Renewable and Sustainable Energy Reviews 61 (2016) 141–154

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Review of corrosion fatigue in offshore structures: Present status and challenges in the offshore wind sector

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ARTICLE INFO

Article history:
Received 4 November 2015
Received in revised form
21 February 2016
Accepted 29 February 2016

Keywords:
Monopile
Fatigue crack growth
Corrosion fatigue
Offshore structures
Free corrosion

ABSTRACT

Offshore wind has been identified as one of the emerging sustainable energy sources in the United Kingdom. Offshore wind turbine support structures are mainly fabricated of welded tubular members, similar to structures used for oil and gas applications, and are exposed to highly dynamic, harsh marine environments. However, their structural details and design requirements are significantly different due to the magnitude and frequency of operational and environmental loadings acting on the support structures. These conditions would significantly affect their structural dynamic response characteristics due to the magnitude of the applied load. This may therefore have some significant effects on the crack growth behaviour and the extent to which corrosion can be associated with damage to the support structures. However, the magnitude of the applied load might depend on turbine size, water depth, soil conditions and type of support structures. It is therefore essential to design wind turbine support structures against prescribed limit states to ensure economical and safe operation. This paper presents a review of corrosion fatigue in offshore structures as regards the effects of seawater, environment and mechanical loading. Existing literature which documents results from previous campaigns is presented, including works referring to oil and gas structures, highlighting the significant difference in the aspects of loading and use of modern fabrication processes, with a view to illustrating the requirements for an update to the existing corrosion fatigue database that will suit offshore wind structures' design requirements.

Contents

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http://dx.doi.org/10.1016/j.rser.2016.02.017
1364-0321/

Nomenclature

CAPEX	capital expenditure
CPc	cathodic protection
GWEC	Global Wind Energy Council
HAZ	heat affected zone
HSS	high strength steels
PWHT	post-weld heat treatment
S-N	stress life
TMCP	thermo-mechanical controlled process

1. Introduction

Fatigue failure in offshore structures, such as oil and gas structures and structures for renewable energy applications can occur due to the magnitude of cyclic loadings which they experience in service. Fatigue cracks can develop from pre-existing defects which may be introduced into structures during manufacturing, transportation and installation etc. Fatigue cracks, if not controlled can grow into failure or collapse of the structures when an unstable stage of the crack growth is reached. Therefore, defects or cracks in offshore structures need to be reliably inspected and monitored to ensure that the structures are fit for design purpose. Offshore structures are vulnerable to corrosion attacks due to the harsh marine environment and this may lead to significant levels of damage to the structures and hence a reduction in service life. The corrosion crack growth mechanisms can be amplified under fatigue loading due to the synergistic interaction of the applied cyclic loads and the influence of the corrosive environment. The extent of the damage is influenced by a significant number of variables, some of which are discussed in a later section.

Crack growth behaviour of steels used for offshore oil and gas applications has been studied over the years, for example in [1] and [2], in order to understand the behaviour of the structures in marine environments. However, newer types of structure, such as wind turbine structures, are being developed and installed offshore. Monopile structures have been the most commonly used support structures. At the moment, there is deficit of information on corrosion fatigue crack growth behaviour in these large diameter structures and therefore this remains an area of study that needs to be addressed and better understood. The understanding of corrosion fatigue can only be achieved by testing [3], so that confidence can be gained regarding the behaviour of the steel structures offshore.

The existing design guidance was developed based on studies conducted on oil and gas structures over 30 years ago. However, a significant number of the first monopile structures are operating based on these standards, which are well outside the scope of larger diameter monopoles [4] as well as their design requirements, due to the volume of manufacturing, and the magnitude and frequency of operational and environmental loadings acting on the support structures. However, the magnitude of the applied load might depend on turbine size, water depth, soil conditions and type of support structures [5,6]. Other important research areas that need to be addressed for a better understanding of behaviour of offshore monopile support structures include the following:

- The extent of corrosion fatigue crack growth in monopile structures with respect to the operational loads envelope such as the effects of loading frequency,
- Environmental condition such as the free corrosion conditions, which have been a major threat to wind monopile supports, most importantly the internal section,
- The behaviour of the steels used for monopile fabrications with respect to currently used modern materials and manufacturing techniques,
- The behaviour of steel weldments with thicknesses similar to those used for offshore monopile support structures,
- The extent to which mean stress can enhance crack growth behaviour in monopile steels.

The two most commonly used fatigue assessment techniques are the stress life (S–N) approach and the fracture mechanics approach. A review of the currently used S–N curves is provided in [3]. However, in this paper, most of the results presented have been obtained using the fracture mechanics approach. Some of the recent developments in the wind sector with respect to wind turbine structures are introduced in the first part of this paper while the latter part provides a literature review on the corrosion crack growth in offshore structures.

2. Overview of different types of offshore wind turbine support structures

The need for renewable energy source has significantly increased the volume of the planned wind structures that will be installed offshore. At the end of 2013, the wind producing capacity in the UK was over 50% compared to the rest of the World [7] as shown in Fig. 1. Table 1 also shows the list of commissioned offshore wind farms in the UK from 2000 to 2013. From projections, approximately 40,000 jobs will be provided by the offshore wind industry by 2020 if research funding, testing and demonstration facilities are fully executed by the Government [8]. From the Global Wind Energy Council (GWEC) report and statistics [9], as shown in Fig. 2, offshore wind energy has increased by 4 GW from 2011 to over 5 GW at the end of 2012 globally, with the UK having the highest installed capacity of around 2 GW and 3 GW in 2011 and 2012 respectively.

The majority of the offshore wind farms in the UK is currently installed in shallow water depths of approximately 30 m with the wind turbines supported on monopile structures. Monopiles are the

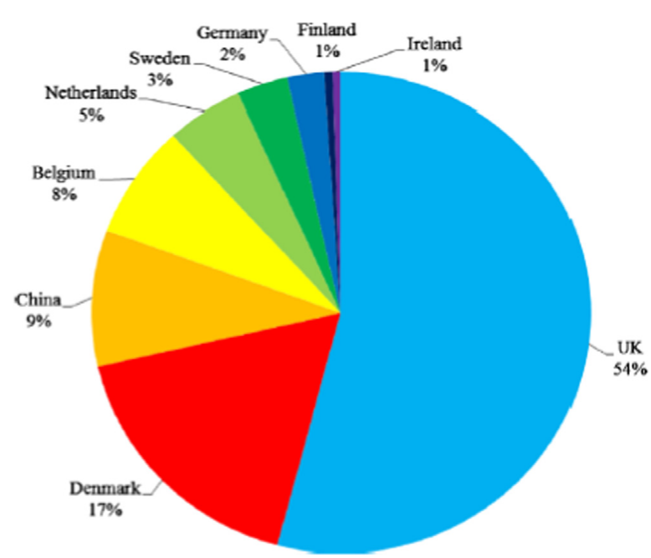


Fig. 1. Statistical breakdown of installed offshore wind capacity [7].

Table 1
United Kingdom commissioned offshore wind farms [7].

Year of installation	Project	Capacity (MW)	Total capacity (MW)	Max water depth (m)	Max distance to shore (km)	Wind turbine manufacturer	Crown estate round
2000	Blyth	3.8	4	6	1	Vestas	1
2003	North Hoyle	60	64	12	7.5	Vestas	1
2004	Scroby sands	60	124	10	3	Vestas	1
2005	Kentish flats	90	214	5	8.5	Vestas	1
2006	Barrow	90	304	15	7	Vestas	1
2007	Beatrice	10	314	40	25	Repower	1
2007	Burbo Bank	90	404	10	5.2	Siemens	1
2008	Inner Dowsing	97.2	501	10	5.2	Siemens	1
2008	Lynn	97	598	10	5.2	Siemens	1
2009	Rhyl Flats	90	688	8	8	Siemens	1
2009	Robin Rigg	180	868	5	9.5	Vestas	1
2010	Gunfleet Sands	173	1041	8	7	Siemens	1
2010	Walney Phase 1	183.6	1225	23	14	Siemens	2
2011	Walney Phase 2	183.6	1408	30	14	Siemens	2
2012	Greater Gabbard	504	1912	32	36	Siemens	2
2012	Ormonde	150	2062	21	9.5	Repower	1
2012	Thanet	300	2362	23	12	Vestas	2
2012	London Array 1	630	2992	25	20	Siemens	2
2012	Sheringham Shoal	316.8	3309	23	23	Siemens	2
2013	Lincs	270	3579	15	8	Siemens	2
2013	Teeside	62.1	3641	18	2.2	Siemens	2
	Total	3641					

most commonly used wind turbine support structure due to their design simplicity and suitability for water depths of up to 30 m. One of the major design requirements of these types of structures is their ability to withstand load cycles of approximately 10^9 which is equivalent to a 20 year service life [10]. However, a cost-effective design life can only be achieved if careful considerations are given to the volume of installations and the degree operational loads envelope, which the structures are subjected to in service compared to structures used for oil and gas applications. One of the most critical factors in the installation of wind structures is the suitability of the support structures for specific sites and this may depend primarily on water depths. This implies that at increased water depth, the costs involved in the installation of the structures are likely to significantly increase. However, an advantage of the offshore wind structure over oil and gas structures, regardless of the initial capital cost, is the fact that the operating costs are lower when the structures are in operation [11].

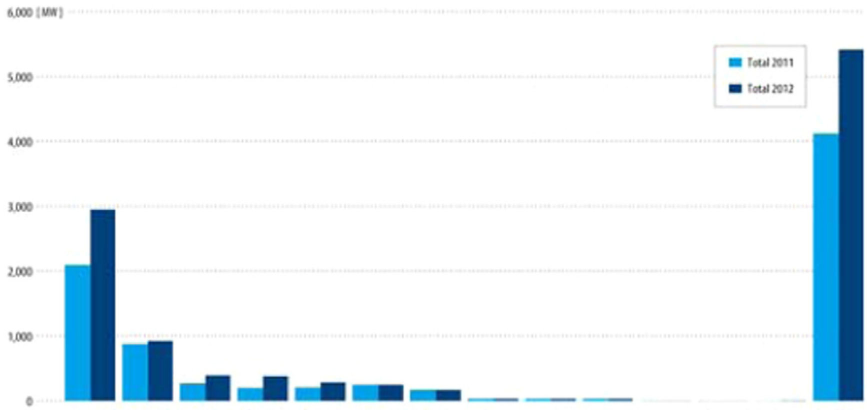
Monopiles have a typical wall thickness of 150 mm, are 6 m in diameter and a weight of up to 650 tonnes [12]. However, the major limitation of monopile supports is their flexibility in deeper waters. This is because monopiles experience some levels of deflection and vibration which are influenced by axial loads, lateral loads and bending moments. Therefore, the diameter and thickness of the monopile structures may have to be increased if they are intended for use in deeper water depths and this will significantly increase the production and installation costs. Research is ongoing on the use of other types of support structures such as jackets structures for larger wind turbines, with the possibility of harnessing more wind energy at increased water depths. Jacket structures are suitable for wind turbine installation in water depths of up to 50 m and they have about 50% reduction in the quantity of steel used for their manufacture compared with the monopile structure [10]. Another major challenge associated with the design of offshore wind turbine support structures is the effort involved to accurately predict the environmental and operational loads and the resulting structural dynamic responses of the wind turbine and support structures under the synergistic effects of wave and wind loading [13]. The structures used for oil and gas applications are mainly attributed to wave loads when designing for extreme loading conditions, while wind turbine structures experience wave and wind loads. This may therefore result in complex random loading situations due to the number of parameters that may be involved [14].

Therefore, some of the currently available design concepts developed for oil and gas structures may not suit wind turbine support design requirements due to the significant differences in the design. It was also mentioned that the current design guidance could be acceptable for single structures but may become costly for use in structures with significant production volumes [3] such as the wind structures. Therefore, an approach to understanding the behaviour of wind turbine monopile support structures with respect to fatigue damage is to study their responses with respect to the type of environmental conditions encountered in service. This can only be realised through tests conducted on representative materials and structures in appropriate environments [15]. However, numerical or theoretical approaches may also be alternatives towards the understanding of the behaviour of monopile structures but experimental data are required to validate them for confidence in and reliability of the results.

Currently, about 96% of the commissioned offshore wind structures are supported on monopile structures while the remaining 4% are supported on jacket structures [7]. Due to the rapid development of the wind industry, other support structures such as Tripod, Tripile and floating structures are proposed for offshore wind farms installations depending on water depth, turbine size, soil conditions and cost of installation. Different types of support structures for offshore wind turbines with their associated water depths are shown in Fig. 3. The figure shows that at some particular water depths, the most appropriate support structures will be the floating types. The floating support structures include the tension leg platform (TLP), semi-submersible and spar buoy platforms with each having specific design requirements but these are not discussed here. However, it has been mentioned that the design and installation costs of the floating structures are similar to those of fixed supports structures in deeper waters and that the floating structures design are expected to be economical [16] but this prediction has not been established at yet.

3. Offshore wind energy economics

Offshore wind generation is largely based on experience and technology acquired from onshore wind, but the project cost for



	UK	Denmark	PR China	Belgium	Germany	Netherlands	Sweden	Finland	Ireland	Japan	Norway	Portugal	South Korea	TOTAL
Total 2011	2,093.6	874.3	262.6	195.0	200.3	246.8	163.7	26.3	25.2	25.2	2.3	2.0	2.0	**4,119.3**
New 2012	854.2	46.8	127.0	184.5	80.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	3.0	**1,295.6**
Total 2012	2,947.9	921.1	389.6	379.5	280.3	246.8	163.7	26.3	25.2	25.3	2.3	2.0	5.0	**5,415.0**

Fig. 2. Global growth of wind sector [9].

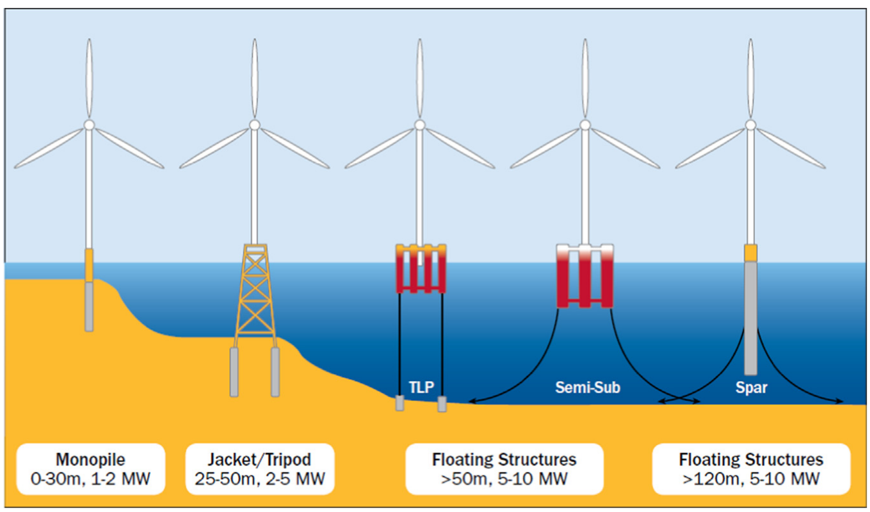


Fig. 3. Offshore wind support structures [16].

offshore wind structures is significantly higher than land based ones. This is due to the additional costs required of the substructure, which may also depend on the type of support structure, coupled with the effects of the harsh marine environments. Zhixin et al. [17] stated that the offshore wind system is two or three times higher than the onshore system, while Esteban et al. [18] attributed the cost of wind structures to sea operations. The operation and maintenance of wind turbines located in the Northern Baltic Sea is more challenging due to the cold climate and icing conditions [19]. This implies that the operation and installations costs of wind structures are also site dependent. At the moment, one of the major challenges for the offshore wind industry is cost-reduction for wind structures with the production and installation of the substructures covering about 20% of the capital expenditure (CAPEX) [16]. Musial et al. [13] also stated that the overall cost of the offshore systems is associated with the foundations, installation, operation and maintenance. Operation and maintenance of the foundation is around 30% of the total cost while the cost of grid connection to the shore is about 25% of the wind turbine [20]. This implies that if the production and installation costs of the substructures are reduced, there is likely to be a significant reduction in the overall cost of the wind structures. The combined cost of electrical grid connection, foundations and support structures, logistics and installations, operating and maintenance was also mentioned to be around 57% to 71% in [21]. As the wind industry is playing a key role in the UK's target of generating energy from renewables, it has been suggested that there should be collaborative efforts between the government and industry to ensure that the cost of generating power from offshore wind is reasonably reduced [11].

4. Challenges in design of monopile support structures against corrosion fatigue damage

Apart from the operational loads envelope encountered by monopile support structures, they are subjected to relatively harsh marine environments. A review of the structural dynamic response characteristics of offshore wind turbines was presented by Adedipe et al. [5]. In their study, the extent to which corrosion can be associated with damage to the monopile support structures across the relatively narrow band of frequencies reported in the literature was investigated. Due to rapid development in the wind sector, offshore steel manufacturers now use modern materials and fabrication techniques for the production of thicker plates for monopiles and other types of support structures. Therefore the behaviour of the newer types of materials with respect to the area of application needs to be understood. Also, fabrication techniques, such as the types of welding process employed nowadays, are likely to significantly influence crack growth behaviour in the materials in air and seawater environments. This is because of possible changes in the microstructure of the weld materials and level of weld induced residual stresses as a result of material thickness, material type, welding input parameters, and levels of restraints employed during welding etc. Therefore, the type of crack growth behaviour, such as those reported in [1,2], may be significantly different from those in the current steel grades, considering the types of fatigue testing facilities, data acquisition techniques and improved fabrication procedures that are employed currently.

It was also mentioned that the currently adopted design standards for offshore wind turbine structures are the design codes and semi-empirical correlations developed by certification authorities such as Det Norske Veritas (DNV, 2011) and American Petroleum Institute (API, 2007) for the oil and gas industry using fatigue data collected from small diameter flexible pipes [4]. Due to the significant numbers of fabrication techniques, inspection and design techniques that have evolved recently, Brennan [3] also mentioned the need for an update to the existing design standards that are used for the first generation of monopile and tubular joint steel structures. Given the manufacturing volumes of wind structures, it may therefore be implied that there is a requirement for new design solutions for wind structures in order to ensure their fitness for purpose. To this end, the aforementioned challenges for the design of offshore wind support structures highlights the need for a better understanding of the corrosion fatigue crack growth behaviour in the structures with respect to their dynamic response characteristics. To bridge the gap in knowledge on the effects of corrosion on fatigue behaviour in oil and gas structures and offshore wind turbines supported on monopile structures, there is also a need to carry out experimental tests on representative materials and structures in appropriate environments.

The literature search has revealed that the data available on corrosion fatigue crack growth in medium strength steels used for offshore structures are those realised from BS4360 50D steel in the 1970s and 1980s. However, it must be mentioned that although the database is without doubt a huge one, it can be considered out of date. Newer grades of steels such as S355J2+N steel are now being used for offshore wind monopile fabrication and due to better fabrication techniques, these grades of steels have improved properties in order to enhance toughness and weldability [22]. Therefore, the fatigue data realised from the old BS4360 50D steel grades may not be the same as those obtained from the current grades of steels such as S355J2+N steel due to material variation. Some results were also obtained from the 355D steel grades in air, for example in [23–25].

Crack growth rates in S355 EMZ parent and HAZ materials in air were compared with those obtained from RQT 701 and S460 steels by Mecozzi et al. [23]. The slopes obtained from the da/dN vs. ΔK plots for S355 EMZ and S460 steels were found to be significantly higher than those obtained from RQT 701 steel. Lower crack growth rates were also observed in the HAZ compared to in parent materials for all the steels tested. The result was explained with respect to possible influence of compressive residual stresses in the HAZ materials. Crack growth behaviours of S355 and S690 steels in air were also compared in [24]. For all the stress ratios tested, crack propagation in S355 steel was found to be lower than in S690 steel. The finer grain of the S690 steel was used to explain the propagation behaviour of the material. In Chahardehi et al.'s work [25], two compact tension (CT) specimens fabricated from BS7191 355D steel were also tested in air to obtain the Paris constants of the material. The crack growth behaviour of the specimens was similar across all the stress intensity factor ranges tested. However, the major drawback in the studies discussed above is that seawater tests were not conducted particularly for the S355 steel grades. Also, the material composition of these steels is somewhat different from that of S355J2+N steel; a typical example of the material properties can be seen in [24]. In the following section, a review of corrosion fatigue in offshore structures with respect to the effects of the environment and some other associated factors is presented.

5. Seawater environmental conditions

Seawater covers up to 71% of the Earth's surface with approximately 3.5% by weight of sodium chloride solution. It is challenging to replicate the natural seawater environment in the laboratory [26]. This is probably because of the significant variation in the environmental zones with respect to temperature, oxygen content, pH salinity etc. The pH of seawater ranges from 7.8 to 8.3 and is considered to be mildly alkaline. It has been mentioned that fatigue behaviour can be significantly influenced by variations in temperature, pH, dissolved oxygen and salinity [27]. These variables have been studied under laboratory conditions. For example in [1], it was found that a reduction in pH from 8.5 to 6.5 and a reduction in oxygen concentration from 7 to 1 mg/l had a marginal effect on crack growth rates in 50D steel, while an increase in temperature from 5 °C to 20 °C increased the crack growth rates by a factor of 2. A significant number of corrosion fatigue tests have been conducted in the laboratory at a temperature between 8 °C and 10 °C in order to represent typical North Sea conditions. However, the crack growth behaviour of steels under the above mentioned parameters may depend on the seawater composition. Most studies conducted on corrosion fatigue behaviour of marine structures have used artificial seawater prepared according to the specifications given in ASTM D1141 [28] as an alternative seawater environment, while some investigations have used either 3.5% NaCl [29,30] or natural seawater [1]. Therefore, crack growth data obtained under these environments are likely to be different.

6. Simulating service load conditions

It is understood that most structures in service experience variable amplitude loadings with different magnitudes and loading sequences which are also referred to as load interaction effects. However, the majority of fatigue data are obtained under constant amplitude loading. This is because data obtained using constant amplitude loading serve as the baseline for the understanding of the structures, are easier to analyse and are readily compared with results from other sources. Laboratory tests are studied under short duration and an attempt to simulate realistic service load conditions may not be feasible due to time constraints and cost-implications. However, fatigue crack growth data realised within the laboratory simulated seawater environment might be extrapolated to predict the crack growth behaviour of real structures.

It should be mentioned that crack growth analysis under spectrum loading is far from easy and time consuming due to the load interaction effects [31] which cannot be completely accounted for. However, material data obtained under constant amplitude loading could be used to implement prediction under spectrum loading if the load interaction effects can be adequately quantified. It has been shown that the load interaction effects were negligible in the corrosion fatigue crack growth of ABS EH36 steel tested under constant amplitude and spectrum loading [31]. The result is shown in Fig. 4. In this type of situation it may be implied that the fatigue data realised under constant amplitude loading could be utilised for fatigue life estimations, neglecting the load interaction effects.

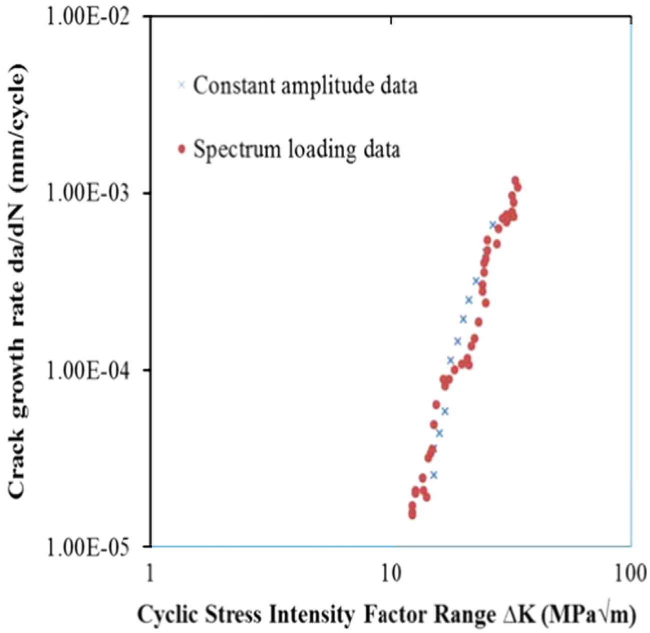


Fig. 4. Corrosion fatigue crack growth in EH36 steel conducted under constant amplitude and spectrum loadings [31].

7. Factors influencing fatigue crack growth in marine environments

In wind turbine support structures, corrosion mechanisms are expected to be driven by the synergistic effects of the harsh marine environments, wind and wave loads that the structures experience in service, compared to oil and gas structures where wave loads are primarily the concern. It should be mentioned that this type of study has not really been addressed in the public domain. Considering the significant quantity of steel used for monopile fabrications, there is the possibility for defects between the parent material and the weld region irrespective of the level of the quality control measures employed during the welding process. These defects can be significantly amplified in corrosive environments due to the synergy between fatigue loadings and harsh marine environments.

Corrosion fatigue is a failure mechanism which cannot be absolutely understood. This is due to the nature of the electrochemical interaction of the material involved, and the nature of the environment coupled with the significant number of the associated variables involved in the corrosion fatigue process. Some of the important factors influencing the corrosion fatigue behaviour in metals have been categorised as mechanical, metallurgical and environmental variables [32,33]. The mechanical variables include: loading frequency, stress intensity factor, loading waveform, load interaction effects (variable amplitude loading), residual/mean stresses, material type and geometry; metallurgical variables are microstructure and material composition, mechanical properties, heat treatment etc.; the environmental variables include: temperature, pH, level of cathodic protection (CP), coating type, oxygen concentration etc. These significant numbers of variables indicate how complex the corrosion fatigue process is and how difficult it is to justify all the variables economically. However, it is important to understand the interaction of the various factors in the corrosive environment and their effects on the material response so that the representative environment that best describes the actual service condition can be achieved with minimal experimental variations [26]. In most cases, important parameters based on the investigator's decision are varied while others are kept constant. Therefore, care must be taken when experimental data are compared with investigations from other sources during data interpretation and comparisons.

Simulating the effects of the above mentioned variables on crack growth rates using large scale specimens may not be a cost-effective approach. This is because tests using large scale specimens are expensive, laborious and also depend on the capacity of the test machine. This is why the majority of the corrosion fatigue crack growth studies have been conducted using small scale laboratory specimens such as compact tension (CT), single edge notched specimens, or bars. These specimens can also be used to represent the through thickness direction of crack growth in welded joints as closely as possible. Another advantage of small scale specimens is that a good number of variables can be studied under laboratory conditions and the obtained crack growth data from such studies may be extrapolated to real structures. All the variables influencing corrosion fatigue crack growth are not discussed independently in this paper but some of them, including those within the scope of this paper, are discussed in later sections.

Some investigations have also examined the interaction of a number of variables influencing the corrosion fatigue behaviour of materials. For example Bhuyan et al. [34] investigated the effects of environment and mechanical loadings, such as frequency, load ratio and waveform, on corrosion fatigue crack growth in CSA G 40.21M 350WT steel with a yield strength of 405 MPa. It was found that there was a marked influence of the environment on crack growth rates when the temperature was kept between 0 °C and 4 °C at a loading frequency of 0.05 Hz. It was also reported that the effect of frequency in air was negligible and no significant effects of the increase in stress ratio from 0.05 to 0.3 was evident in the air environment. A similar behaviour was also reported by Johnson et al. and Vosikovsky [35,36], as slightly higher crack growth rates were observed in seawater at an *R*-ratio of 0.3 relative to an *R*-ratio of 0.1. This may be due to the behaviour of materials with respect to increasing stress ratios, environmental conditions and the magnitude of the stress ratio used for testing. Investigations that addressed some associated mechanical and environmental factors influencing corrosion fatigue behaviour in offshore structures are discussed in the following sections.

7.1. Frequency effect on fatigue crack growth

Corrosion fatigue crack growth in most studies is usually referenced to the response of the material in an air environment. This can be quantified using either the S–N or the fracture mechanics approach. However, regardless of the approach used, it should be noted that the frequency content of the loading cycle is one of the important parameters that control corrosion fatigue process. Lower cyclic frequencies have been shown to be more damaging in corrosive environments compared to the response in air [1,2]. This is due to the longer time a crack tip is exposed to the electrochemical elements per cycle [5]. This implies that, using a higher frequency for crack propagation in seawater will significantly reduce the environmental influence of the corrosive environment. Crack growth behaviour of BS4360 50D steel in seawater at higher frequencies has also been reported to be similar to those obtained in air [1], which implies that the influence of frequency on fatigue crack growth is more appreciable in seawater than in air. The use of a higher frequency for fatigue tests conducted in an air environment also depends on the capacity of the test machine. A higher cyclic load frequency may introduce vibrations in the fatigue test machine and this may significantly influence the results. Another possible explanation with respect to crack growth rates is that, at a higher loading frequency, the applied test load may not be adequately delivered at the crack tip.

It is worth mentioning that the fatigue and fracture mechanics tests conducted in the 1970s and 1980s on medium strength steel grades were realised at the wave excitation frequency of 0.1–0.2 Hz [1,2,37–39], with most of them reported at a cyclic load frequency of 0.1 Hz. More recently, Griffiths and Turnbull [40] used a loading frequency of 0.167 Hz to compare the effect of soaking or exposure time on fatigue crack growth rates in CT specimens extracted from AISI 4340 and BS4360 50D steels respectively. Havn and Osvoll [41] also investigated the effect of CP on crack growth rates in BS4360 50D steel at a loading frequency of 0.2 Hz. As mentioned in Section 7, because wind turbine structures encounter wind and wave loadings during operation, the cyclic load frequency which is relevant for testing monopile structures' representative materials is expected to be different from those used for oil and gas structures. An extensive search of the literature has shown that the corrosion fatigue crack growth behaviour of offshore structural steels using the cyclic loading frequency that might be experienced by wind turbine monopile support structures has rarely been reported. Therefore, for a better understanding of the corrosion crack growth behaviour in the structures, there is a need for material testing under the cyclic loading frequency and conditions that might be experienced by wind structures in service.

As mentioned earlier, it has been established that at higher cyclic load frequencies, the effect of corrosive environment on crack growth rates is not significant [1]. Vosikovsky [42] also studied crack growth behaviour of X65 steel at various loading frequencies, as shown in Fig. 5. It was found that at lower ΔK, crack growth rates were increased as the loading frequency was decreased from 10 Hz to 0.01 Hz. However, at higher ΔK, the crack growth curves deviated to the reference air curve. However, it was mentioned that Fig. 5 is valid under a constant load ratio [43]. It can also be seen from the figure that the data obtained at a loading frequency of 10 Hz in seawater nearly converged with the reference air curve, regardless of the level of CP. This implies that increasing loading frequency for corrosion fatigue tests is not a compromise to arrive at a reduced testing time.

Therefore, care must be taken when selecting the cyclic loading frequency value for corrosion fatigue tests due to the associated crack opening time. For example, in Thompson's work [44], a frequency of 0.5 Hz was used for testing in order to minimise the experimental time in contrast to the approximate wave loading frequency of 0.1 Hz as reported in various test programmes. It should be mentioned that at a loading frequency of 0.1 Hz, the crack tip is exposed to the corrosive environment for a longer time compared to a frequency of 0.5 Hz. This implies that the damaging effect of seawater would be higher at a lower cyclic load frequency. An alternative to arrive at a realistic testing time would be to increase the stress level. However, care must also be taken when selecting applied stress in order to avoid plasticity at the crack tip.

It was mentioned in Vosikovsky's work [42] that the tests were conducted at ambient temperature and that a hydrogen embrittlement mechanism was likely to be responsible for the observed crack growth rates under CP and free corrosion potentials. This implies that the manner of crack growth in seawater at higher ΔK as shown in Fig. 5 may also be both material and environment dependent. However, the type of crack growth curves shown in Fig. 5 was not evident in the Thorpe et al. and Scott et al. works [1,2] for tests conducted on BS4360 50D steel. In their studies, tests were conducted under a simulated North Sea wave load of 0.1 Hz. In seawater, crack growth rates were found to be higher than in air across the ΔK ranges tested. This can also be supported, as shown in Fig. 6, for tests conducted under constant stress intensity factor ranges ΔK. It can be observed that crack growth rates increased with decreasing cyclic load frequencies. In air, the influence of frequency has been shown to be insignificant [41,42] and it was also mentioned that frequency effects on crack growth rates in air are, in most cases, assumed to be negligible [43]. This suggests that frequency can be increased to an appropriate level for an air test in order to save testing time. In a study of fatigue crack behaviour in TStE 355 and EStE 690VA steels [45], a marginal effect of frequency was also seen in air over a frequency range of 0.02–40 Hz but in free corrosion conditions and under CP, increasing the loading frequency to 10 Hz exhibited nearly the same crack growth rates as in air.

The major drawback in the Thorpe et al. and Scott et al. investigations is that weld materials were not considered as test data were obtained from parent materials. The weld area is a potential spot for crack initiation due to the levels of stress concentrations imposed by weld geometry and the magnitude of residual stresses introduced during welding. Fatigue cracks are initiated at the weld heat affected zones (HAZ) and propagate into the unaffected parent materials [35]. This is because the HAZ contains a heterogeneous microstructure with varying mechanical

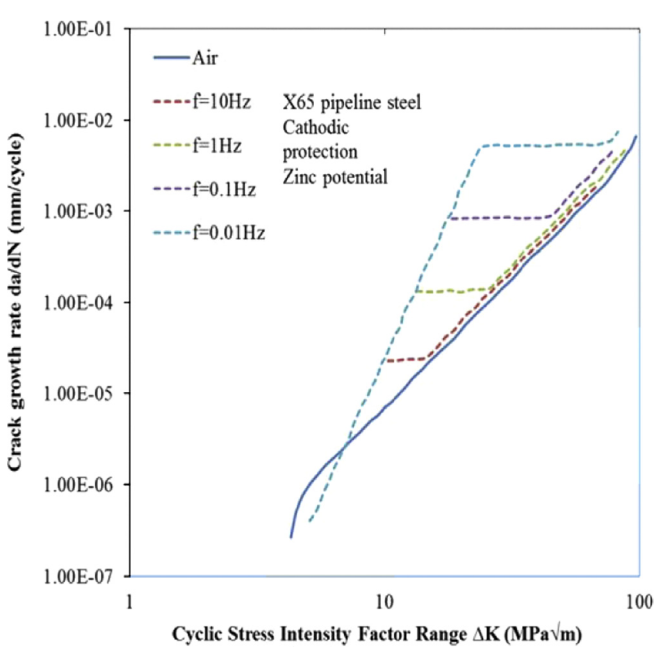


Fig. 5. Frequency effects on fatigue crack growth in X65 pipeline steel [42].

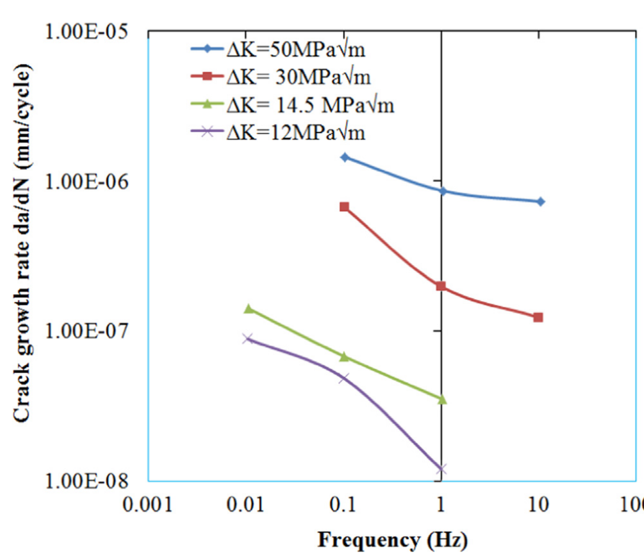


Fig. 6. Frequency effects on corrosion fatigue crack growth [1].

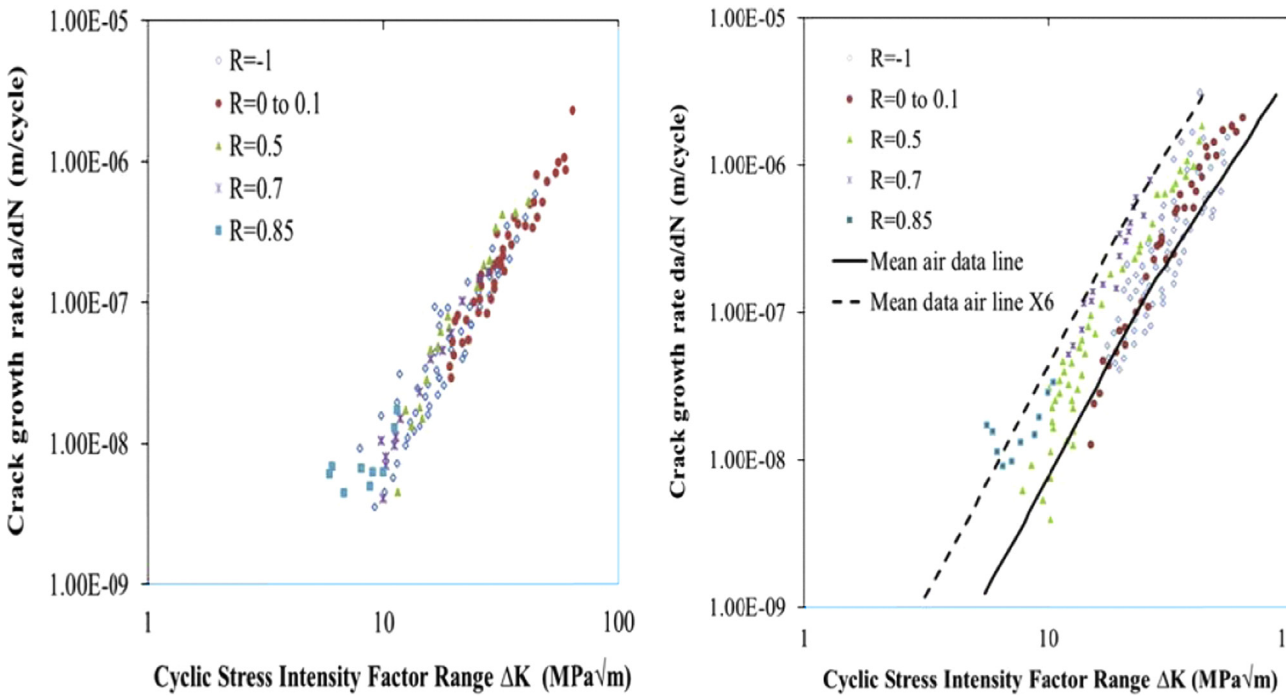


Fig. 7. Crack growth rates of BS4360 50D steel in air and seawater [1].

properties. However, the degree of crack propagation in the HAZ may depend on the member thickness and the HAZ dimension. Considering the microstructure variations in the HAZ, the crack growth behaviour may be significantly different from the associated base materials; however, this depends on the type of weld induced residual stresses [46]. Therefore, fatigue crack growth behaviour of parent materials may not be sufficient to fully understand the damage mechanisms in offshore structures such as monopiles.

However, it must be mentioned that the HAZ is a region where the fatigue crack growth behaviour cannot be fully understood due to microstructure variation. Microstructure variation can influence fatigue crack growth rates thus leading to roughness induced crack closure, change in crack path and delayed crack growth [47,48]. The magnitude of these factors may depend on the type of weld induced residual stresses – either tensile or compressive. Although, in a previous study [49], the tests conducted under the North Sea wave frequency of about 0.13 Hz on base and materials extracted from C–Mn–V steel conforming to BS4360 50D steel, revealed that there is no marked difference between the crack growth rates obtained from parent material and HAZ ones in a seawater environment. The results were explained by a fair difference in hardness values measured in both materials. A similar behaviour was also reported from tests conducted on the HAZ of high strength steels (HSS) in the region of 400–600 MPa [22]. However, this needs to be addressed further under a cyclic load frequency similar to what is experienced in offshore wind monopile support structures in order to fully substantiate this claim.

7.2. Mean stress effects on fatigue crack growth

Mean stress effects on crack growth rates are generally described with respect to the cyclic stress ratios used for testing. Mean stress, or stress ratio, is a variable that influence the fatigue crack behaviour of materials in air and seawater but its effect depends on material type, specimen geometry and loading state [50]. An increase in mean stress will result in an increase in crack growth rates but this depends on the crack growth region, material and environment [51]. At a lower stress intensity factor range in a seawater environment, crack growth rates may be higher, lower or similar to those measured in an air environment. This also depends on the level of closure imposed at the crack tip with respect to the loading ratio [52]. At an increased stress ratio, the influence of seawater on crack growth rates may be significantly higher than in an air environment. This is probably due to a larger crack tip exposure area or crack opening displacement which occurs at a higher stress ratio.

The effects of mean stress have been studied in different seawater environmental conditions and materials [1,36,53]. These investigations have revealed different crack growth responses with increasing R-ratios. For example, in Thorpe et al.'s work [1], tests were conducted in natural seawater. At free corrosion potential, increasing mean stress resulted in an increase in crack growth rates across all the ranges of ΔK tested and at an R-ratio of 0.5–0.7, the effect of stress ratio gave an upper bound of approximately six times the crack growth rates observed in air. These results are shown in the right of Fig. 7. However, a significant amount of scatter was obtained from the results as shown in the figure. In the left of Fig. 7, tests conducted at stress ratios of -1 to 0.85 in air are compared. It can be seen that the data points are clustered around the mean air data regardless of the increase in stress ratio. In other words, there was no marked effect of the stress ratio in air. In the seawater tests, as shown on the right of Fig. 7, it is possible that at higher stress ratios, crack growth rates were also significantly influenced by the interaction of the environment and loading frequency with respect to crack opening time.

In Vosikovsky's work [36], it was found that at a lower cyclic frequency, crack growth rates in X70 pipeline steel tested in a 3.5% sodium chloride solution were enhanced in a similar manner to those reported for X65 steel (Fig. 5). The influence of the stress ratio was also found to have appreciable influence on crack growth behaviour both at threshold and near threshold stress intensity factor ranges. At increased ΔK ranges, the effect of the stress ratio diminished both in air and the 3.5% sodium chloride solution.

However, significantly different crack growth behaviours were observed by Appleton [53] on tests conducted on BS4360 50D

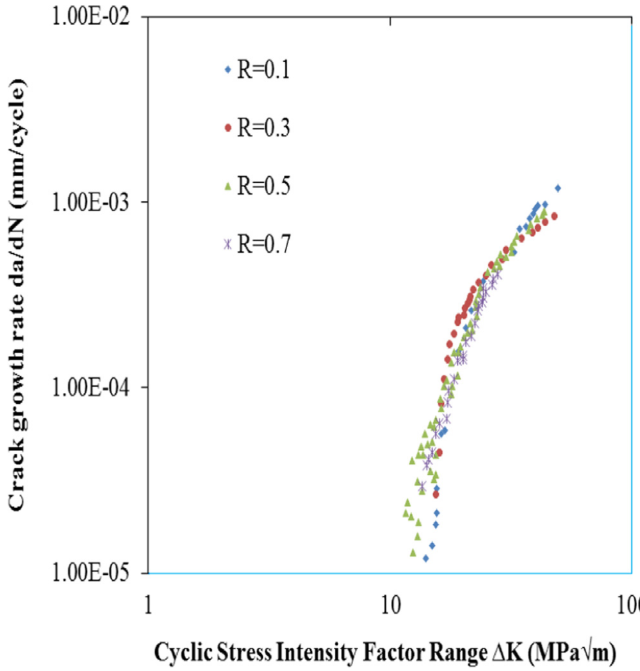


Fig. 8. *R*-ratio effect on crack growth rates in BS4360 50D steel [53].

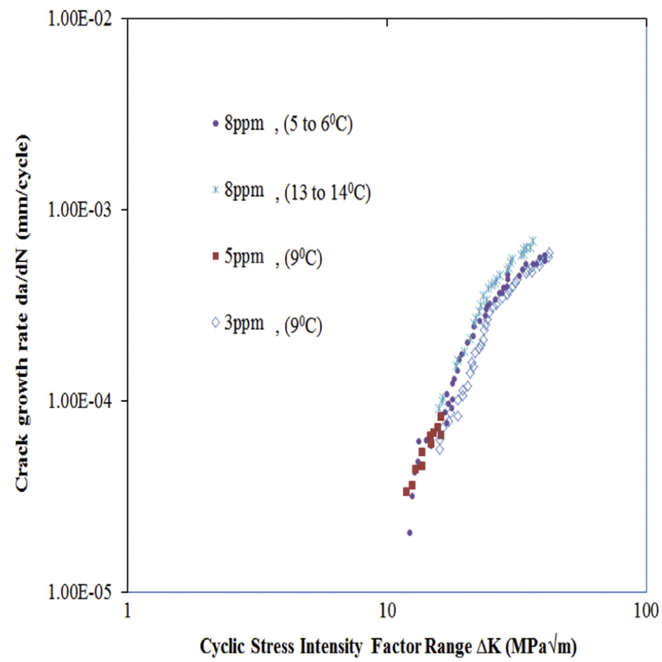


Fig. 9. *R*-ratio effects on BS4360 50D steel at different temperatures [53].

steel. It can be observed that there was no marked effect of mean stress on crack growth rates as shown in Fig. 8. However, at lower ΔK, the observed crack growth rates as shown in the figure may be related to the marginal effects of mean stress but at higher ΔK, the crack growth curves converged and deviated from the linear segment of the da/dN vs. ΔK plot. In Appleton's work, tests were conducted at an ambient temperature of 23 °C using a 3% NaCl solution; Vosikovsky's data were also obtained at a room temperature of 24 ± 2 °C while Thorpe et al.'s tests were conducted at temperatures of 5–10 °C. Therefore, it is possible that crack growth data presented from the above studies were also significantly influenced by changes in temperature and variations in the environmental media.

However, in Appleton's work, some tests were also conducted using ASTM artificial seawater at a temperature of 9–14 °C, as shown in Fig. 9. It can be seen that an increase in the test temperature increased crack growth rates, particularly at higher ΔK. From some previous studies, tests have also been conducted at a temperature range of 5–10 °C [1,2,35] with the aim of simulating the average temperature of the North Sea. Therefore, it is expected that the range of temperatures reported in those studies compared to Appleton's work are likely to have appreciable influence on crack growth rates.

To account for the effect of tensile residual stresses in welds, a higher mean stress or *R*-ratio of about 0.5 or 0.6 is usually used for testing, while an *R*-ratio of 0 is used for base materials [41]. However, the tensile residual stress profile may be limited to the near surface of a material. For relatively thick materials, such as those used for monopile fabrications, both tensile and compressive residual stress types are likely to be present. In that case, the overall magnitudes of the through thickness residual stress distribution would be required to account for the effect of mean stress on crack growth rates. Different sources of mean stresses in structures have been categorised as stresses due to dead weight loading, weld induced residual stresses and locked up stresses introduced during fabrication [54]. This implies that residual stresses present in welds may also be considered as mean stresses. Under constant amplitude loadings, a number of models have been developed to measure the effects of mean stress on crack growth rates [55–59]. These fatigue crack propagation models were developed with respect to a number of curve fitting parameters but the discussion is outside the scope of this paper. However, considering the levels of uncertainty associated with residual stresses in welds, it may be difficult to completely account for the influence on crack growth behaviour.

If residual stresses are considered as mean stresses, crack growth behaviour may be related to either acceleration or delay mechanisms. Under compressive residual stresses, delay in crack growth may occur and this is beneficial to fatigue crack growth. Generally, the presence of residual stress would have an effect on the applied ΔK, depending on whether the residual stress type is tensile or compressive [60]. Fatigue crack growth is enhanced under tensile residual stresses while compressive or beneficial residual stresses could increase the resistance to crack growth. If the fatigue crack is propagating through a compressive residual stress field, this will introduce a compressive stress cycle even when a tensile stress cycle is applied. Therefore, the applied ΔK may not be altered but the effective stress ratio is, depending on the extent of the residual stress distribution. This implies that the residual stress distribution will be superimposed on the applied stress cycle. For instance, if tensile residual stress exists ahead of a crack under a compressive stress cycle, the crack might actually be experiencing a tensile cyclic stress. This can also be explained, as shown in Fig. 10, for the case of a tensile residual stress up to the magnitude of yield stress. This is probably why higher *R*-ratio fatigue data are suggested as the appropriate results for estimating fatigue lives of welded joints [35].

Stress relief techniques such as post-weld heat treatment (PWHT) are applied on welds in order to remove residual stresses but it must be mentioned that the effect of residual stresses may not be completely removed. This is due to the levels of uncertainty associated with residual stresses [54,61]. However, some situations may arise that require an understanding of crack growth behaviour in the presence of residual stresses, in as weld materials. Some weld improvement techniques may also reduce local stress concentration or introduce beneficial compressive residual stresses into weldments, so that fatigue lives can be significantly increased. It was mentioned that a stress relief process using heat treatment was beneficial in C–Mn steel resulting in improved fracture toughness of the HAZ [62], but this may be material

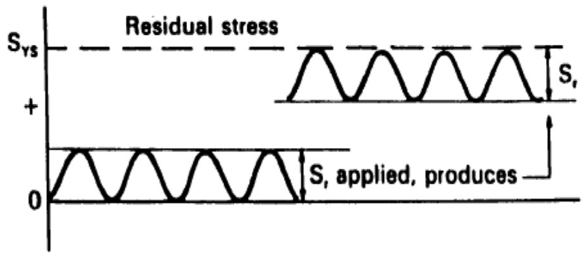


Fig. 10. Superimposed pattern of applied and residual stress [61].

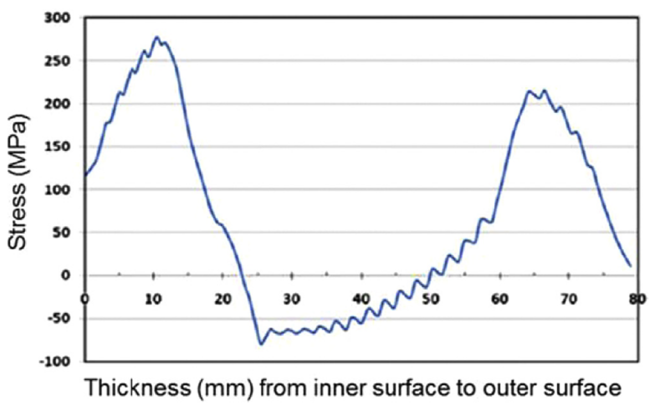


Fig. 11. Residual stress distribution in 316L stainless steel [63].

dependent. It was also mentioned that residual stress with a magnitude of about 20–30% of material yield strength would still be present in welded joints after the application of PWHT [61]. A review of weld improvement techniques coupled with their associated advantages and limitations can be found in [61].

During crack propagation, residual stresses are released gradually or redistributed and may eventually disappear as the crack grows. However, the redistribution of residual stresses ahead of the crack tip may be directly related to the magnitude of the externally applied load. Therefore, the effects are likely to occur when the crack is still shallow [54]. It was mentioned by Austin [54] that, in weld plates, the damaging segment of the residual stress field is about a quarter of the thickness of the plate, and with a compressive stress field in the middle of the plate due to the self-equilibrating behaviour of residual stresses. An example is shown in Fig. 11 for a study of residual stress distributions in 76 mm thick 316L stainless steel pipes that were joined by an automated narrow gap welding process. It was found that the tensile segment of the residual stress distribution existed close to the surface of the weld plate, while compressive residual stress occurred in the middle [63]. It can also be seen from Fig. 11 that the tensile segment of the residual stress distribution is nearly a quarter of the thickness of the plate. However, the effects of residual stresses may be material dependent but the manner of residual stress distribution shown in Fig. 11 is in agreement with what was reported by Austin [54].

If the residual stress distribution shown in Fig. 11 for weld material is considered as the mean stress for an externally applied stress ratio of 0.1, it implies that the residual stress distribution changes the stress ratio from 0.1 to a negative value. In such a situation, negative stress ratio data may be utilised to correct for the effects of mean stress on crack growth behaviour in the material.

7.3. Effect of cathodic protection

Some of studies conducted on the behaviour of offshore structures with respect to cathodic protections (CP) are discussed in this section. The effects of the corrosive environment were found to enhance fatigue crack growth rates by a factor of 2/4 relative to in air, depending on the stress intensity factor range and applied levels of CP [30,64]. This was observed from tests conducted on BS4360 50D steel in 3.5% NaCl solution which may be different from the data obtained in laboratory simulated seawater prepared according to ASTM D1141 [28]. The two primary processes that have been identified with corrosion in marine structures are the anodic, oxidation reaction and cathodic, reduction reaction [26]. It was mentioned that the former process is the major environmental influence of free corrosion condition while the latter is associated with CP [26,54]. Corrosion fatigue crack growth is primarily controlled by dissolution of metal at the crack tip and hydrogen embrittlement [65]. At high dissolution rates, it was mentioned that the mechanism of crack blunting is likely to occur, particularly at higher stress intensity factor ranges accompanied by a larger plastic zone size [66]. The two major reactions occurring under CP are oxygen reduction and reduction of water leading to hydrogen production [54]. The reduction of oxygen is a cathodic reaction while hydrogen reduction might occur due to a low level of dissolved oxygen and cathodic over protection, either by impressed current or sacrificial anode CP systems [26]. Both the S–N and the fracture mechanics have been used in various test programmes to study the effect of CP on the behaviour of steels in marine environments. However, corrosion fatigue damage is associated with both crack initiation and propagation, which can only be addressed by the fracture mechanics approach. Therefore, the approach can be used for the design of structures through monitoring their behaviours with respect to inspection intervals. Also, if fatigue cracks are discovered in structures, fracture mechanics can be employed as a useful tool to quantify the severity of the cracks and to plan for remedial actions against possible failure.

Coatings are also alternative corrosion protections to CP particularly in monopile support structures. However, coatings are applied on the outside of the monopile structures but the inside should also be considered as a potential crack initiation site. The fact that a free corrosion condition is never designed for in marine structures does not absolutely guarantee it from occurring and also corrosion protection (coatings) may be damaged during transportation, installation and operation. Therefore, there is a need for a better understanding of the actual effects of corrosion in marine structures. However, in situations where crack initiation or damage occurs inside the monopile structure, it would be a challenging task to carry out an inspection, especially when there are multiple crack initiation sites. It is therefore important to also consider the effect of corrosion inside the monopile structures when estimating their expected operation lives. This is because the inside of currently installed monopile structures are not protected either by coating or CP and contain a significant amount of seawater and oxygen access [67]. Over time, corrosion may be induced and hence fatigue damage, leaving the structures to operate under a free corrosion condition. The only alternative for internal protection of future monopile structures might be to employ a protective coating during the design and fabrication stage.

Installation of CP systems inside the monopile structures may not be an appropriate approach for corrosion protection due to the hydrogen production and change in water chemistry. Efforts have been made to investigate the possibility of installing internal CP systems in monopile support structures [68]. This study is at an early stage and further experimental studies on the application of the selected types of galvanic anodes on representative materials, operating under similar loading conditions experienced by monopile structures, may reveal a better understanding of the performances of the corrosion protection systems. However, the installation costs of internal corrosion protection systems based on manufacturing volumes of monopile structures need to be carefully considered. In other words, there may be a significant increase in the capital expenditure, considering the additional costs that might be incurred at the project setting up stage concerning corrosion control measures. However, the original design life of the structures can be extended if proper inspection and monitoring facilities are deployed. The use of better inspection techniques coupled with a good understanding of crack propagation behaviour will inform the frequency of inspection so that a fitness for purpose can be achieved [30].

Due to the significant volumes of anticipated wind structures offshore, compared to oil and gas structures, there is a need to operate the wind structures with lower costs and close to the actual design capacity [15]. However, at the moment, there is lack of information concerning free corrosion conditions in representative monopile steels. Most of the previous research studies regarding offshore oil and gas structures were conducted under free corrosion potentials and with CP. The free corrosion potential of −0.65 V or −0.7 V with respect to Ag/AgCl electrodes have been used in steels [1,35]. A value of −800 mV has also been referred to as the effective corrosion protection in steel structures [69]. Some studies, for example [1], have investigated the effects of CP at potentials between −0.6 V and −1.3 V with respect to Ag/AgCl electrodes on crack growth behaviour of BS4360 50D steel. It was found that crack growth rates were higher at higher levels of CP than at free corrosion potential [1]. Lindley and Rudd [69], also reported the effects of CP on the corrosion fatigue behaviour of welded RQT501 steel by varying the levels of potential between −900 mV and −1050 mV with respect to Ag/AgCl electrodes. The results when compared with those obtained from BS4360 50D revealed that crack growth rates in both steels were significantly higher in seawater than in air regardless of the levels of CP. It was found that the effectiveness of CP was more appreciable at near threshold stress intensity factor ranges than in the Paris region.

It should be mentioned that crack growth data obtained under a free corrosion potential in seawater are likely to be different from those obtained under free corrosion conditions without any protection. This is because a free corrosion potential in a CP system may still be associated with hydrogen production as a result of cathodic reaction, especially when the CP system is not well designed. This may result in some levels of hydrogen embrittlement at the crack tip leading to an increase in crack growth rates. Crack growth rates in BS4360 50D steel have also been attributed to hydrogen embrittlement at all the applied potentials, including free corrosion potential [2]. Hydrogen production from CP systems would result in an increase in fatigue crack growth rates [37]. In high strength steels (HSS) such as SE702, the effect of hydrogen produced by CP in 3.5% NaCl increased at lower stress intensity factor ranges and decreased at increased crack growth rates [43]. The influence of CP on hydrogen embrittlement was also found to be more significant in HSS such as SE702 than in BS4360 50D steel [37]. In X65 pipeline steel, Vosikovsky [42], found that in seawater, below the plateau region where there was an increase in crack growth rates at increased ΔK, the effect of hydrogen embrittlement near the crack tip was more significant.

Corrosion fatigue behaviour of super duplex stainless steel was also investigated to examine its applicability in the offshore wind sector [70]. Tests were conducted on Zeron 100 weld metal in synthetic seawater at a temperature of 20 °C under potentials of +600 mV and +1034 mV with respect to saturated calomel electrodes. Crack growth rates were found to be higher in seawater than in air. The crack growth behaviour of the weld material in seawater was found to be similar to those measured in the equivalent base materials. However, it was mentioned that the measured crack growth rates in seawater were significantly influenced by the test temperature.

As mentioned earlier, due to the significant volumes of offshore wind structures, a CP system may not be a cost-effective approach for the steel monopile structures. However, crack growth data obtained under a free corrosion condition using representative parent and weld/HAZ steel materials may be useful for a conservative estimation of the service performance of monopile structures. These types of studies have rarely been reported in the literature and hence remain inadequately understood. As such it is recommended to address this current gap in knowledge with respect to the types of medium strength steels used for monopile fabrications. However, a considerable effort has been made on studying the corrosion fatigue behaviour of HSS weldments. These are briefly discussed in the following section.

8. Corrosion fatigue of high strength steels

Steels used for the design of marine structures have been classified into conventional steels (yield strength 350 MPa), HSS with yield strength in the range of 400–600 MPa and extra HSS with yield strength of 700– 900 MPa [22]. Other types of steels above 900 MPa yield strength are also available from steel manufacturers but these are not discussed here. The intention of the review presented in this section is to introduce the crack growth behaviour of the commonly used HSS for offshore applications. Significant efforts have been made towards understanding the behaviour of medium strength steels such as 4360 50D. There has also been significant interest in the use of HSS for the fabrication of marine structures in the past. HSS with yield strength between 450 MPa and 700 MPa are normally used for fabrication of the leg members of jack-ups [37]. One of the drawbacks in using HSS for offshore structures is that they are not easily weldable due to their high carbon equivalent values [71] coupled with the addition of other alloying elements. However, offshore steel manufacturers have now employed modern fabrication techniques with the intention of improving steel performances. Another disadvantage in using HSS compared to medium strength types, is their susceptibility to hydrogen embrittlement [72], which also occurs due to CP [73]. A review of the performance of HSS has been conducted in [74], where it was also mentioned that HSS are susceptible to hydrogen embrittlement.

Therefore the behaviour of some HSS in air and seawater are likely to be different from medium strength steel grades. For example in the work of Zhang and Brook [50], crack growth tests were conducted on RQTuf 501 with yield strength of 462 MPa in air and in seawater at stress ratios of 0.1–0.7. It was found that there was little effect of stress ratio within the range of ΔK tested. The RQTuf 501 steel exhibited similar fatigue crack growth behaviour under variable amplitude and constant amplitude loadings with crack growth retardation playing a primary role in the variable amplitude loading. Corrosion fatigue crack growth in SE702 steel with yield strength of 780 MPa was also found to be slightly better than those measured in BS4360 50D steel regardless of CP, but in air crack growth behaviour in the two steels were similar [75]. It was also found that the HAZ material exhibited a slightly better fatigue crack growth behaviour than parent material in air, but there was a reduction in the observed difference in seawater. It is anticipated that newer types of medium strength steels used for offshore installations are likely to be more resistant to crack growth than HSS due to the susceptibility of the latter to hydrogen embrittlement. It would therefore be useful to compare the crack growth behaviour in both medium and high strength steels for an adequate understanding of their behaviours in marine environments.

9. Fatigue crack growth in weldments

Most offshore structures are fabricated from welded joints which are potential spots for fatigue crack initiation. The weld heat affected zones are associated with different microstructures and mechanical properties depending on the type of welding process used. Crack growth behaviour in HAZ materials may depend on the crack initiation site – either close to the weld or parent materials. The types and properties of the filler material used in welding are also important factors that can influence the properties of weldments and the crack growth rates. The HAZ are generally known, with tensile residual stresses which may be up to the magnitude of the yield stress. These stresses can be reduced under cyclic loading, under a stress amplitude higher than the material endurance limit [76]. The implication of this is that tests conducted under a high mean stress may be sufficient enough to cancel out the effect of residual stress as the fatigue crack propagates, as discussed in Section 7.2.

The HAZ regions are less tough and are associated with less fatigue resistance when compared to the base material [77]. However, this may depend on the particular region of the HAZ with respect to the different microstructures, mechanical properties and type of welding process. Another factor that may influence the HAZ microstructure and hence crack growth behaviour is the number of welding passes. The microstructure of the coarse grain HAZ region may be refined by tempering through the subsequent welding deposits during multi-pass welding [78]. Hence, some of the weld induced residual stresses may be relaxed in the process. However, this may depend on the cooling rates, the composition of both the steel and the filler material. At this juncture, it must be mentioned that the behaviour of an HAZ to fatigue crack growth may be material dependent, due a number of associated factors influencing the HAZ properties, as mentioned above. The discussion presented in this section is to provide an understanding of the behaviour of weldments regardless of material types.

Fukuda et al. [49] investigated the crack growth behaviour in stress relieved HAZ and base material of C–Mn–V steel having a similar composition to the BS4360 50D steel in air and in synthetic seawater. The tests were carried out at a loading frequency of 5 Hz in air and 0.1333 Hz in seawater with the temperature maintained at 15 °C. Crack growth rates in the HAZ material were similar to those obtained in the parent material regardless of the difference in test conditions. The crack growth behaviour was explained with the slight difference in the hardness values of the two materials. However, this may also be related to the influence of the welding conditions accompanied by the heat treatment employed after fabrication. The HAZ is associated with varying microstructures; therefore it is likely that crack growth rates in an HAZ will be enhanced in seawater due to the rates of metal removal.

Crack growth rates in parent, HAZ and weld specimens fabricated from BS 4360 50D steel were also investigated by Thompson [44]. The HAZ and weld specimens were extracted with the notches located 1 mm from the fusion zone and at the weld centre line. Crack growth rates were lower in the weld than in the HAZ and parent materials for tests conducted in air at ΔK less than 37 MPa$\sqrt{m}$. The direction of crack growth in the HAZ materials was also found to be towards the parent materials. The preferred crack path of the HAZ material was attributed to the decrease in hardness values across the HAZ. Healy et al. [79] also found that microstructure variation ahead of the crack tip was responsible for a preferred crack path in weld CSN3:82 cast steel, as the crack deviated from the tougher regions of the HAZ. A similar phenomenon was also reported by Trudel et al. [46] in CA6NM stainless steel weld. Therefore, due to the heterogeneous nature of HAZ, crack path deviation from the HAZ region towards the parent material is likely to be experienced during propagation.

Crack propagation can be influenced by several factors including crack closure induced by residual stresses, as previously mentioned. For example, in Tsay et al.'s study [78], crack growth behaviour in EH36 TMCP (Thermo-mechanical controlled process) steel was investigated. The HAZ specimen notch was located about 1 mm from the fusion zone. It was found that, due to residual stress induced crack closure at lower ΔK below 22 MPa$\sqrt{m}$, crack growth rates were lower in HAZ specimens than in base materials. More recently, some results on crack growth rates in parent and HAZ materials fabricated from S355J2+N steel were presented in [6]. Crack growth rates were higher in parent materials than in HAZ in air, but in seawater, crack growth rates were found to be similar in both materials. The results were explained with possible effects of residual stresses in the materials. However, more tests are needed in order to interpret the results with respect to the effects of residual stresses. In some cases, crack path deviation accompanied by a saw tooth like pattern might also occur during propagation leading to a da/dN vs. ΔK relationship as shown in Fig. 12. This was observed in Q345 steel with a yield strength of 370 MPa [47]. The crack growth rates in the weld materials were lower than in the parent materials at a lower stress ratio, but at a higher stress ratio the resistance to crack growth was nearly the same in both materials. The effect was explained by residual stress induced crack closure in the HAZ.

At a higher R-ratio ($R \geq 0.5$), the crack surfaces are fully open, therefore the manner of crack growth shown in Fig. 12 may not be observed for tests conducted at higher stress ratios. In a situation when a specimen's notch tip is located near the compressive segment of the residual stress distribution, delayed crack growth is likely to occur due to crack closure phenomenon. However, for a tensile residual stress type, accelerated crack growth might occur. The effect of residual stresses in C–Mn weldments with yield strength of 490 MPa was investigated in air and in seawater by Bertini and Beghini & Bertini using CT specimens [80,81]. For the three materials tested, i.e. parent, HAZ and fusion zones, crack growth rates were higher in the base material than in HAZ and fusion zones in both air and seawater environments. The results were explained with crack closure induced by residual stresses. This was described by the change in slope of BFS versus the applied load, as shown in Fig. 13. The only drawback in the Bertini [80] investigation was that no data were obtained under a free

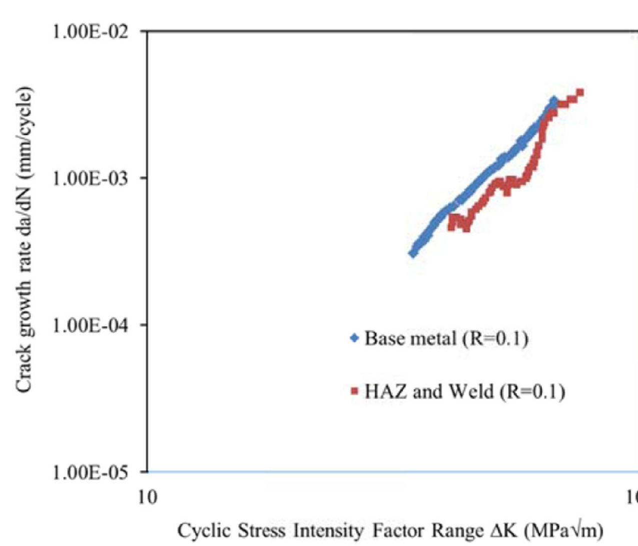


Fig. 12. Crack growth rates comparison in HAZ and base materials [47].

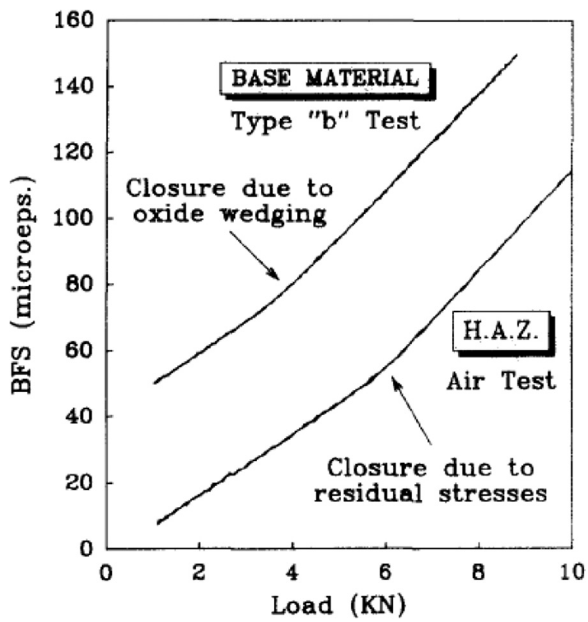


Fig. 13. Crack closure effects on fatigue crack growth [80].

corrosion condition as all the seawater tests were conducted under CP.

As mentioned in Section 7.3, despite the existing database concerning medium strength steels used for offshore installations, very limited data are available on HAZ and weld materials, particularly for tests carried out at higher stress ratios. It should also be mentioned that the results obtained from these studies may not be the same as those obtained from modern steels such as S355J2+N steel. This is due to the fact that modern steels now have improved properties which are achieved by the addition of other alloying elements which may significantly influence the microstructure of the material and hence the crack growth behaviour. Therefore, experimental tests conducted in appropriate environments are needed in order to understand the crack growth behaviour of the newer grades of medium strength steels used for offshore structures such as monopile support structures.

10. Conclusions

The need for an understanding of the behaviour of offshore wind monopile support structures has been highlighted with respect to the state of art and challenges in the offshore wind sector. Crack growth behaviour in different steels has been reviewed and particular attention given to the steels used for offshore installations. The following conclusions can be drawn from this paper:

- Currently available fatigue design guidance needs to be updated to suit the design requirements of offshore wind structures.
- There is need for an understanding of the behaviour of parent, HAZ and weld materials similar to those used for monopile fabrications in an environment that simulates what the structures experience in service as closely as possible.
- A review of literature has shown that corrosion fatigue crack growth behaviour of steels in marine environments can be influenced by a number of variables. Significant differences in environmental test conditions may also result in appreciable variations in crack growth behaviour of the materials subject to dominating parameter used in testing.
- Mean stress effects on fatigue crack growth may depend on materials and test environments. The effect may not be significant in an air environment, but in seawater, an increase in stress ratio can influence crack growth rates with respect to the interaction of the environment and loading frequency.
- Fatigue crack growth behaviour in weldments is not only material dependent but may also be significantly influenced by the environment, loading conditions, microstructure, welding procedure and residual stresses.

Acknowledgements

The authors acknowledge the support of the Petroleum Technology Development Fund (PTDF), Nigeria which is supporting the Ph.D. of Oyewole Adedipe. The authors also wish to thank the Global Wind Energy Council, Ship Structure Committee, Dr Aoife Foley and Paraic Higgins for permission to use the Figures from their published works.

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