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Investigation of the effect of pitting corrosion on the fatigue strength degradation of structural steel using a short crack model

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Abstract

Steel support structures of offshore wind turbines (jackets and monopiles) undergo both fatigue and corrosion damage, impacting their lifetime. This paper investigates how pitting corrosion, caused by being exposed to the marine environment, affects the fatigue strength of structural steel. A short fatigue crack model is used to estimate the minimum required applied load amplitude which causes a growing crack emanating from the bottom of a semi-elliptical pit. Pit growth rate data, reported in literature, is employed to update the pit size and its sharpness at each time step. The modelling results show the fatigue strength degradation as a function of the exposure time to the corrosive environment. As exposure time increases, it is observed that degradation happens more quickly in the early years followed by a gradually decreasing degradation rate of the fatigue strength in the following years.

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Keywords: Short crack modelling; fatigue strength; pitting corrosion; corrosion-fatigue

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1. Introduction

Pitting corrosion due to exposure to a marine environment is known to degrade the fatigue resistance of high-strength structural steels used in offshore structures. This can lead to a shorter service life of the structure. Accurate lifetime estimations require a fatigue assessment approach that includes the effect of corrosion pit evolution on the fatigue strength of steel. Experimental evidence on the fatigue behavior of pitted structural steel (Fatoba and Akid, 2022) has demonstrated that a considerable part of the fatigue life is consumed in the pit to short crack transition and short crack propagation regimes. This necessitates employing a short fatigue crack model which allows for taking into account the effect of material microstructure. Degraded fatigue strength due to pitting corrosion can be computed as an output of a such model. In that regard, fatigue strength is defined as the minimum applied stress amplitude required to have a propagating short fatigue crack.

Microstructurally short fatigue crack modelling approaches can be classified into three groups: empirical-based, mechanism-based, and discrete dislocation-based models (Christ et al., 2014). Although empirical-based models have shown to be simple and often yield a good agreement with experimental data, they do not include a physical explanation of the short crack growth. Mechanism-based models use the distribution of dislocations to model the short cracks. These models can be solved relatively simply and the results are more accurate than the previous group. The most physical explanation is offered by discrete dislocation-based models such as crystal plasticity. However, time-consuming and complex simulations make this modelling approach significantly less computationally efficient compared to the mechanism-based models (Hansson et al., 2008). To this end, a mechanism-based short crack propagation model, originally developed by Navarro and De los Rios (1988b) (NR model), has been implemented in this study to estimate the fatigue strength of pitted components. In the next step, available field data on the sharpness and size evolution of pits in a marine environment have been gathered and analyzed. Having this information, fatigue strength degradation with time of structural steel S355 in the North Sea environment is estimated.

Nomenclature

D	Average grain diameter
DDT	Distributed dislocation technique
E	Young's modulus
i	Grain number
K-T	Kitagawa-Takahashi
K_{th}	Threshold stress intensity factor amplitude
n	Normalized fatigue crack length
OWT	Offshore wind turbine
r_0	Barrier length
α	Pit depth
β	Pit half-width
ν	Poisson's ratio
σ	Remotely applied normal stress amplitude
σ_{FS}	Fatigue strength amplitude of intact material
σ_{FS}^{P}	Fatigue strength amplitude of pitted material
σ_{RS}^{i}	Minimum value of applied remote stress amplitude required to overcome the *i*th barrier in intact material
$\sigma_{RS}^{i,P}$	Minimum value of applied remote stress amplitude required to overcome the *i*th barrier in pitted material
σ_{BS}^{i}	Strength of the *i*th barrier
ψ^{i}	Solution given by the numerical method

2. Short fatigue crack propagation model

2.1. Model formulation

The NR model is a microstructural fracture mechanics model which takes into account the effectiveness of microstructural barriers (i.e. grain boundaries) to arrest short cracks during the early stages of growth. It uses the Kitagawa-Takahashi (K-T) diagram (Kitagawa and Takahashi, 1976) as an effective method to map the strength of each successive microstructural barrier and implicitly accounts for the effect of the environment on the resistance of the material to crack propagation. In this research, the material resistance to crack propagation in sea-water environment is represented using Vallellano's approximation of the K-T diagram (Vallellano et al., 2000). It uses the fatigue strength in air, long crack threshold stress intensity factor, and grain diameter as input parameters. The model is based on a 2D representation of a single pit (with a semi-elliptical cross-section) and on the assumption that the short crack emanates from the bottom of the pit along a straight line (Balbín et al., 2021), as illustrated in Fig. 1. α and β are the pit depth and the pit half-width, respectively, D is the average grain diameter, and σ is the remotely applied normal stress amplitude.

In the first step, starting as an initial crack with the size of half of a grain diameter, the crack propagates from the pit bottom along a straight line. Reaching the next grain boundary, if the remotely applied stress is large enough, it overcomes the barrier and continues to propagate through it. Otherwise, the crack gets arrested by the barrier until the remotely applied stress increases to the required value to overcome the barrier. Then the same process repeats for the crack in the next grain. The model represents the crack and the barriers using the distributed dislocation technique (DDT) (Hills et al., 1996).

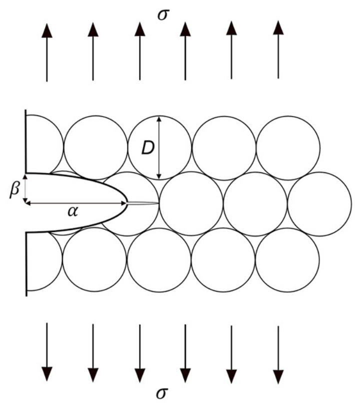

Fig. 1. Schematic of the pitted material and a crack emanating from the bottom of the pit through the material grains.

The model allows to relate the stress at the grain boundaries to the remotely applied stress amplitude (σ). Using the K-T diagram, the minimum value of applied remote stress amplitude required to overcome the ith barrier (σ^{i}_{RS}) can be obtained. Based hereon, the model is able to compute the strength of that barrier (σ^{i}_{BS}). This relation for the case of a crack in a semi-infinite medium is as follows (Balbín et al., 2021):

$$\sigma^{i}_{BS} = \frac{1.12}{\cos^{-1}(n)} \frac{\pi}{2} \sigma^{i}_{RS} \tag{1}$$

In which n is the normalized crack length defined as the ratio of the crack length to the length of the crack plus the barrier length (r_0). In the model, the microstructural barrier is a small region of length equal to the typical size of the grains interface. More details on the formulation of the model can be found in Navarro and De los Rios (1988b, 1988a, 1992).

2.2. Fatigue strength determination

When a crack overcomes the first grain boundary in an intact component (a component without a pit) subjected to a certain applied stress, it can propagate through all subsequent grains (Chaves and Navarro, 2009). As a result, the fatigue strength of a plain component is equal to the required remote stress for the crack to cross the first grain boundary ($\sigma_{FS}=\sigma^1_{RS}$).

However, when a crack emanates from a pit, the stress gradient generated by the stress concentration effect of the pit causes the crack to pass through the first few grains more easily. So, there remains the possibility of having a non-propagating crack once the crack crosses through the first few grains. Assuming the barrier strengths remain unchanged by introducing the pit, a relation can be established between the remote strength of each barrier in the non-pitted component (σ^i_{RS}) and the pitted component ($\sigma^{i,P}_{RS}$):

$$\sigma^{i,P}_{RS} = 1.12\frac{\pi}{4}\sqrt{\frac{iD}{r_0}}\frac{\sigma^i_{RS}}{\psi^i} \quad (2)$$

where ψ^i is a solution given by the numerical method. Fig. 2 schematically shows how the fatigue strength of microstructural barriers varies with crack length according to the NR model.

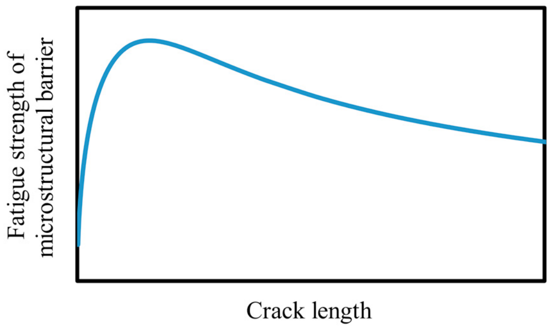

Fig. 2. Schematic curve showing how the fatigue strength of microstructural barriers varies as the crack propagates from the pit bottom.

Finally, the fatigue strength of a pitted component (σ^P_{FS}) can be obtained as the maximum computed fatigue strength of microstructural barriers (i.e. the maximum point in the chart shown in Fig. 2):

$$\sigma^P_{FS} = max\{\sigma^{i,P}_{RS}\} \quad (3)$$

Chaves and Navarro (2009) have explained the derivation of the formulation for evaluating the fatigue strength of pitted components in depth.

3. Material

The input material parameters in the NR model are the average grain diameter (D), the fatigue strength amplitude (σ_{FS}), the threshold stress intensity factor amplitude (K_{th}), Young's modulus (E), and Poisson's ratio (v).

The focus of this research is on offshore wind turbine (OWT) substructures, with structural steel S355 being the most commonly used material. The material properties for S355GS+10 steel provided by Anandavijayan et al. (2021) are employed as inputs to the model. Their material fatigue characterization tests are conducted in air with a load ratio of 0.1. Grain size of roughly 10 µm has been reported for S355 (Borko et al., 2018; Dzioba and Lipiec, 2016; Lehto et al., 2016). The key material characteristics used in the model are listed in Table 1.

Table 1. S355 material properties

Material parameter	Value
Threshold stress intensity factor amplitude (K_{th})	12 MPa$\sqrt{\text{m}}$
Fatigue strength amplitude at 10^7 cycles (σ_{FS})	200 MPa
Young's modulus (E)	210 GPa
Poisson's ratio (ν)	0.29
Average grain size (D)	10 μm

4. Results and discussion

4.1. Pit sharpness and size evolution in the marine environment

Available field data (Blekkenhorst et al., 1986) of maximum pit depth in structural steel coupons with different compositions exposed to North Sea conditions for 2.6, 4.0 and 7.2 years have been analyzed to determine the pit depth growth rate. The measured maximum pit depths for the steel with the composition that best resembles S355 steel are summarized in Table 2.

Table 2. Maximum pit depth growth rate in high strength low alloy steel exposed to the marine environment (Blekkenhorst et al., 1986)

Exposure time (years)	2.6	4.0	7.2	Maximum pit depth growth rate
Maximum pit depth (mm)	0.75	1.82	2.85	0.409 mm/year

A second set of data (Haute and Thibaux, 2022) on pit configuration and dimensions following 1.9 years of exposure of S355 steel coupons to the North Sea environment in the submerged condition is utilized to define a relation between pit depth and pit width. Fig. 3 shows the average measured pit widths corresponding to the various pit depths.

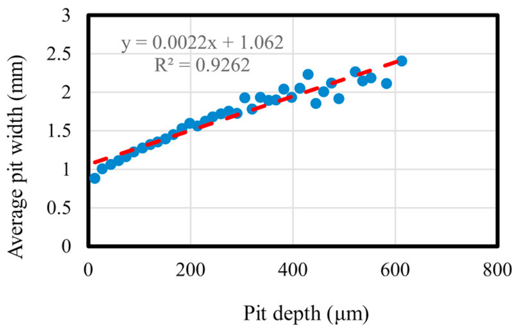

Fig. 3. Pit depth versus pit width measurements in S355 steel after being exposed to the marine environment for 1.9 years (Haute and Thibaux, 2022).

According to these data, the cross-section of the corrosion pits has, on average, a semi-elliptical shape with a maximum depth growth rate of 0.409 mm/year. As shown in Fig. 3, a linear trendline is fitted through the data points. The derived relation between the pit depth (α in mm) and width (2β in mm) is 2β=2.2α+1.062. This relation is used to extrapolate the measurements and estimate the pit width for longer exposure times.

4.2. Fatigue strength computation results

Having the pit configuration evolution during the exposure time to the sea environment and using the short crack model, the fatigue strength of microstructural barrier versus crack length curves for different exposure times (with the time step of half a year) is plotted in Fig. 4. As mentioned earlier, the maximum value for each curve shows the fatigue strength of the material considering the pit configuration at that specific exposure time. So, the line which goes through the maximum points is the fatigue strength line. This line shows the fatigue strength degradation of the material (i.e., the stress level below which there will possibly be no propagating crack) during the service time because of pitting corrosion. Fig. 5 shows the calculated decrease in fatigue strength of S355 steel due to corrosion pit evolution representative of the North Sea environment. It is observed that degradation occurs faster in the early years of exposure, with subsequent gradual decrease in the fatigue strength degradation rate. The fatigue strength reaches to around 45% of its initial value after around 7.5 years of exposure for the considered case.

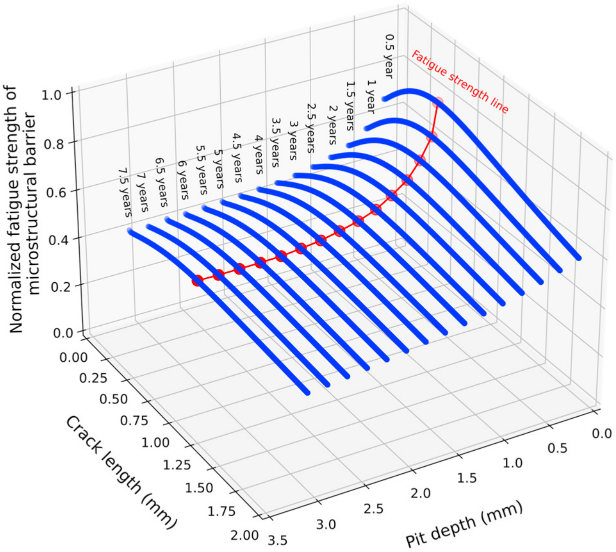

Fig. 4. Normalized fatigue strength of microstructural barrier versus crack length curves for various pit depths during the exposure period of the S355 steel to the sea environment – Modelling results.

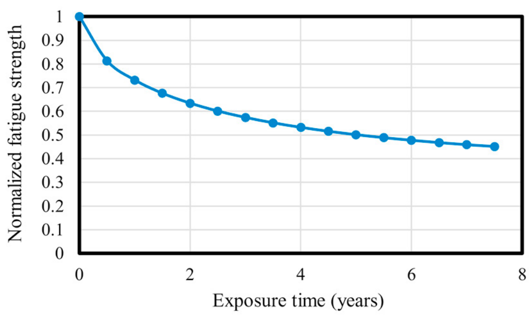

Fig. 5. Reduction in fatigue strength of structural steel S355 as the time of exposure to corrosive environment increases - Modelling results.

5. Conclusions

This paper studied the effect of pitting corrosion on the decrease in fatigue strength of structural steel, used in offshore wind turbine support structures, in terms of exposure time to the marine environment. The short fatigue crack propagation model estimates the fatigue strength of a pitted component as the minimum applied stress amplitude required to have a propagating crack emanating from the pit bottom. The pit shape is assumed to be semi-elliptical and the pit dimensions (pit depth and pit width) serve as input parameters to the model. Consequently, to be able to estimate the fatigue strength degradation over time, the corrosion pit configuration evolution is assessed using field data reported in the literature. According to the simulation results for 7.5 years of exposure of S355 steel to the North Sea environment, the normalized fatigue strength degradation rate is predicted to be almost 0.27 per year in the first year which decreases to around 0.02 per year in the last year.

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