

A framework to assess structural integrity of ageing offshore jacket structures for life extension



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ABSTRACT

The structural integrity assessment of ageing structures for possible life extension has been identified as a growing challenge in the oil and gas industry worldwide. Although the available guidelines provide a general assessment process, it is necessary to have more detailed guidelines. This can be achieved by adding relevant theories and models which can capture time-dependent structural degradation more precisely. To address this, a new framework for possible life extension is proposed in this paper. The proposed framework provides more precise corrosion models, new damage theories and assessment guidelines to predict the remaining fatigue life and check the structural adequacy in all the limit states during the whole extended service life. Initially, the paper presents the proposed framework in detail. The framework approach is then applied to an ageing jacket as a case study and results are compared with conventional approach. The proposed approach results in a remaining life of ten years as compared to one year using the conventional approach. Thus, the jacket structure can be safely operated for an additional nine years using the proposed approach. Recommendations are also made on increasing the remaining fatigue life using life improvement techniques. Finally, the applicability, significance and validity of the proposed framework are discussed.

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1. Introduction

A number of offshore platforms worldwide are approaching or have already exceeded their design life [1–8]. More than 50% of offshore installations on the Norwegian Continental Shelf (NCS), the United Kingdom Continental Shelf (UKCS) and the Gulf of Mexico Shelf are currently operating beyond their original life [3,9–12]. This figure is around 70% for around 800 platforms in the Middle East region [13]. The replacement of all these structures at once presents an operational and technical challenge [14,15]. The use of infrastructure from an existing field is sometimes a precondition for the development of a newer oil/gas field [16]. The enhanced production and drilling techniques, falling profit margins due to low oil prices, uneconomical small field discoveries and plenty of remaining oil reserves in existing fields are factors which are also encouraging operators to undertake more life extension studies. It is important to use the existing infrastructure efficiently and estimate its structural integrity and remaining service life more accurately.

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Ageing was recently categorized as functional ageing, technological ageing, knowledge based ageing and organizational ageing [8,17–20]. While the functional ageing includes material degradation issues such as fatigue, corrosion, dents, damages etc., technological ageing may refer to the old standards and regulations that are no longer considered sufficient for safe design. Knowledge based ageing may occur in cases where original design documents have become outdated due to availability of new knowledge such as new analysis methods, new models, new standards etc. Organizational ageing is the ageing of personnel and insufficient competence. While each of these key issues are important while addressing the problems of ageing, material degradation caused by fatigue and corrosion is a major cause of failures. Fatigue is a major hazard for offshore structures and in some cases fatigue cracking may reduce the overall structural integrity [21]. Corrosion changes the mechanical properties (i.e. degrades the strength) of steel with time [22]. Uniform corrosion is the most common form and can cause local structural collapse due to changes in structural stiffness [3,23,24]. Localized corrosion such as pitting and crevice corrosion is restricted to small areas and can cause local stress concentrations [25]. Corrosion fatigue is the result of cyclic loading in a corrosive environment and may reduce the fatigue strength by more than 60% for various corrosion levels [26]. A corrosion protection system (CPS) is generally employed to counteract corrosion but has a typical life of only 5–15 years [27]. It is ineffective in the splash zone due to the intermittent action of waves and tides [28]. Also, localized corrosion can start even before CPS loses its effectiveness [29]. The maintenance and repair of CPS for fixed offshore structures are generally very costly and sometimes impractical [30]. Other degradation mechanisms include erosion, creep, hydrogen related cracking, damage, blockages and accumulated plastic deformation [19,20]. It is reported that more than 60% of leaks on hydrocarbon systems are caused by ageing processes [18]. These ageing mechanisms can cause serious damage and even lead to major structural collapse. Although much research is carried out on ageing processes, failure has occurred and is still occurring in offshore structures [31]. Also, there are several uncertainties involved in fatigue assessment of ageing structures. These uncertainties can exist due to stochastic nature of the wave motion, dispersion in material characteristics of corroded members, scatter in the considered *S-N* curve for corroded detail, use of empirical relations in determining of stress factors and others. Such uncertainties together with poor inspection planning increases the risks of failures [32]. It is reported that the most severe accidents induced by fatigue were caused by gross errors like the absence of fatigue design check, bad design detailing and gross fabrication defects [32]. There is a need for detailed design checks using more precise assessment guidelines and a better understanding of complex ageing mechanisms.

Over the past two decades, a significant amount of research has been carried out to understand ageing and associated mechanisms. A number of initiatives have been taken in respect of the development of assessment guidelines and a framework for the life extension of aged structures. Also, attention was paid on the development of risk based inspection guidelines for the planning of inspection for fatigue cracks [33]. The Health and Safety Executive (HSE) has launched several key programmes (KP) on the UKCS, including a detailed investigation of ageing installations [34–36]. On the NCS, the Norwegian Oil Industry Association (OLF), together with the Petroleum Safety Authority (PSA), is establishing the necessary assessment guidelines [4,10,37]. The inclusion of the assessment procedures and frameworks for existing structures started in the mid-1990s with the insertion of a section in API RP 2A [38]. However, both the input and acceptance criteria given are tied to US waters. Subsequently similar sections were added to ISO 2394 in 1996 [39]. This was followed by ISO 13822 in 2001 [40] and ISO 19900 in 2002 [41]. The last addition to the international standards was an assessment section in ISO 19902 in 2007 [42], but it contains only minimal detailed or quantitative information [5]. In the UK, a structural integrity management framework for jacket structures was issued by the HSE in 2009 but was again based on API and ISO standards [43]. Around the same time, OLF and PSA initiated a project to establish the necessary standards and guidelines for life extension projects in the NCS region [37]. The outcome was the establishment of a new NORSOK standard N-006 [44] and the issue of recommended OLF guidelines [45] for the life extension of facilities. In 2014, API released a new standard, API RP 2S1M [46]. In 2015, a new DNV guideline was established on the use of probabilistic methods for planning of inspections for fatigue cracks in offshore structures [33]. It recommends the modelling of uncertainty variables (such as physical uncertainty, statistical uncertainty, measurement uncertainty) as stochastic variables, each having a defined probability distribution function based on engineering judgement, past experiences from similar problems or analytical results [47]. The British Standard BS 7910 is also an important document for probabilistic inspection planning methods such as RBI [48]. In addition to the above standards, life assessment guidelines and frameworks, which describe the overall assessment process, were discussed by researchers in the past [19,49–51]. These standards and the published literature provide a general assessment process for offshore structures and some procedures for the fatigue integrity assessment of details which cannot be inspected for fatigue cracks. However, it is advisable to have more detailed guidelines for offshore jackets; this can be achieved by adding relevant theories and models, which can capture the time-dependent structural degradation more precisely. Recommendations, which can estimate structural degradation in the absence of any corrosion measurement data or in cases where no significant corrosion is observed, are also necessary. The available guidelines are not sufficient to choose precise fatigue strength curves, which represent the time-dependent localized structural changes such as localized corrosion, dent, cracks, etc. Furthermore, recently proposed fatigue damage theories have not been included for a more accurate estimation of remaining fatigue life.

To overcome the above problems, this paper proposes a new framework for structural integrity assessment for the life extension of ageing jacket structures. The proposed framework provides the theories and guidelines necessary to predict the remaining fatigue life and check the structural adequacy in ULS, SLS and ALS during the whole extended service life. The proposed framework also provides recommendations on various issues such as simulation of time-dependent structural degradation, precision of loading history, effect of localized corrosion on stress concentration factors, selection of proper fatigue strength curves, determination of stress cycles and planning for mitigation and strengthening. Recently suggested,

more precise fatigue damage theory is also included in the proposed framework. Initially, the paper presents the proposed framework in detail. Then, the significance of ageing is highlighted quantitatively through a case study performed on an ageing offshore jacket structure. The structure is assessed using the proposed framework, as well as conventional approaches, and the remaining lives are compared. Finally, conclusions are drawn and recommendations are made on the use of the proposed framework for a more precise structural integrity assessment.

2. Proposed framework for structural integrity assessment and life extension

This section proposes a framework for structural integrity assessment and a more precise estimation of the remaining life of an ageing jacket structure. The assessment should be carried out for all limit states, i.e. ULS, SLS, ALS and FLS. The FLS is considered the most critical limit state as fatigue is the primary source of failure in welded structures and the remaining life is mainly governed by fatigue criteria [52,53]. The FLS being the most critical limit state may not always be true, particularly in benign waters. However, almost 25% of all structural damage requiring repair on offshore installations is classified under fatigue damage [54]. Fatigue in interaction with corrosion results in corrosion fatigue and can reduce the remaining life quite significantly. The uncertainty in the input parameters, such as loading history and stress concentration factors, also affects the remaining life predictions. It is important to determine these parameters more precisely for a more accurate prediction of the remaining life. The proposed framework provides precise corrosion models, new damage theories and assessment guidelines to predict the remaining fatigue life more accurately. The structural adequacy is checked for all other limit states as well. Finally, recommendations are made on strengthening mitigations and inspection/maintenance plans during the extended life. It is noted that, for a single structure, the assessment procedure might involve going through all paths of the framework, depending on the different degradation states of the fatigue critical details. Also, the proposed framework can be used for both deterministic and probabilistic analysis approaches. While the deterministic approach requires the use of design values (mean plus two standard deviation) of the parameters in the proposed framework, the probabilistic approach involves the use of a distribution function for each of these parameters. These distribution functions can be imported in probabilistic finite element method employed simulation tools and hence the failure probability of the structure can be determined. The use of such probabilistic tools can be computationally demanding for complex structures.

The framework is divided into five blocks, block A to block E, as shown in Fig. 1. These blocks include several stages of an assessment process from data collection to strengthening mitigations. A brief outline of various fatigue assessment approaches is presented with recommendations for selecting a suitable approach in Block A. Recommendations are made on the simulation of structural degradation and past loadings in the available finite element models in Block B and Block C. Guidelines on the selection of the proper fatigue strength curve for the selected detail are also included, followed by damage calculations using Miner's rule and the recently developed damage theories in Block D. Remaining life is estimated at the end, and recommendations are made on possible strengthening mitigations in Block E. The proposed framework is shown in Fig. 1, and a detailed explanation about each block is given in the following sub-sections.

2.1. Data collection, screening and selection of fatigue assessment approach (Block A)

Data and information collection is the first and one of the most important stages in an assessment study. The details of the data collection, screening and selection of fatigue assessment approaches are shown in Block A of the framework presented in Fig. 1. Documentation from the design phase and operational phase, as well as from the expected extended phase, should be collected as explained below.

2.1.1. Documentation during design, fabrication and installation phase

These include design documents, structural drawings, loading details, structural calculations, available finite element models, as well as fabrication and installation reports. Any reports of accidents during the lifting, transportation and installation phase should be collected. In addition, it is important to collect all the initial codes and standards used during the design phase.

2.1.2. Documents during the operational phase

These include documentation of any accidents and incidents during the service life, damage and modifications to the structure, risk assessment reports, as well as any modified finite element models of the structure. It is important to collect all inspection and maintenance reports, as well as any material-testing reports, to document the status of the structural degradation and any potential fatigue cracks. It is also important to list all the findings and repairs that are carried out during the operational phase.

2.1.3. Documents during the extended life phase

These include expected operational as well as environmental loads. Information regarding any modifications required to cater for future needs, in terms of both technology and equipment, should be collected. The current set of codes and standards addressing the life assessment and life extension also need to be documented.

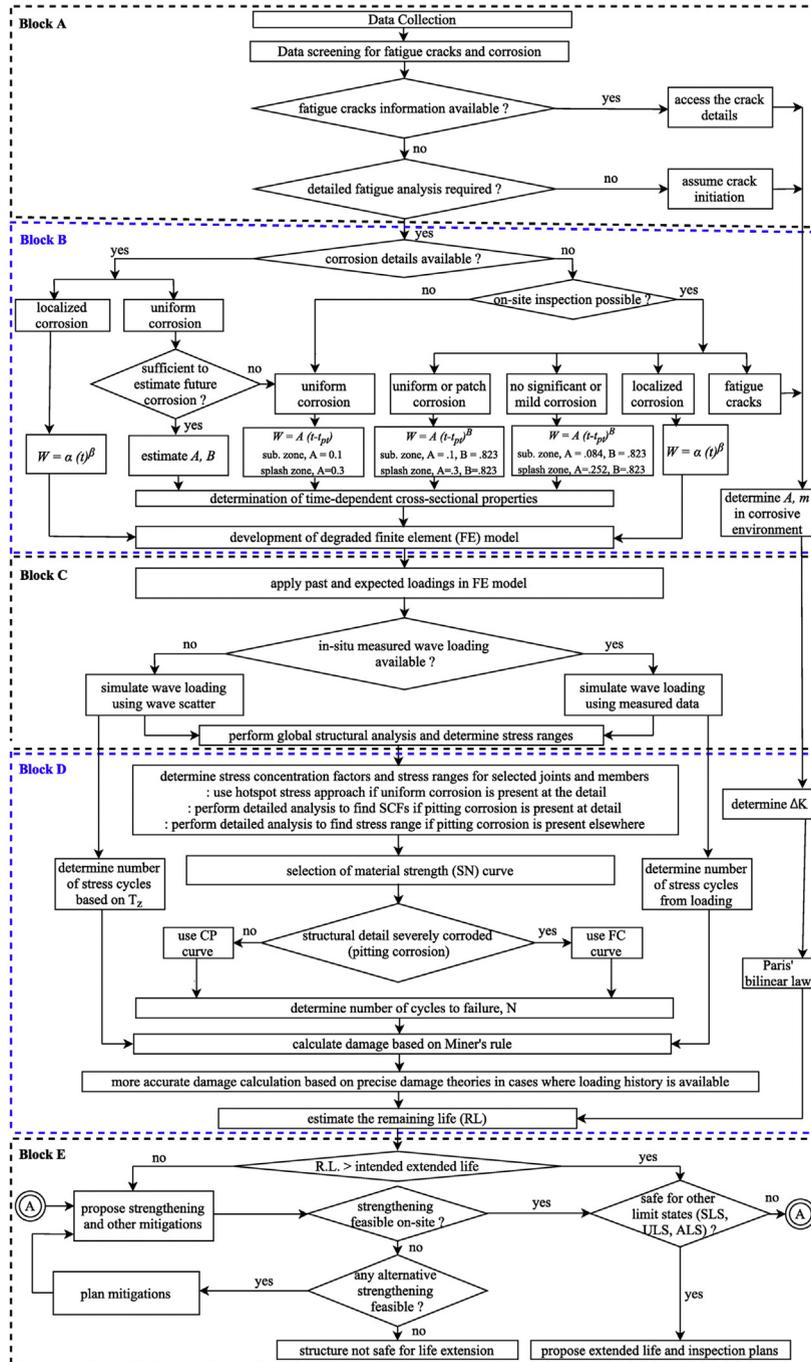


Fig. 1. Proposed framework for structural integrity assessment and life extension of ageing offshore structures.

2.1.4. Selection of fatigue assessment approach

The collected data should be screened for all structural degradation information, including extent of structural degradation, member thickness measurements and fatigue cracks. The selection of a suitable fatigue assessment approach is an essential part of any assessment process. For offshore structures, two well-known fatigue life assessment approaches are: (a) the damage tolerance approach and (b) the safe life approach [55,56]. The damage tolerance approach assumes the existence of a fatigue crack and then estimates the future life, using crack propagation theories, while the safe life approach estimates the crack initiation and propagation life, using detailed category-based fatigue strength curves. It is known that the crack initiation life of a structural element is much higher than the crack propagation life [56]. The industry practice for the fatigue design of offshore jacket structures is based on the use of the safe life approach and is also recommended in design standards [57,58]. Moreover, it is recommended that the damage tolerance approach be used where fatigue crack information is available, such as in cases of existing ageing structures. In such cases, the safe life approach is no longer applicable after a crack has initiated. The linear elastic fracture mechanics can describe the probable crack behaviour and its propagation towards the final failure.

2.1.4.1. Safe life approach – S-N method. The safe life approach is based on S-N curves of detail category. In this assessment method, a more accurate prediction of remaining life can be made using recently proposed precise damage theories [59–61]. For a detailed fatigue assessment of tubular joints in jacket structures, hot spot stress based T curve should be carefully chosen based on the extent of corrosion at the joint [58]. In cases where detailed fatigue assessment is not required, remaining life can be predicted by assuming a crack initiation and using the damage tolerance approach based on linear elastic fracture mechanics.

2.1.4.2. Damage tolerance approach - linear elastic fracture mechanics method. This method is based on the crack growth law, which can be represented by several models [48,62–64]. The most frequently used conventional model is Paris' law as given in Eq. (1) [65].

$$\frac{da}{dN} = A(\Delta K)^m \quad (1)$$

where da/dN is the crack growth rate, ΔK is the stress intensity factor range, A and m are the constants that depend on material and the applied conditions, including environment and cyclic frequency. A re-assessment of the available test data for fatigue crack growth rates was made in 1998 to capture the environmental effect on these constants and recommendations are also available on the use of more precise two-stage relationships [48,66–68]. The stress intensity range ΔK can be expressed as shown in Eq. (2).

$$\Delta K = K_{max} - K_{min} \quad (2)$$

where K_{max} and K_{min} are the maximum and minimum stress intensity factor corresponding to maximum and minimum stress ranges. The stress intensity factors for tubular joints can be determined numerically using a finite element or boundary element analysis of the joint. Alternatively, analytical solutions are provided by standards, which are deduced from semi-elliptical cracks in plates [48]. The other parameters of the crack propagation curve (A , m) can also be found in standards [48].

2.2. Simulation of degradation and development of degraded FE models (Block B)

The structural degradation should be simulated, and degraded FE models should be developed as per Block B of the framework presented in Fig. 1. The collected data is further screened for all available structural degradation information. This includes all the past inspection reports and thickness measurement records, as well as the current status of degradation in the structure. It is recommended that the finite element (FE) model of the structure should first be developed using this available information. Any geometrical modifications to the structure during the installation and operational phase should be modelled. The jacket and the topside should be modelled in finite element software using the beam/frame elements. In addition, precise modelling of the foundation should be carried out, using the available soil stiffness information. The finite element model should be verified against any available structural dynamic response measurement data; modifications should then be performed to account for the effect of time-dependent structural degradation of the structure. This model is named the “degraded FE model”, and the simulation of degradation is explained in detail below.

2.2.1. Simulation of uniform corrosion

Uniform corrosion is the most common form of corrosion and is uniformly distributed on the surface. This results in the reduction of member thickness and thereby the reduction of the effective cross-sectional properties of the members, such as effective area, second moment of area, torsional constants and warping constants. This may cause change in the overall stiffness of the structure and the structural response (i.e. stress, displacement and dynamic characteristics). It is essential to accurately include the time-dependent effect of uniform corrosion in the finite element model, using suitable corrosion wastage models. Several studies have shown that uniform corrosion can be simulated with a good approximation by a

nonlinear function [69–75]. The nonlinear corrosion wastage model assumes no degradation in the first phase when the protection system is effective. This is followed by a nonlinear process of growth over time, as shown in Eq. (3).

$$W(t) = A(t - t_{pt})^B \quad (3)$$

where $W(t)$ is the thickness wastage in millimetres, t is the lifetime and t_{pt} is the corrosion protection time in years. The model has two parameters, A and B , whose values should be precisely determined. The standard deviation of the thickness wastage is given by Eq. (4) [76,77].

$$\sigma_{W(t)} = 0.67 W(t) \quad (4)$$

2.2.2. Simulation of localized corrosion

Pitting is a localized form of corrosion and is regarded as one of the most hazardous types of corrosion for offshore structures [78,79]. Such localized corrosion is very likely to occur in the splash zone area, where corrosion protection systems (CPS) are ineffective [80]. Also, pitting corrosion may even start before the CPS loses its complete effectiveness [29]. Although pitting corrosion has no significant effect on the global stiffness of the structure, it can cause local stress concentrations at the structural detail and thus reduce the fatigue life [25,81,82]. It is therefore essential to take pitting corrosion into account, while determining stress concentration factors at the corroded structural detail. It is recommended that, in addition to the global structural analysis, a local stress analysis be performed near the pits to determine secondary stresses and estimate the fatigue life more precisely. The pit depth has been acknowledged as a critical factor for pitting corrosion and is the key parameter to describe the pitting rate [78]. The propagation of pit depth is conventionally described by a power-law model [83], analogous to that for uniform corrosion, and is shown in Eq. (5). Moreover, no coating period (t_{pi}) is considered, as pitting corrosion can start even in the presence of CPS.

$$W(t) = \alpha(t - t_i)^\beta \quad (5)$$

where $W(t)$ is the propagation of pit depth, t_i is the pit nucleation time and t is the pit propagation time. In practice, the time for the pit nucleation (t_i) is negligible compared to the pit propagation time [84]. Hence the pit growth is usually described by Eq. (6).

$$W(t) = \alpha(t)^\beta \quad (6)$$

The α and β are model parameters and should be determined precisely. Wang et al. [85] also proposed a simple engineering model by adopting a two-parameter (m, α) Weibull function to describe the growth of macro-pits in the function of exposure time, as given in Eq. (7). The corresponding pit growth rate is given by Eq. (8).

$$W(t) = d_m \{1 - \exp[-[\alpha(t - t_i)]^m]\} \quad (7)$$

$$W'(t) = d_m m \alpha (t - t_i)^{m-1} \exp[-[\alpha(t - t_i)]^m] \quad (8)$$

where m and α are the shape and scale parameters respectively, and d_m is the long-term pit depth. For the shape parameter greater than 1, the pit growth rate shows an increasing phase, followed by a maximum and a decreasing phase. The pitting corrosion rates drop monotonically for $m \leq 1$. This new model is only applicable to the growth phase of macro-pits. More guidelines on the selection of these parameters can be found in Wang et al. [85].

2.2.3. Time-dependent sectional properties of corroded cross sections

The cross-sectional properties of the members or locations where uniform or patch corrosion is observed should be modified as per the time-dependent thickness reduction, Eq. (3). These modified cross-sectional properties are used to develop a degraded FE model. Such a change is not required for members where pitting corrosion is observed, as there is no significant loss of material and hence no significant reduction in the stiffness.

The effective cross-sectional area of a corroded section is given by

$$A_{eff}(t) = A_0 - \sum_{i=1}^n W_i(t) l_i \quad (9)$$

where A_{eff} is the effective area, A_0 is the initial cross-sectional area, l_i is the length of uniform corrosion spread over the cross section at the i^{th} corroded surface, as shown in Fig. 2(a). The $W_i(t)$ is the average corrosion penetration in mm at the i^{th} corroded surface of the cross section, and t is the age in years.

The reduction in the member cross section shifts the neutral axis by a distance, $e(t)$. This shift can be obtained using Eq. (10).

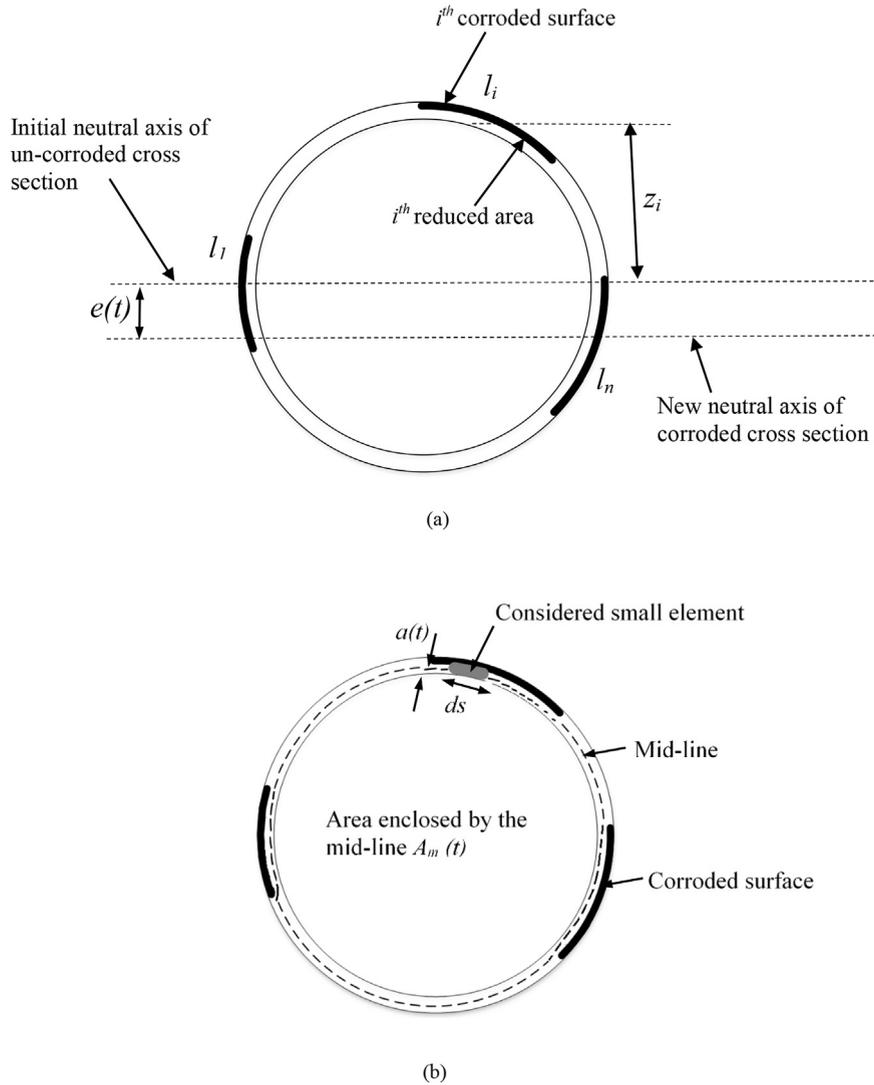


Fig. 2. Schematic representations of (a) effective cross-sectional parameters of corroded tubular cross section (b) torsional parameters of corroded tubular cross section.

$$e(t) = \frac{\sum_{i=1}^n W_i(t) l_i z_i}{A_{eff}(t)} \quad (10)$$

where z_i is the height from the initial neutral axis to the centroid of the i^{th} reduced area (i.e. lost area at the i^{th} surface).

The effective second moment of area of the corroded cross section is calculated about the new neutral axis and can be obtained using Eq. (11).

$$I_{eff}(t) = I_0 + A_0 e(t)^2 - \sum_{i=1}^n \left\{ \Delta I_i + W_i(t) l_i [z_i + e(t)]^2 \right\} \quad (11)$$

where I_0 is the second moment of area of the uncorroded cross section, ΔI_i is the second moment of i^{th} reduced area about its own neutral axis.

The effective torsional constant for the closed cross section of a corroded member can be obtained using Eq. (12).

$$I_{T,eff}(t) = \frac{4A_m(t)^2}{\oint ds/a(t)} \quad (12)$$

where $A_m(t)$ is the area enclosed by the midline of the cross section as shown Fig. 2(b). The enclosed area $A_m(t)$ keeps shifting with time due to a continuous shift in the midline as a result of corrosion. The ds is the developed midline length and $a(t)$ is the thickness of the considered small element of the cross section.

The thickness $a(t)$ of the considered small element of the cross section can be written at a time t using Eq. (13).

$$a(t) = a_0 - W(t) ; \text{ when } t > t_{pt} ; a(t) = a_0 ; \text{ when } t \leq t_{pt} \quad (13)$$

where a_0 is the thickness of an uncorroded small element, $W(t)$ is the average corrosion penetration in mm at the considered location and t_{pt} is the corrosion protection time in years.

2.2.4. Parameters of uniform corrosion model

The average corrosion penetration is the corrosion wastage due to uniform corrosion and can be determined using Eq. (3). The values of parameters A and B can be determined by fitting previous corrosion measurements with a proposed nonlinear variation in Eq. (3). However, if the corrosion details are insufficient for the estimation of the above parameters, it is recommended that the values be selected conservatively from Table 1. The values of these parameters can be found in the work of several researchers [27,28,32,76,77]. It is suggested to ignore any remaining potential of sacrificial anodes. This is to have some conservatism in the estimation of remaining life.

2.2.5. Parameters of localized corrosion model

In addition to accounting for uniform corrosion in global analysis, it is recommended that a local stress analysis be performed near the pits to determine secondary stresses, if precise fatigue assessment is required. The pits can be simulated as per the corrosion model explained in Eq. (6). The parameters α and β can be taken based on the material type, as per Table 2 [86,87].

2.2.6. Parameters of crack growth law in marine environment

The material parameters, A and m , in Paris' law, are influenced by the surrounding environment and need to be correctly determined for offshore structures in the marine environment. For welded joints, use of mean plus two standard deviation values with stress ratio, $R \geq 0.5$ is recommended for conservatism and to allow for the influence of residual stresses [48]. The values of the parameters, A and m , for the crack growth law in Eq. (1), are given in Table 3 [48].

Table 1
Mean values of model parameters for uniform corrosion [27,28,32,76,77].

Inspection findings	Splash zone area		Other areas	
	$A(mm)$	B	$A(mm)$	B
Not performed – unmanned facility or high costs involved	0.3	1	0.1	1
Severe corrosion found – uniform corrosion with many patches and pitting corrosion	0.3	0.823	0.1	0.823
No significant corrosion – slight uniform corrosion with few patches	0.252	0.823	0.084	0.823

Table 2
Model parameters for pitting corrosion [86,87].

Material type	Parameters	
	$\alpha (mm)$	β
Carbon steel in sea water	0.092	0.511
Mild steel in sea water	0.0028	0.3877

Table 3
Parameters of crack growth law in marine environment (recommended values for stress ratio $R \geq 0.5$) [48].

Marine environment	Stage A		Stage B		Intersection between Stage A and B $\Delta K_0 (N/mm^{3/2})$
	A^a	m	A^a	m	
Free corroding environment	1.72×10^{-13}	3.42	7.48×10^{-7}	1.11	748
Cathodic protection at -850 mV	2.10×10^{-17}	5.10	2.02×10^{-11}	2.67	290
Cathodic protection at -1100 mV	2.10×10^{-17}	5.10	1.02×10^{-7}	1.40	415

^a For da/dN in $mm/cycle$ and ΔK in $N/mm^{3/2}$.

2.2.7. Feasibility of on-site inspections

In cases where degradation/corrosion information is not available, it is recommended to explore the possibilities of on-site inspections. These inspections can be limited and should contain at least some thickness reduction measurements, along with photographs. Several non-destructive monitoring techniques are used in industry for evaluating the corrosion resistance of materials and detecting fatigue cracks without causing damage. A brief description of non-destructive testing (NDT) methods is presented by past researchers [88–90]. Simpler detection methods like general visual inspection (GVI) and close visual inspection (CVI) cannot be used to detect small fatigue cracks. In such cases, other methods like flooded member detection (FMD), eddy current (EC), magnetic particle inspection (MPI) and alternating current field measurement (ACFM) should be used together with the probability of detection (PoD) curves. Among these, EC method may be preferred for ease of measurement and for its provision of a direct measurement of thickness loss, i.e., corrosion rate [91]. The PoD curves represent the probability of detecting a crack depending on the method used and working conditions such as location of crack with respect to water level or the visibility conditions at hot spot areas [47,92]. The distribution functions for the PoD curves are dependent on qualification and execution of work but can also be taken from recommended guidelines [47]. While doing the on-site inspections, special attention should be paid to the hot spot areas in the splash zone.

The degraded FE model should be developed based on the on-site inspection findings. The uniform or patch type of corrosion can be simulated using the model parameters given in Table 1. It is advisable to take parameters on the conservative side if inspections are not performed or if the details are subjected to severe corrosion. Any findings of localized pitting corrosion should be accounted for precisely to determine the model parameters of Eq. (6) or to check the accuracy of the available/determined model parameters of the pitting corrosion wastage model given in Table 2. The stress concentration factors should be calculated in cases where pitting corrosion is observed at the fatigue critical details. Localized corrosion found on the members should be accounted for by modelling them in detail and performing a more detailed local stress analysis. As discussed above, the modification of cross-sectional properties should not be required for the members/locations where pitting corrosion has been recognized, if there is no significant change in the stiffness or stability of the member. It is recommended that the damage tolerance approach be used in cases where fatigue cracks are found during the on-site inspections. The parameters of the bilinear law should be determined based on the extent of corrosion at the crack location and as per Table 3.

2.2.8. Corrosion fatigue

The mechanical degradation of material, when the structure is subjected to repetitive cyclic stress in the presence of a corrosive environment, is corrosion fatigue. This is a failure mechanism which is not yet fully understood [93]. However, it can have a significant impact on the fatigue life, reducing it by more than 60% for various corrosion levels [26]. Although the precise modelling of this mechanism is a complex task, it is essential to take it into reasonable consideration for life extension.

2.3. Simulation of loading and structural analysis (Block C)

The past and future loading should be applied, and structural analysis should be performed as per Block C of the framework presented in Fig. 1. The collected data should be screened for all past loadings over the design life of the structure. These include operational loads as well as environmental loads. The operational loads should be updated for any changes during the lifetime of the structure, based on inspection and maintenance records. In cases where sufficient information is not available or data records are missing, it is recommended that operational load values be taken from the design standards [38,42,58,94]. Any additional requirements for higher operational loadings during the extended life should be simulated in the degraded FE model. The environmental loads include mainly the wave and the current loading. It is advisable to use a 100-year return period wave for ultimate limit state assessment and a 10000-year return wave for accidental limit state assessment. The wave and current parameters for the above-mentioned return periods can be taken from the original design documents. In cases where the information is missing, the recommendation is to take these values from the design standards [38,42,58,94]. For the fatigue limit state assessment, the data collected during the operational phase should be screened for any records of real wave measurements. Such available data should be employed for estimating the past and future wave loading on the structure at the specified location. In cases where no wave measurement data is available, the wave environment can be approximately simulated using the long-term wave scatter diagram for the specified location. The wave scatter diagrams can be either found in the design documents or taken from design standards.

The structure should be analysed for past as well as future loadings. The load cases and load combinations can be made as per the standards for the various limit states. It is recommended to first perform a quasi-static analysis to ascertain the overall integrity of the structure. A linear elastic analysis should be performed for a preliminary estimation of the overstressed members in ultimate limit state. Such a preliminary analysis is required to screen critical locations for a detailed fatigue assessment. In cases where preliminary analysis results are found to be severe with plenty of overstressed locations, performing a nonlinear analysis is recommended for more precise analysis. The nonlinear analysis should capture both the geometrical and the material nonlinearities. Based on the ultimate limit state preliminary analysis, critical locations should be identified for a detailed fatigue assessment. For a detailed fatigue assessment, a suitable fatigue assessment method should be selected depending upon the sensitivity of the structure to dynamic effects.

2.3.1. Fatigue assessment methods for jacket structures

Two different methods are used for the fatigue analysis of jacket structures. These are deterministic discrete wave fatigue analysis (deterministic fatigue analysis) and frequency response fatigue analysis (frequency domain fatigue analysis, spectral fatigue analysis or stochastic fatigue analysis). The deterministic approach requires calculation of fatigue damage for each sea state in the wave scatter diagram to determine the total fatigue damage. This approach is traditionally preferred for jacket structures in low to moderate water depths as these are not sensitive to dynamic effects [47,53,58,94]. A stochastic fatigue analysis is generally performed for structures with significant dynamic response such as deep-water structures and requires the determination of hydrodynamic transfer functions [47,53,58,94]. It is recommended to perform a deterministic fatigue analysis for jacket types structures in low to moderate water depths [47,53,58,94]. For deep-water jackets with a fundamental natural period exceeding 2.5 s, a deterministic fatigue analysis may still be recommended by determining a dynamic amplification factor using recommended guidelines [47,53].

The fatigue assessment should be performed for the critical locations using the available loading history or wave scatter diagram. It is advisable to apply wave loading from 0 to 180° at 30-degree spacing. A suitable wave theory should be used, depending upon the water depth at the location as well as the wave parameters [95,96]. The wave loads should be applied, together with permanent and variable loads, to capture the mean stress effects. The load combinations should be as per standard codes and guidelines. A nonlinear structural analysis is recommended for the determination of stresses in the members for each sea state of the wave scatter diagram.

2.4. Stress evaluation and estimation of remaining fatigue life (Block D)

Analysis should be performed to determine stress ranges and to estimate the remaining fatigue life as per Block D of the framework presented in Fig. 1.

2.4.1. Evaluation of stress ranges at the critical locations

The analysis should be performed for each sea state of the wave scatter, and the maximum stress range should be determined for all the members at the critical joints/locations identified in Section 2.3. The hot spot stress (HSS) approach is widely used for the fatigue assessment of jacket structures. The presence of uniform corrosion reduces the member thickness uniformly and hence it is still reasonable to use the HSS approach for such cases. The stress concentration factors (SCFs) can be determined as per standard codes and guidelines, and the superposition method can be applied to determine the maximum hot spot stress range [58]. The HSS approach can also be applied at the joint detail if localized corrosion is present at a distance of more than four times the member thickness [58]. In cases where localized corrosion is present at the detail, a comprehensive detailed local analysis is recommended. This can be done by making a separate finite element model of the detail, including the pits and a more refined mesh. The local secondary stress state should be determined, and use of the notch stress approach is advised for fatigue life assessment. In the presence of localized corrosion away from the joint detail (at a distance of more than four times the member thickness), a comprehensive detailed local analysis should be performed separately. The member with pits should be modelled considering required mesh sensitivity, and local stresses should be evaluated to identify the most critical locations. The maximum stress ranges at this location can then be utilized to determine the fatigue life, using a suitable $S-N$ curve. Alternatively, the pits can also be assumed to be dents, and the stress concentration factors can be determined using the formulae for dents provided in the standards or textbooks [97]. The stress ranges are employed for fatigue life estimation, using either the safe life or the damage tolerance approach. Life estimation using the safe life approach is firstly discussed; this is followed by the damage tolerance based linear elastic fracture mechanics method.

2.4.2. Selection of fatigue strength ($S-N$) curve

The selection of a suitable $S-N$ curve depends on the type of detail category and the method used for stress evaluation. The current state of degradation at the detail category also influences the selection of $S-N$ curve, as surface roughness and hydrogen embrittlement are the governing factors of fatigue strength. It is recommended to use a free corrosion (FC) curve in the cases where severe uniform and pitting corrosion are found at the detail. The cathodic protection (CP) $S-N$ curve can be used for corrosion-free details. For tubular joints in jacket structures, hot spot stress based T curve can be selected from design standards and recommended practices [58]. The number of actual stress cycles (n) can be determined using the zero up-crossing time period for the corresponding sea state of the wave scatter diagram [58,98]. The stress cycles can be counted from the measured wave loading history, if available.

2.4.3. Calculation of fatigue damage

The yearly fatigue damage for each sea state can be calculated using Miner's rule [56,99]. The yearly fatigue damage covering all sea states can be calculated using Eq. (14) as per standard codes [100].

$$D_L = \sum_{i=1}^{n_s} D_i P_i \quad (14)$$

where D_L is the yearly fatigue damage covering all sea states, n_s is the number of discrete sea states in the wave scatter diagram, D_i is yearly fatigue damage for individual sea states and P_i is the sea state probability. A design fatigue factor (DFF)

should be considered in the damage calculations depending upon the consequence of fatigue failure and the probability of inspection and repair. The DFF can be obtained from the design standards and recommended practices [47,58,94,101]. A high value of DFF represents a reduced probability of fatigue cracking and a value of 10 is recommended for areas not accessible for inspection and repair. This value can also be used if it is desired to omit future scheduled inspections during the extended life of the structure.

The fatigue damage can be determined using the Miner's rule where loading history is unknown. However, under variable amplitude loading conditions, Miner's rule can lead to unreliable predictions of remaining life, since it did not properly take into account the loading sequence effect [56,59,102]. In cases of existing ageing structures where loading history might be known, it is recommended to use the recently proposed "sequential law" [59,60] to capture the load sequence effect more precisely. This paper presents only a summary of the sequential law. It can be explained briefly by assuming a component subjected to a certain stress range, σ_i , for n_i number of cycles at load level i . This results in a residual life of the component: $(N_i - n_i)$ cycles at load level, i . The stress, $\sigma_{(i)eq}$, which corresponds to the failure life $(N_i - n_i)$ is obtained from the $S-N$ curve and is named as i^{th} level damage stress amplitude or stress range. The new damage indicator, D_i , can then be written as

$$D_i = \frac{\sigma_{(i)eq} - \sigma_i}{\sigma_u - \sigma_i} \quad (15)$$

where σ_u is the intercept of the $S-N$ curve with the ordinate at one quarter of the first fatigue cycle. Assuming that the same damage is transformed to the next load level $i+1$, the damage equivalent stress at level $i+1$ can then be calculated. Subsequently, the corresponding equivalent number of cycles to failure and the residual life at the load level $i+1$ can be obtained using the $S-N$ curve. The cumulative damage at load level $i+1$ can then be defined. The above procedure is followed until the cumulative damage becomes unity and a more precise estimation of remaining fatigue life is obtained. A detailed description of the sequential law, including the damage stress model and the new damage indicator D_i , can be found in work by previous researchers [59,60].

2.4.4. Selection of crack propagation curve

In cases where the linear elastic fracture mechanics method is adopted to estimate remaining life, it is recommended that a suitable crack propagation curve be selected. The stress intensity factors, ΔK , should be determined from a detailed finite element modelling of the crack, which is computationally demanding. Alternatively, analytical solutions are provided by standards, which are deduced from semi-elliptical cracks in plates [48]. The crack growth rate can then be determined using a suitable crack propagation curve. The crack propagation curves in the marine environment can be found in design standards and research articles [48,103–105]. The remaining fatigue life can be estimated based on the critical crack growth size.

2.5. Assessment for other limit states and strengthening/inspection for extended life (Block E)

If the remaining fatigue life is found to be satisfactory, it is advisable to check the structure for other limit states (ULS, SLS, ALS) as per Block E of the framework presented in Fig. 1. While the ULS checks are performed to check the structural strength against ultimate load conditions, the SLS checks requires the deflection of structural members within allowable limits. The ALS checks are performed for accidental situations like ship collisions, dropped objects, fire, explosions and seismic actions. For each of these limit states, the structure should be checked for both its current degradation state and considered degradation in the future. These checks should be performed on the same principles as that of the design standards and using the Load Resistance Factor Design philosophy [92,94,101]. The ULS check should be performed for all the load categories (permanent load, variable load, environmental load and deformation load) using the load combination factors in design standards [92,94,101]. The combinations of different environmental loads (wind, waves, current, ice) should be as per the recommended guidelines to obtain ULS combinations with 10^{-2} annual probability of exceedance [101]. The ALS checks for existing structures should also be performed using the design criteria and the load factor is 1.0 for all load categories. The accidental loads and abnormal environmental loads with 10^{-4} as the annual probability of exceedance should be considered [101]. In the assessment of all these limit states, the material factor should be taken from the design standards [92,94,101]. Under the above LRFD approach, an acceptable safety margin is achieved by checking the structure based on characteristic values of load effects and resistances, and appropriate partial safety factors in each of the above limit states [32]. The characteristic values correspond to a confidence level of 95% and a failure probability of 5%.

If all the limit state checks are satisfactory, for both current and future degradation, the extended life of the structure can be proposed. It is advisable to propose a proper inspection and maintenance plan for the structure during its extended life, as per the standards [46,47,92,106]. The intervals for condition monitoring should be adjusted to take into account an increased likelihood of fatigue cracks due to damage accumulation during the initial design life [92]. The Norsok standard N-005 is an important document for the condition monitoring of load bearing structures [106] and should be referred for more information on monitoring intervals, implementation process and selection of inspection methods. However, if the remaining life is not found to be satisfactory for any of the limit state checks, suitable mitigations need to be recommended. These mitigations can consist of possible strengthening, reduction of actions or reduction of operational changes. The strengthening can take the form of grouting of members and joints, adding extra braces at overstressed locations, or adding stiffeners or brackets. Several fatigue life improvement techniques related to the weld can also be used. Examples of these are grinding,

Tungsten Inert Gas (TIG) dressing and hammer peening [58,107]. It is advisable to refurbish the anodes wherever possible. More information on mitigation and strengthening can be found in the design standards [46,92]. The proposed strengthening and mitigation should be checked for feasibility at the offshore site location. On-site inspections are recommended to check the feasibility of proposed strengthening as well as any other feasible alternatives. Mitigations should be planned in case the proposed strengthening is not feasible and alternatives are found. However, in cases where proposed strengthening is not feasible and no alternative mitigations are found, the recommendation is that the structure should not be used beyond its designated service lifetime.

3. Case study: Structural integrity assessment of an existing jacket structure for life extension

A case study is performed on an old existing jacket type of platform in the Gulf of Suez, the Red Sea. The jacket is assessed for its structural integrity, and its remaining life is estimated using the proposed framework. The obtained assessment results are compared with conventional assessment approaches. Hence, the significance of the proposed framework is confirmed.

3.1. Data collection, screening and selection of fatigue assessment approach

The data from the initial design, operational as well as expected extended life, was collected. This includes structural drawings, material properties, loading details and some of the past inspection reports. The inspection reports were screened for all structural degradation information, including the member thickness measurements and fatigue cracks. A suitable fatigue assessment approach was also selected as per the proposed framework. The initial target life of the structure was 25 years and a design fatigue factor of three was taken in the initial design calculations. The design life of the structure is now over and the presented analysis is performed at the end of initial target life.

3.1.1. Structural and material details

The platform, which was installed in 1988, is a four-leg jacket structure. The age of the jacket is 28 years and is well suited for consideration as an aged offshore installation. The jacket has four main legs and is installed in a water depth of 33.5 m. Diagonal braces are present in both the horizontal and vertical planes. All the members have a tubular cross section. The topsides have three levels: the cellar deck, the production deck and the helideck. The material type is A36 with a density of 7850 kg/m³ and a modulus of elasticity of 200 GPa. The yield strength and ultimate tensile strength are 248 MPa and 400 MPa respectively. An image of the structure at the offshore site is shown in Fig. 3(a).

3.1.2. Selection of fatigue assessment method

The structural degradation information was screened for any fatigue cracks; none were found in the inspection records. As the structure is approaching the end of its design life, a detailed fatigue assessment, including simulation of past and future structural degradation, is required for possible life extension. Hence, a safe life approach was used for the fatigue assessment, as described in Block A of the proposed framework presented in Fig. 1.

3.2. Simulation of degradation and development of degraded FE models

The structural degradation information was also screened for any corrosion measurement details. Thickness reduction measurements were not found in the inspection reports. However, recent site inspections have revealed the presence of mild corrosion in the submerged zone and some patch corrosion in the splash zone of the jacket structure, but no significant localized corrosion and no fatigue cracks were found. It is recommended that the uniform corrosion model parameters be selected as per Block B of the proposed framework presented in Fig. 1.

3.2.1. Conventional and framework proposed approaches for selecting model parameters

Conventionally, the degradation is not considered at all in cases of mild corrosion, as the material loss is very low. Also, the model parameters are conventionally taken as per the design standards for simulating patch corrosion [28,42,92,108]. These parameters, as per conventional approach, are shown in Table 4. However, it is advisable not to ignore the degradation effects, even in cases of mild corrosion, and to select the proposed model parameters to represent mild corrosion as per Table 4. It is noteworthy that the model parameters given in the design standards for patch corrosion are very conservative and can result in an underestimation of the remaining fatigue life. It is recommended that patch corrosion be simulated in the splash zone, using the proposed model parameters in the framework for the considered jacket structure. These considered parameters for the proposed approach are shown in Table 4.

3.2.2. Development of degraded finite element models

A finite element model of the structure was developed in FE software SAP 2000 [109], using frame elements. The finite element model and global geometry is shown in Fig. 3(b). The jacket members were degraded, using the conventional and proposed framework approaches. Also, separate model parameters were applied to the members in the splash zone and the submerged zone, as per values mentioned in Table 4. The time-dependent cross-sectional properties were determined using Eqs. (9)–(12), and degraded FE models were developed for the jacket structure.

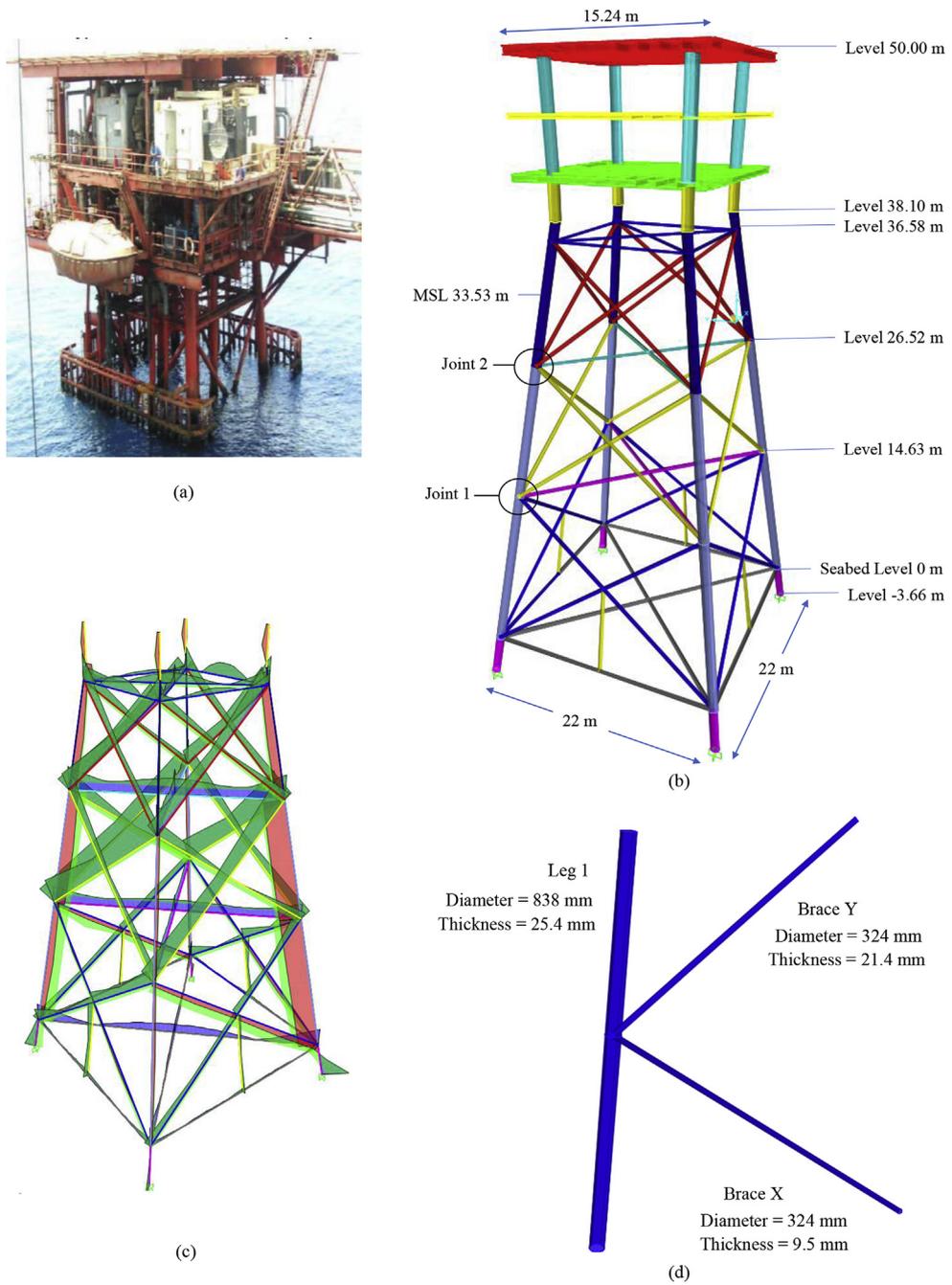


Fig. 3. (a) Considered offshore jacket platform (b) finite element model of the platform and critical joints (c) stress envelope in members for ULS assessment (d) details of critical joint 2.

Table 4

Model parameters for conventional approaches [28,42,92,108] and as per proposed framework.

Model parameters	Splash zone area		Other areas	
	A(mm)	B	A(mm)	B
Conventional approach	0.3	1	0	0
Proposed approach	0.3	0.823	0.084	0.823

3.3. Load simulation and structural analysis

The collected data was screened for loadings over the design life of the structure. This included all permanent loads, variable loads and environmental loads. The loadings considered were the dead load, live load, wave load, current and the wind loads. A nonlinear multistep static structural analysis was performed. The nonlinearities considered were the geometrical nonlinearities in the structure (P- Δ analysis) and the force nonlinearities in the wave loadings.

3.3.1. Loading details and simulation

The permanent and variable loads were defined. The variable load was applied as uniformly distributed loads on the deck. An intensity of 2.4 kN/m² was applied to the helideck, while a 9.6 kN/m² live load was applied to the cellar and production decks. For SLS and ULS checks, a 100-year return period wave, with a wave height of 7.92 m and time period of 8 s, was used. For the FLS check, in the absence of any measured wave heights, the wave loading was simulated using a long-term wave scatter diagram at the installation location, as described in Block C of the proposed framework presented in Fig. 1. The considered wave scatter diagram was derived from actual measurements taken at the site from the period 1992 to 2014. These measurements were carried out and provided by a met ocean consultant company [110]. The current and wind loads were applied in the same direction as that of the wave.

3.3.2. Load cases and load combinations

The dead load and live load were defined as individual load cases. The wave load was defined in seven directions, and seven wave load cases were defined. Since the structure is symmetrical, the directions were chosen from 0 to 180°, spaced at 30° intervals. The wave load was derived using a suitable wave theory as per the applicability criteria of wave theories. A nonlinear 5th order Stoke's wave theory was found to be applicable for the considered jacket. The current and wind loads were defined, along with the wave load. The load cases were combined as per the load combination factors given in the design standards.

3.3.3. Structural analysis

A nonlinear multistep static analysis was performed. For SLS and ULS assessment, a 100-year return period wave was used in the analysis, and a preliminary estimation of overstressed joint locations was made. The stress envelope plot for the ultimate limit state assessment is shown in Fig. 3(c) for the worst load combination. Two critical joint locations were identified from the stress plot, as shown in Fig. 3(b). Detailed geometry of the joint in splash zone (joint 2) is shown in Fig. 3(d). A deterministic fatigue assessment was performed for the critical joints, according to the guidelines mentioned in section 2.3.1. The analysis was also performed separately for each of the degraded models.

3.4. Stress evaluation and estimation of remaining life

Hot spot stress (HSS) approach has been used for fatigue life estimation of considered joints as no localized corrosion was observed. Hence, a global analysis was performed as also mentioned in the proposed framework in Block D and also in Section 2.4.1. However, in cases where localized corrosion is present at the details, it is recommended to perform a notch stress based fatigue analysis where secondary stress state should be determined using detailed thin shell FE analysis.

Forces and moments in the chord and brace members of the considered joint were extracted from the global finite element analysis. The nominal axial and bending stress ranges were subsequently calculated for each of the load combinations under each sea state. The hot spot stress concentration factors for considered joint members were also calculated using the recommended guidelines [58]. The nominal stress ranges were combined using the method of superposition wherein hot spot stress ranges were evaluated at eight locations around the circumference of the intersection for each of the load combinations using formulae given in the guidelines [58]. The maximum value of the geometrical stress ranges is taken as the hot spot stress range value for the most critical member in the considered joint. This was repeated for all the sea states in the wave scatter and for each of the degraded models. The maximum hot spot stress range value and hence the potential crack location is identified at the saddle position of the critical brace member of joint 2. For illustration, the hot spot stress range calculations are shown for the critical brace member of joint 2 in uncorroded model (i.e. model with no degradation) and for one sea state.

Table 5

Forces and moments in the critical brace of Joint 2^a (uncorroded model, one typical sea state).

Load combination	F_x , max	F_x , min	M_{ip} , max	M_{ip} , min	M_{op} , max	M_{op} , min
DL + LL + wave 0	-1.07E+05	-1.29E+05	3.07E+02	-1.08E+03	-1.48E+04	-2.64E+04
DL + LL + wave 30	-1.08E+05	-1.29E+05	2.59E+03	-2.62E+03	-1.48E+04	-2.63E+04
DL + LL + wave 60	-1.16E+05	-1.26E+05	6.13E+03	-4.37E+03	-1.49E+04	-2.58E+04
DL + LL + wave 90	-1.20E+05	-1.26E+05	8.36E+03	-5.71E+03	-1.40E+04	-2.43E+04
DL + LL + wave 120	-1.21E+05	-1.29E+05	7.75E+03	-5.15E+03	-1.12E+04	-2.38E+04
DL + LL + wave 150	-1.20E+05	-1.32E+05	3.65E+03	-2.96E+03	-8.81E+03	-2.51E+04
DL + LL + wave 180	-1.18E+05	-1.36E+05	-6.50E+01	-1.78E+03	-8.20E+03	-2.53E+04

^a All units are in N, m.

Table 6
Hot spot stress ranges in critical brace of Joint 2^a (uncorroded model, one typical sea state).

Load combination	σ_1	σ_2	σ_3	σ_4	σ_5	σ_6	σ_7	σ_8
DL + LL + wave 0	8.26	-7.25	-15.09	-10.67	3.42	18.93	26.77	22.35
DL + LL + wave 30	14.81	-2.51	-15.01	-15.35	-3.35	13.97	26.47	26.81
DL + LL + wave 60	20.95	1.64	-17.08	-24.24	-15.64	3.67	22.39	29.54
DL + LL + wave 90	26.03	5.71	-17.07	-28.96	-23.01	-2.69	20.09	31.98
DL + LL + wave 120	24.69	2.10	-20.43	-29.70	-20.29	2.31	24.84	34.11
DL + LL + wave 150	14.53	-9.62	-26.38	-25.92	-8.52	15.63	32.38	31.92
DL + LL + wave 180	7.91	-14.86	-26.04	-19.08	1.92	24.68	35.87	28.91

^a All units are in MPa.

The forces and moments in the brace member are shown in Table 5 for each load combination and the calculated hot spot stress ranges are shown in Table 6. It was not necessary to perform any detailed local analysis separately, as no localized corrosion was found at the detail or on the members. This is also discussed in the proposed framework in Block D and in Section 2.4.1. The number of cycles to failure, N , was determined using the hot spot stress range for each sea state. In the HSS approach, the T curve should be selected as the relevant fatigue strength curve for tubular joints. The environmental effect on the T curve should be carefully examined, as described in Block D of the proposed framework presented in Fig. 1. The CP protected seawater curve was used in this case, as no severe pitting corrosion was found at the structural detail. The number of stress cycles in a year was determined using the zero up-crossing period (T_z) for the corresponding sea state. The yearly fatigue damage for each sea state was calculated, and the long-term yearly fatigue damage accumulation for all the sea states was calculated as per Eq. (14).

The fatigue damage in the selected joints was determined using both conventional and proposed framework approaches given in Section 2, Fig. 1. The fatigue damage and the thickness reduction versus the age of the jacket was plotted. The damage was plotted only for the most critical brace member of the considered critical joint. The results for the two critical joints are shown in Fig. 4(a) and Fig. 4(b) respectively. A DFF of three was applied in the calculation of the fatigue damage, to account for safety factors [101]. Hence, the DFF is included in the presented fatigue damage values by multiplying the calculated damage by three. The results are also shown for the case where on-site inspections are not possible. The remaining life was estimated using both conventional and proposed framework approaches, and the results are shown in Table 7. It is observed that the conventional approach over estimates the remaining fatigue life for the joint in the submerged zone. This is due to the fact that degradation is not modelled at all in cases of mild corrosion. A low remaining fatigue life is observed for the joint in the splash zone. The remaining life is only one year using the conventional approach; however, using the proposed approach, it is around 10 years and seems more realistic. Recommendations are made to improve the fatigue life of the joints in the splash zone by the use of fatigue improvement techniques.

3.5. Assessment for other limit states and strengthening/inspection plan for extended life

It is intended to extend the life of the considered jacket structure by 20 years. Based on the proposed approach, the remaining fatigue life is 37 years for the critical joint in the submerged zone; this is considered safe for further extension of life. However, the remaining life of the critical joint in the splash zone is found to be only 10 years as per the proposed approach, and mitigations to improve the fatigue life are suggested in the next section. The jacket should also be assessed for other limit state checks, as described in Block E of the proposed framework presented in Fig. 1. A 100-year return period wave, with a wave height of 7.92 m and time period of 8 s, was used for the wave loading. The jacket was analysed as per the design standard [94].

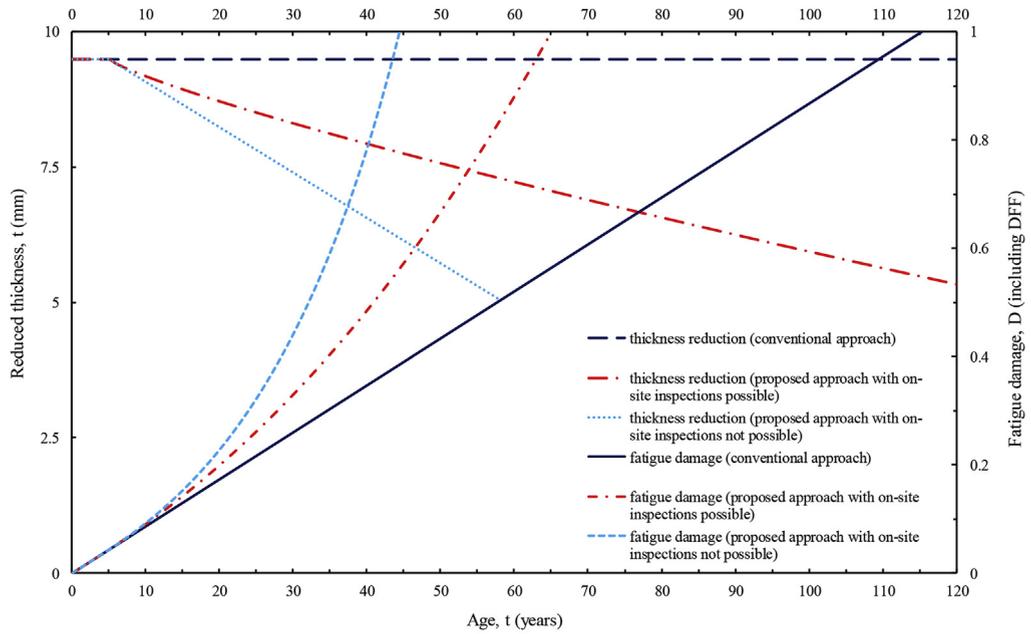
3.5.1. Serviceability limit state (SLS) checks

The free vibration natural time periods and vibration modes for the undamaged model were determined. The values of the natural time periods are 0.90 s, 0.90 s and 0.67 s, respectively, for the first three modes. The first and second modes are sway modes in the two transverse directions. The third mode corresponds to the torsional vibration mode. The variation of the natural period with ageing is shown in Fig. 5(a) and Fig. 5(b) for the conventional and proposed approaches respectively.

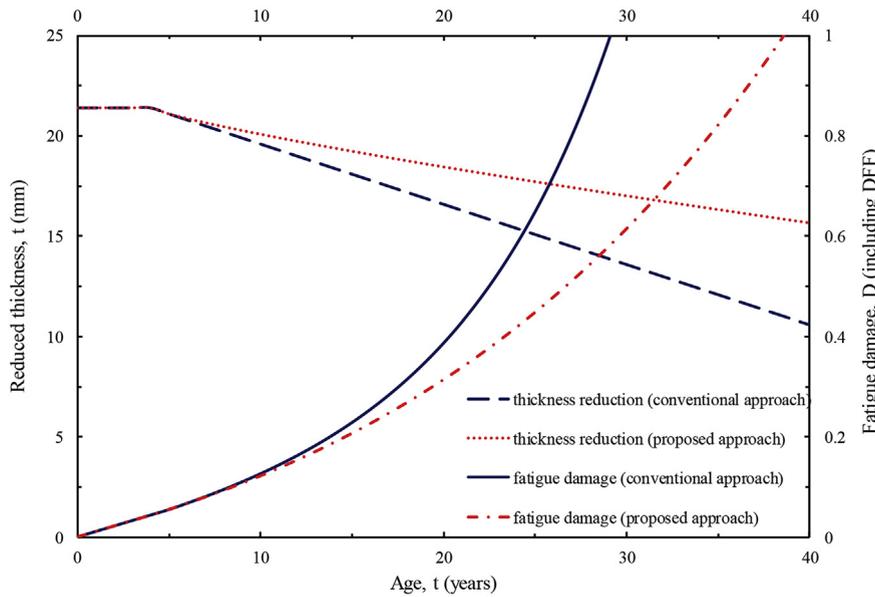
The variation of leg displacement in global X direction is also observed with ageing for the worst load combination. The variation of leg displacement with ageing is shown in Fig. 6(a) and Fig. 6(b) for the conventional and proposed approaches respectively. The displacements were found to be within satisfactory limits, and the SLS checks are not found to be critical.

3.5.2. Ultimate limit state (ULS) checks

Variation in the member capacities with ageing is found for critical members. The highly-stressed members were identified as critical members for the ULS checks. These are: one of the main legs (leg 1) and one vertical bracing at each elevation. The variation is shown in Fig. 7(a) and Fig. 7(b) for the conventional and proposed approaches respectively. From Fig. 7(a), it is observed that the bracing members have already violated the ultimate limit state check using the conventional approach and should have given some problems eight years earlier. However, the bracings are still in place and no damage has been reported. This is probably due to higher model parameters used in the conventional approach and hence leading to conservative



(a)



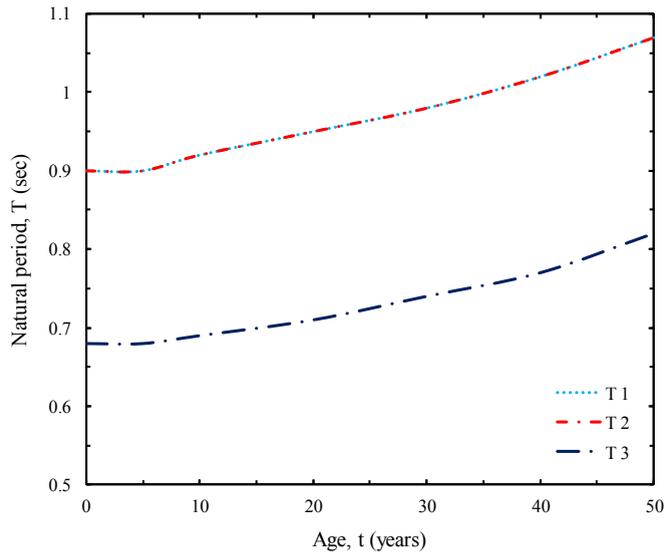
(b)

Fig. 4. Fatigue damage (including DFF) and member thickness variation with age in (a) critical joint 1 (b) critical joint 2.

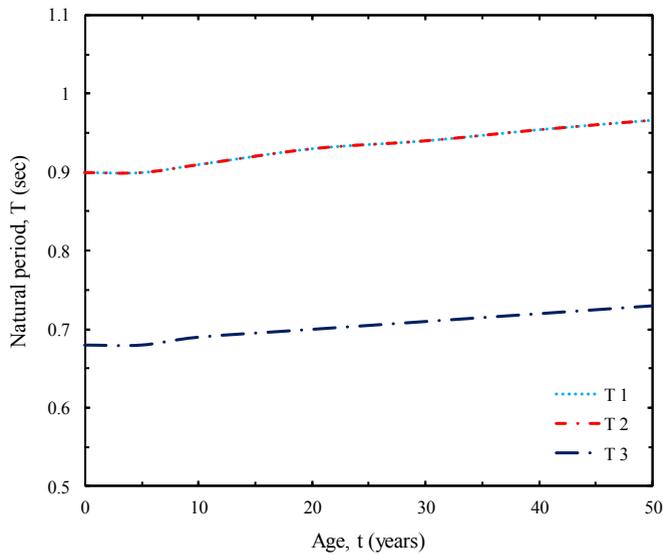
Table 7
Remaining design life of critical joints as per conventional and proposed framework approaches (in years).

Approaches	Calculated total life from Fig. 4		Remaining life ^a	
	Joint 1	Joint 2	Joint 1	Joint 2
Conventional approach	115	29	87	1
Proposed approach	65	38	37	10

^a Obtained by reducing the current age (i.e. 28 years) from the calculated total life (i.e. when $D = 1$) as per Fig. 4.



(a)



(b)

Fig. 5. Variation of natural periods with age (a) conventional approach (b) proposed approach.

results. The utilization ratio results seem more reasonable, using the proposed approach that include more precise model parameters. The expected remaining life of the central and bottom bracings is around four years and 12 years respectively. As the life span of the structure needs to be extended by 20 years, these members require potential strengthening for the safe operation of the structure during the extended life.

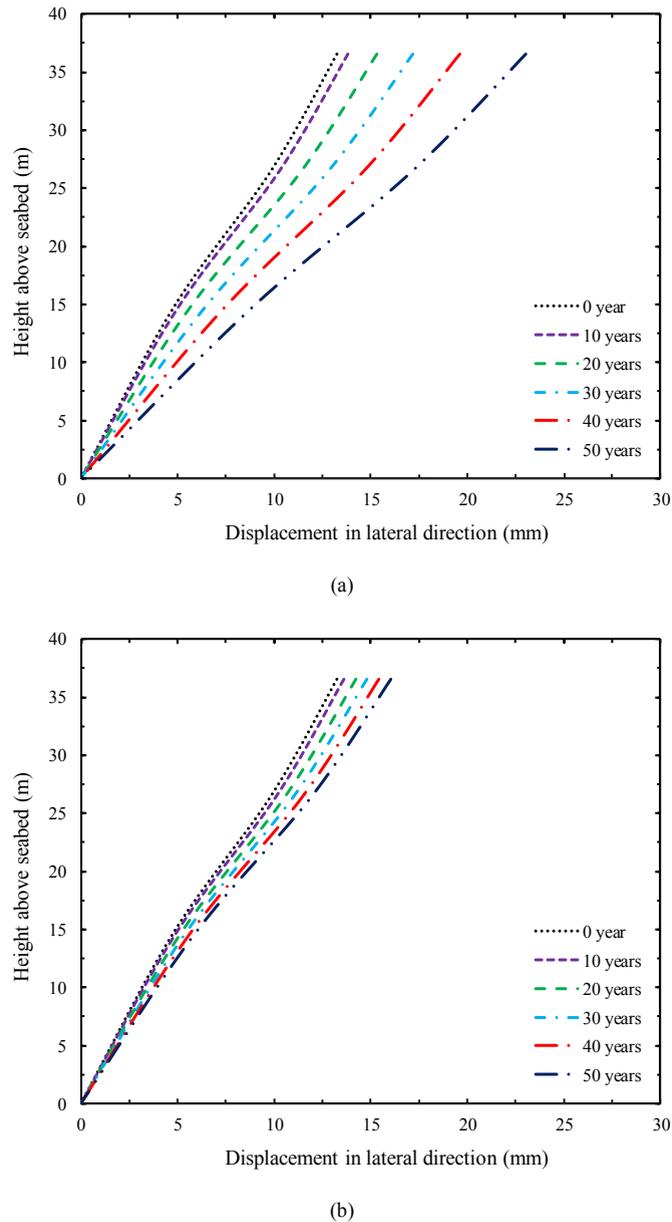
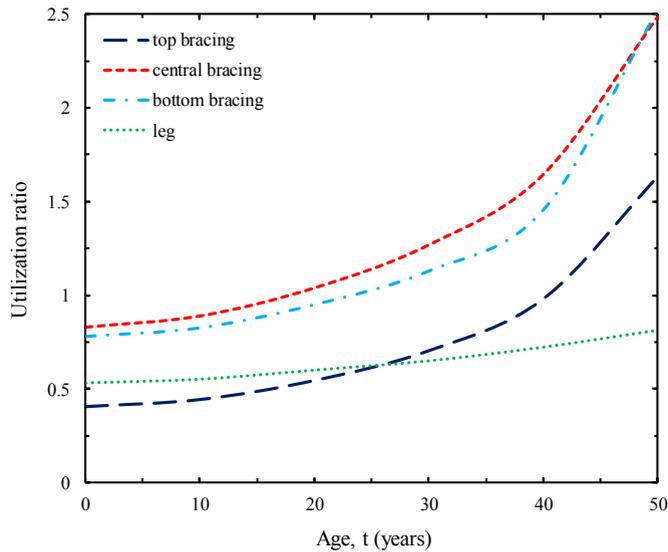


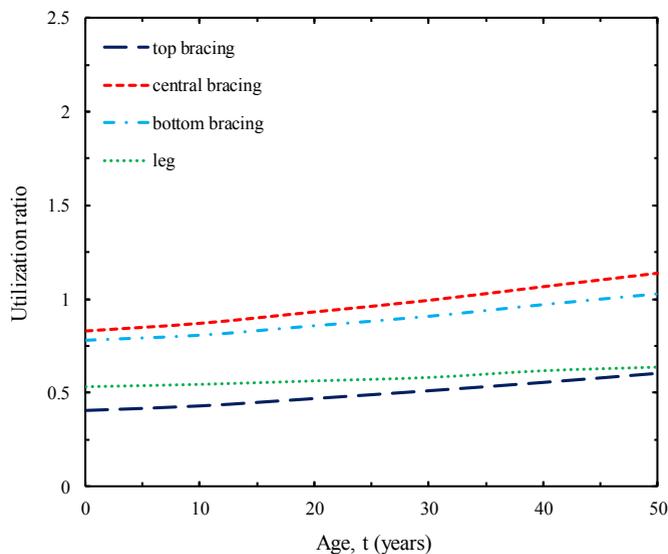
Fig. 6. Variation of leg displacement with age using (a) conventional approach (b) proposed approach.

3.5.3. Strengthening/inspection plan for extended life

The considered jacket structure was analysed for various limit states using the proposed framework. It is intended to extend the service life by another 20 years. Although the critical joint in the submerged zone is found safe for extended life as per the proposed approach, the critical joint in the splash zone has a remaining life of only 10 years, as shown in Fig. 5(b). The remaining life needs to be improved by 10 more years and hence a life factor of 2 is desired. It is recommended that the fatigue life of the joints in the splash zone be increased using fatigue improvement techniques such as hammer peening, grinding or TIG dressing. The fatigue life can be improved by up to a factor of 4 for yield strength higher than 350 MPa using these improvement techniques [58]. In case of hammer peening method, this factor depends on the tool used and workmanship. It is therefore recommended to perform fatigue testing of the detail, with and without hammer peening, to decide on a factor. Other mitigations, such as grouting of joints, reduction of operational loads or removal of marine growth, are also possible. More information on the fatigue life improvement techniques can be found in the standards and recent literature [58,106,111,112]. The ultimate limit state assessment was also carried out, with some bracing members found overstressed, as shown in Fig. 7. The proposal of suitable mitigation plans is recommended for these overstressed members. The mitigations



(a)



(b)

Fig. 7. Variation of ULS utilization ratio in critical members (a) conventional approach (b) proposed approach.

can consist of possible strengthening, reduction of actions or even reduction of operational changes. The strengthening can be in the form of grouting of overstressed members, adding extra braces at overstressed locations, or adding stiffeners. The reduction of wave action is made possible by the regular removal of marine growth or anti-fouling protection. The structure should be reassessed after carrying out suitable mitigations. The strengthening mitigations are outside the scope of this paper, as they require close coordination with on-site inspection in order to check the feasibility options. The service life of the jacket structure can be extended if the proposed strengthening mitigations are found feasible offshore and the strengthened structure satisfies all limit state checks. It is also advisable to outline an inspection plan for the extended service life. Regular maintenance inspections should be performed, and the inspection intervals should be adjusted to take into account an increased likelihood of fatigue cracks. The time intervals should be as per standard codes and such that potential fatigue cracks are detected with a high level of certainty prior to becoming a threat to overall structural integrity. Refurbishment of the anodes in the CPS is also recommended. Additional CPS clamps can also be provided if necessary. Probabilistic inspection

planning methods such as RBI can also be used to plan in-service inspection during the extended life. More details about the probabilistic inspection planning methods can be found in several condition monitoring codes and standards [46,47,92,106].

3.6. Comparison and discussion of results

The structural assessment of the considered jacket structure was carried out for various limit states. The time-dependent structural degradation was simulated using both the conventional and proposed framework approaches. In the absence of any thickness reduction measurements, site inspections were carried out, and the presence of mild corrosion was reported in the members of the submerged zone. Also, inspection reports mentioned patch corrosion in the members of the splash zone. Conventionally, these inspection findings have been interpreted in different ways due to the lack of suitable guidelines on simulating structural degradation. Mild corrosion is generally not modelled using conventional approaches. Moreover, patch type of corrosion is conventionally simulated using model parameters, provided by the codes, which are very conservative and can underestimate the remaining fatigue life. To reduce the variability in the interpretation of inspection findings, recommendations are made in the proposed framework on the selection of a suitable corrosion wastage model and its model parameters for members in various zones. The remaining fatigue life of critical joints was determined using both the conventional and proposed framework approaches. An assessment was also carried out for SLS, by considering lateral displacement and modal vibrations. The ULS checks were also performed for all critical members.

The results shown in Fig. 4(a) and Table 7 demonstrate that the conventional approach overestimates the remaining fatigue life by around 2.3 times for critical joint 1, which is in the submerged zone. This is mainly due to the conventional approach neglecting degradation in cases of mild corrosion. Fig. 4(a) also shows that the proposed approach provides a too conservative remaining life of only 16 years for critical joint 1 when the case of on-site inspection is not possible. Fig. 4(b) and Table 7 show a short remaining life for the joint in the splash zone. The remaining life is found to be only one year using the conventional approach (i.e. model parameters obtained by the design standards). However, the remaining life is found to be around 10 years using the proposed framework approach and seems more reasonable. Recommendations are made to increase the fatigue life of the joints in the splash zone by means of fatigue improvement techniques.

An assessment was also performed for the free vibrations and other limit states. The natural periods of the structure were determined using both the conventional and proposed framework approaches and were found to be away from the wave periods. For SLS assessment, Fig. 6 shows that leg displacement increased by almost 70% at the end of the extended life using the conventional approach, while the increment in leg displacement up to the end of the extended life is around 21% using the proposed framework. Although the displacements are within the allowable limits for both approaches, the results obtained using the proposed approach seem more realistic. For ULS assessment, Fig. 7 shows that the bracing members are overstressed and violate the checks using the conventional approach. According to the conventional approach, the ULS checks of the central and bottom bracings were violated eight years earlier, as shown in Fig. 7. However, damage has still not been found on any of these members. This is probably due to the higher model parameters used in the conventional approach, hence leading to conservative results. However, such high levels of conservativeness are not desirable in life extension studies, and more precise model parameters should be used. The results of ultimate limit state checks seem more reasonable with the employment of the proposed approach, which includes the use of more precise model parameters. The central and bottom bracings are expected to violate the ULS checks after four and 12 years, respectively, using the proposed approach. In order to extend the life of structure by 20 years, strengthening mitigations are desired for these bracings for safe operation during the extended life. Strengthening can be provided as per the recommendations made above in Section 3.5.3.

4. Conclusions

In this paper, a framework is proposed to assess the structural integrity of existing aged offshore structures for possible life extension. The assessment should be carried out for all limit states. The FLS is considered the most critical limit state, and the framework is based on both safe life and damage tolerance approaches. The assessment procedure might involve going through all the paths of the framework, depending on the different degradation states of fatigue critical details in a single structure. The significance of the proposed framework is highlighted through a case study on an existing jacket structure. The framework is an attempt to provide more detailed case-dependent guidelines by adding relevant theories and models, which can capture the time-dependent structural degradation more precisely than currently available assessment guidelines and standards. It caters to the needs of practising engineers by providing recommendations on various issues such as simulation of structural degradation in the absence of any corrosion measurements, precision of loading history, as well as the effect of localized corrosion on stress concentration factors. Suggestions are also made on the determination of stress cycles and the selection of a suitable fatigue strength curve, particularly for severely corroded details. Recently developed precise fatigue damage theories are also included for a more accurate estimation of remaining life.

The simulation of structural degradation using the proposed framework approach is compared with the conventional approach, through the case study. Conventionally, either structural degradation is not modelled for cases of mild corrosion or model parameters are taken on the conservative side to represent patch corrosion. The model parameters recommended in the proposed framework constitute an attempt to reduce such variability in the selection of model parameters. The remaining fatigue life of critical joints is found more accurately using the proposed framework approach, as compared to the conventional approach. The structure can also be assessed for other limit states using the framework. Strengthening/inspection plans

for extended life are also recommended. It can be concluded that the proposed framework provides an accurate prediction of remaining life, and the framework is a currently required tool to assess the structural integrity of an ageing jacket structure for possible life extension. The limitations of the proposed framework have been identified. The proposed framework considers only the functional ageing characterised by fatigue and corrosion. Other aspects of functional ageing such as erosion, creep, accumulated plastic deformation have not been considered. Moreover, technological ageing, knowledge based ageing and organisational ageing have been neglected and should be considered wherever applicable. The proposed framework is applied to the considered case study using a deterministic approach but can be used with probabilistic approaches as well. The significance of the proposed framework should be further highlighted on other ageing existing jacket structures using a few more case studies. Thereafter, the proposed framework and given model parameters may be adopted in the assessment standards in future.

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