P., Mahadevan, S., 2001. Damage tolerance approach for probabilistic pitting corrosion fatigue life prediction. Eng. Fract. Mech. 68 (13), 1493–1507.

Shi, P., Mahadevan, S., 2003. Corrosion fatigue and multiple site damage reliability analysis. Int. J. Fatigue 25 (6), 457–469.

Shafiee, M., Animah, I., 2022. An integrated FMEA and MCDA based risk management approach to support life extension of subsea facilities in high-pressure–high-temperature (HPHT) conditions. Journal of Marine Engineering & Technology 21 (4), 189–204.

Shekari, E., Khan, F., Ahmed, S., 2017. Probabilistic modeling of pitting corrosion in insulated components operating in offshore facilities. ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems Part B: Mechanical Engineering 3 (1), 011003.

Shabani, M.M., Shabani, H., Goudarzi, N., Taravati, R., 2019. Probabilistic modelling of free spanning pipelines considering multiple failure modes. Eng. Fail. Anal. 106, 104169.

Sun, J., Ding, Z., Huang, Q., 2019a. Development of EIFS-based corrosion fatigue life prediction approach for corroded RC beams. Eng. Fract. Mech. 209, 1–16.

Sun, J., Ding, Z., Huang, Q., 2019b. Corrosion fatigue life prediction for steel bar in concrete based on fatigue crack propagation and equivalent initial flaw size. Constr. Build. Mater. 195, 208–217.

Wang, H., Liao, H., Ma, X., Bao, R., 2021. Remaining useful life prediction and optimal maintenance time determination for a single unit using isotonic regression and Gamma process model. Reliab. Eng. Syst. Saf. 210, 107504.

Wasim, M., Djukic, M.B., 2022. External corrosion of oil and gas pipelines: A review of failure mechanisms and predictive preventions. Journal of Natural Gas Science and Engineering 100, 104467.

Wang, Y., Chen, Z., Yan, Q., Hu, Y., Wang, C., Luo, W., Cai, B., 2022. A dynamic failure analysis methodology for fault diagnosis of fatigue cracks of subsea wellhead connectors with material aging. Process Saf. Environ. Prot. 159, 36–52.

Xu, Q., Shao, F., Bai, L.Y., Ma, Q.N., Shen, M., 2021. Corrosion fatigue crack growth mechanisms in welded joints of marine steel structures. J. Central South Univ. 28 (1), 58–71.

Xue, X., Li, W., Jia, J., Liu, J., Di, L., 2021. The whole fatigue crack propagation life prediction of Ni-based single crystal super-alloy specimen with single hole based on EIFS and 'Fish-eye' theory. Eng. Fail. Anal. 127, 105550.

Yang, Y., Peng, J., Cai, C.S., Zhou, Y., Wang, L., Zhang, J., 2022. Time-dependent reliability assessment of aging structures considering stochastic resistance degradation process. Reliab. Eng. Syst. Saf. 217, 108105.

Yazdi, M., Khan, F., Abbassi, R., 2021. Microbiologically influenced corrosion (MIC) management using Bayesian inference. Ocean Eng. 226, 108852.

Yuan, X.X., Higo, E., Pandey, M.D., 2021. Estimation of the value of an inspection and maintenance program: a Bayesian gamma process model. Reliab. Eng. Syst. Saf. 216, 107912.

Zhang, Y., Liu, X., Lai, J., Wei, Y., Luo, J., 2021. Corrosion fatigue life prediction of crude oil storage tank *via* improved equivalent initial flaw size. Theor. Appl. Fracture Mech. 114, 103023.

Zhao, T., Liu, Z., Du, C., Liu, C., Xu, X., Li, X., 2018. Modeling for corrosion fatigue crack initiation life based on corrosion kinetics and equivalent initial flaw size theory. Corros. Sci. 142, 277–283.

Zhu, Y., Wang, P., Wang, Y., Tong, R., Yu, B., Qu, Z., 2021. Assessment method for gas supply reliability of natural gas pipeline networks considering failure and repair. J. Nat. Gas Sci. Eng. 88, 103817.