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Numerical Simulation of Material Strength Deterioration due to Pitting Corrosion

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Abstract

Pitting corrosion is an insidious form of localized corrosion affecting characteristics of various engineering metallic alloys. Currently very limited literature exists with regard to systematic characterization of pitted surfaces or the efficient use of numerical methods to assess its effect, i.e. fatigue life reduction caused by the state of a corroded specimen and particularly through the study of stress concentrations considering the geometrical anomalies introduced to a surface. Much of the predictive analysis for corrosion is in fact derived from empirical means. This papers aims at exploring the use of numerical simulation to assess stress concentrating effects of pitting corrosion. Relevant parameters for characterization of pitting corrosion and its intensity are identified through literature review and preliminary simulations. 2-D and 3-D parametric models are subsequently created using stochastic parametric Finite Element Analysis, studying the effect of various randomized characteristics of pitting on the stress concentration factor.

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1. Introduction

Pitting corrosion is the most extreme form of localized corrosion characterized by the formation of pits that penetrate into the metal, resulting in local mass loss. It is considered one of the most significant degradation mechanisms in ageing structures, as fatigue cracks are observed to nucleate and propagate from these corrosion pits under sustained cyclic loading [1]. Pitting corrosion has been shown to reduce fatigue strength of the Al2024 alloy at 105 cycles by at least 40% [2]. Thus, in aircraft, offshore structures and other applications of high criticality or low tolerance of unwanted degradation, it is particularly useful to predict its effect on fatigue life and material strength.

Corrosion is a highly complex phenomenon which is yet to be sufficiently understood; it is difficult to predict the precise behavior of metals under corrosive environments. Much of the anti-corrosion measures adopted in practical applications, such as cathodic protection and anti-corrosion coatings, were in fact derived from experience and empirical evidence, rather than deterministic models [3].

Characterization allows understanding of corrosion mechanisms through relatively simplified mathematical models. By accounting for the physical and chemical interactions between the material and the environment, an appropriate characterization can be applied to model the corrosion behavior, however a deterministic characterization of put corroded surfaces is a non trivial task.

This paper aims to study the effect of pitting corrosion on the stress concentration factor (SCF) and examine its sensitivity to various parameters. The means for achieving this is a parametric numerical simulation using Finite Element Analysis (FEA) on material

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specimens affected by pitting. The numerical simulation is validated against an analytical method.

2. Fundamentals of pitting corrosion and fatigue design

2.1. Pitting corrosion

Pitting is often the most damaging form of corrosion due to the ability of these pits to perforate through the depth of the metal. These perforations result in reduced strength properties through means of increased stress concentrations at these locations, thus serving as critical locations for crack formation. Pitting begins by breakdown of the 'passivation' or oxide layers on the material. The breakdown of this layer is initiated by the presence of highly aggressive anions such as chloride ions. Pitting is considered to be an autocatalytic process; once it is initiated, it alters the local conditions to promote further pit growth.

Pit formation and propagation rate tends to depend on a combination of factors such as environment, alloy composition, temperature and material surface. Similar to pitting potentials, there appear to exist threshold temperatures below which pitting does not occur; likewise, higher temperatures tend to reduce the pitting potential threshold. Rougher surfaces are more susceptible to pitting and exhibit lower pitting potential; this is a result of having more occluded sites which can sustain the conditions for active dissolution.

Pit initiation is considered to be stochastic in nature; various statistical distributions are used to model pit growth at its various stages. At a simplified level, fatigue damage process due to pitting can be classified into seven stages - pitting initiation/nucleation, pit growth, transition to short crack, short crack growth, transition to long crack, long crack growth and fracture.

2.2. Fatigue life design

Fatigue is defined as a cyclic loading applied to a material below its yield strength. Failure of materials arising from fatigue is of significant concern in most engineering applications; over an estimated 80% of mechanical failures are caused by fatigue. Time-varying cyclic loading is typically represented in the form of the stress-time graph, which depicts the cycling of an applied nominal stress and its direction from one extreme value to another.

The study of fatigue can be generally classified into 'high-cycle' and 'low-cycle' fatigue cases; the former typically refers to cases with 10^4 to 10^7 cycles to failure, while the latter is associated with cases with lower than 10^4 cycles to failure. High-cycle fatigue is synonymous with the applied nominal stresses being predominantly in the elastic range of the material, whereas low-cycle fatigue cases exhibit a significant plastic deformation component.

For the assessment of fatigue, the following methods can be used:
- Nominal Stress-Life method
- Local Strain-Life method
- Fatigue-crack Growth method

The nominal stress-life (S-N) method is commonly used for analysis of high-cycle fatigue. It involves carrying out empirical tests to determine the nominal stress required to cause failure at a particular number of load cycles. The results of this test for various numbers of cycles are represented by the S-N curve, which is a plot of the stress range (or amplitude) against the corresponding number of cycles to failure for the specimen. Certain materials such as various steels also exhibit a stress below which they do not fail; this is termed as the 'fatigue limit' and is a key physical characteristic of such materials.

Fatigue life is affected by several factors which result in variations between different specimens of the same material. The effects of these factors on the fatigue limit of various steels are particularly well-documented and can be summarized to the following [4]:
- Component size
- The type of loading
- The effect of notches
- The effect of surface finish
- The effect of surface treatment

Discontinuities in materials interrupt the stress pattern in the specimen and tend to make it non-uniform, resulting in an increase in local stress level [5]. The theoretical stress concentration factor (SCF) K_t is defined as the ratio of maximum local stress σ_{max} to nominal stress σ_{nom}, where the latter is taken as a suitable reference stress value.

It is important to note that K_t is most relevant to ideal elastic materials under dynamic loading, and is purely dependent on geometry and load type.

3. Numerical simulations of pitting

3.1. Literature review

Eksi et al. [6] investigated the effect of corrosion pits on stress concentration factors in a solid Aluminum block through parametric analysis in ANSYS. 3D stress analysis was performed to determine the relation between the stress concentration factors and geometrical properties of the pits, namely aspect ratio (ratio of pit depth to diameter; or a/2c) and shape. The effect of secondary pits was also examined. 31 parametric models were created with varying pit aspect ratios and modelled as semi-elliptical perforations on the surface. A uniaxial tensile stress was applied to one end of the solid while the other was constrained. The SCF was calculated directly from σ_{max}/σ_0, where σ_0 is the applied stress. The principal stress was found to have a maximum value near the mouth of the pit, and a 'critical' band of highest stress values (with <= 1% variation) was found along the central vertical axis of the pit perpendicular to the applied load. It was found that for higher aspect ratios, the band becomes thinner towards the bottom of the pit. On the other hand, for very low aspect ratio pits, the band becomes very wide and dominates much of the pit surface area.

An earlier study discussed experimental and numerical estimation of strength and deformability of steel plates affected by various degrees of pitting intensity [7]. Using previously proposed probability models, corroded specimens were simulated both numerically and experimentally, and validated against empirical data. A periodic array of conical pits was simulated. Of particular interest is the study of various samples at different 'degrees of pitting' (ratio of the pitted surface area to whole/plate surface area). It was found that strength decreases moderately with increase in pit size, while deformability decreases considerably. Deformability was found to have a better correlation with surface roughness rather than maximum pit depth.

Yamamoto et al. [8] compared through non-linear FE simulations the reduction in tensile, compressive and bending strength of steel plates due to pitting corrosion in order to find the most detrimental mode of failure. Pits were assumed to be shaped as circular cones, commonly found in aged bulk carriers. It was found that the tensile mode is most vulnerable to pitting corrosion relative to compression or bending. The 'degree of pitting' parameter and its influence on equivalent specimen thickness was also evaluated; the reduction in equivalent thickness due to tensile loading was found to be greater than other load types.

Jata et al. [9] examined the effect of pitting corrosion on fatigue life of aluminum 7075-T6 alloy through both empirical and numerical fracture mechanical models. A spray corrosion test was used to obtain pit dimension measurements for various exposure time periods. Initial pit measurements were used as an initial crack size input for numerically predicting fatigue lives; the result was compared with the measured data obtained from empirical fatigue testing. The two methods were hence validated against each other as means of fatigue life prediction. The results indicated that pitting corrosion reduce fatigue lives by a factor of 6-8. It was found that the average pit depth measurement provides a closer correlation with fatigue life than maximum pit depth. Also of particular relevance is the observation that the effect of pitting on fatigue life can be related through equivalent stress concentration factors.

3.2. Methodology for analysis

This paper employs the Stress Concentration Factor (SCF) and basis of the Stress-Life approach to fatigue design in order to numerically simulate and evaluate the effect of corrosion pits on the surface of a metallic specimen. A simple 2-D plate of specified geometry and material properties was considered, with corrosion pits simulated as multiple notches on the surface.

The parametric inputs to this simulation and their values depend on the applied pitting characterization as identified by the literature review. The characterization applied was primarily based on physical parameters such as pit geometry and density. Using an appropriate combination of values for these parameters and considering them stochastically, pitting of various levels of severity could be simulated through iterative probabilistic simulations. This allowed a sensitivity analysis to be performed to determine the effect of various individual parameters which influenced the SCF. Finally, a full 3D probabilistic simulation was performed to simulate various intensity levels of pitting in order to determine the most influential parameters affecting SCF. Fig. 1 illustrates the flow chart of the methodology followed. The parametric model was created in the Simulia ABAQUS/CAE package.

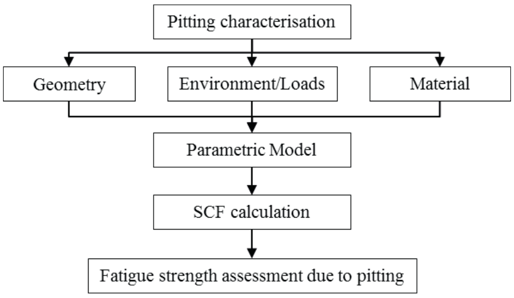

Fig. 1. Simulation methodology flow chart

3.3. Identification of parameters for parametric modelling

Based on the conducted literature review, it is imperative to lay out the assumptions invoked in selecting the parameters for the study:

- Corrosion pits are highly stochastic in nature, appearing in various shapes and sizes; pits will be treated as semi-ellipsoidal/elliptical or conical cracks on the material surface.
- A non-reversed fatigue load is assumed with R=0. A static load will be applied corresponding to the maximum load on the cycle; this load is also used as the nominal stress value.
- Material properties are assumed to be constant throughout the plate.

The geometrical parameters included in the parametric model are:

- Rectangular Plate dimensions: Length, Breadth
- Pitting characteristics: Pit shape, pit radius/ depth, number of pits, pit spacing
- Control parameters for randomization: limits on pit sizes and locations

Environmental/External Parameters:

- Load: Magnitude/direction of uniform pressure applied to side of plate
- Boundary Conditions: Fixed edges/constraints on the plate

Material Parameters:

- Elastic Modulus, Poisson's ratio

Simulation Parameters:

- Meshing: Seed size near pit and rest of plate, mesh element type (tri, quad, quad-dominated)
- Number of iterations/runs

3.4. Output of analysis

The primary objective of the simulations was to investigate the relationships between the SCF and input parameters. Hence, the following were decided upon as outputs to be saved for each iteration of the simulation:

- SCF: This is the key dependent variable to be examined. This was calculated as ratio of the Maximum Von Mises stress in the plate to the applied nominal stress.
- Number of pits (or pit density): This is a key measure of the 'intensity' or degree of pitting.
- Averaged and maximum aspect ratio: Provided the pit dimensions are randomized within each iteration, a 'characteristic' value of the aspect ratio is required for the iteration. This result can be thus plotted against the corresponding SCF value for the iteration.
- Averaged location of pit: Similar to the 'characteristic' aspect ratio calculation, such a parameter would be useful to determine the effect of pit location on the plate. This is calculated by averaging the polar coordinate vectors of all pits.
- Degree of pit collusion in the model: Collusion volume can be defined as the total volume shared between multiple pits. For this simulation, the 'degree' of collusion is defined as the ratio of the collusion volume to the total volume of all pits if there was no collusion.

4. Simulations Results and Discussion

4.1. 2D Simulations

Before working on a 3-D model, a parametric study of a 2-D plate with corrosion pits took place. The objective of this exercise was to test the soundness of the parametric model, and also serve as the basis for validation against an analytical method. Various cases were examined qualitatively with changes to the input parameters; this included large and small inter-pit spacing, pit aspect ratio (depth/diameter) conical and elliptical pits and pit density. Fig. 2 indicatively presents two of the cases that were considered.

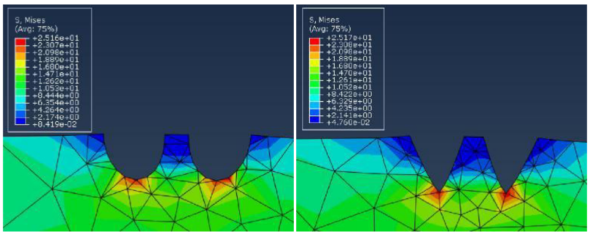

Fig. 2. Elliptical and conical pits with aspect ratio of 1.0.

The bottom of the pit was found to have the greatest stress concentration. Pits with higher aspect ratios were found to have a significantly higher SCF than those with lower aspect ratio pits of the same volume. This is in agreement with the results of [6]. Conical pits were found to have >20% higher SCF than hemispherical pits of the same size and aspect ratio due to their sharper geometries. For multiple pits, pit spacing also appeared to be a significant factor. Lower spacing between pits resulted in an increase in the SCF. However, when combined with the effect of collusion, the results were less clear. For cases with large number of pits, colluded pits had a smaller pit-concentrating effect than pits which were spaced at larger distances from each other.

4.2. 3D Simulations

Much of the simulations performed in 3-D (Fig. 3) were also based on randomised input parameters and thus were more rigorous. The parametric script was developed such that sequential iterations could be performed using the same set of randomised input variables. This type of probabilistic simulation, similar to a Monte Carlo simulation, was used to store the relevant SCF values from each iteration, from which the data could be consequently extracted for further analysis.

The results were similar to the 2-D simulation in that the bottom of the pits exhibited maximum localised stresses. The correlations between maximum SCF and parameters such as pit spacing and aspect ratio were also found to be similar.

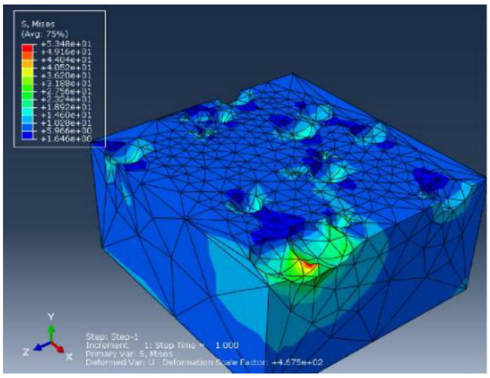

Fig. 3. 3-D simulation of pitted plate with randomized pit distribution and dimensions.

Before progressing to probabilistic simulations of highly randomised and complex cases of pitting, the effect and sensitivity of individual parameters on SCF was studied. In most cases, it was ensured that the number of iterations performed were more than 40 in order to gather sufficient data.

In a realistic scenario, pitting can occur randomly across a vulnerable specimen surface. Thus, before a full-scale randomised simulation can be performed, it is important to check the significance of pit location alone on SCF so that the interactions between the geometrical variation due to the pit with the boundaries of the plate can be identified. Fig. 4 presents the results of a simulation wherein each iteration created a single pit in a different location, sequentially following a circular pattern of a fixed radius. Considering the centre of the plate as a reference point for a polar coordinate system, this simulation thus shows the effect of varying the polar angle coordinate on SCF whilst the polar distance remains constant.

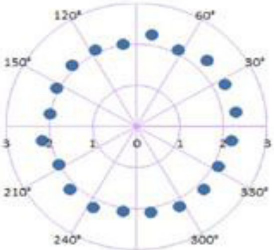

Fig. 4. Effect of pit location on SCF

The aspect ratio of the 3-D pit was found to be highly significant in cases with a single pit. As depicted in Fig. 5, the SCF shows a linear trend in relation to the aspect ratio. Beyond an aspect ratio of 6.0, there appears to a slight decline in the trend-line gradient. However, it is noteworthy that such high SCF values do not correspond to realistic cases, which typically do not involve SCF values of more than 20 [10].

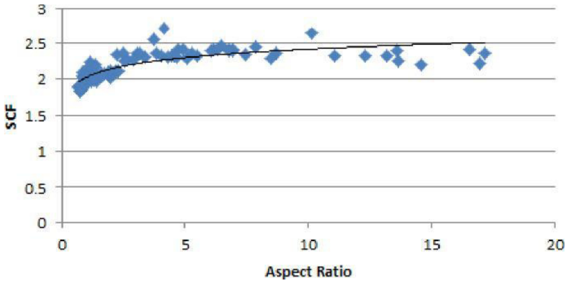

Fig. 5. SCF vs Aspect Ratio for single pit

Pit volume may be defined as the volume occupied by pits in a plate, or the volume of material lost by the plate due to pitting. This parameter was studied both in the cases of a single pit and multiple pits. The results of a single pit case are shown in Fig. 6. In this simulation, the pit aspect ratio and location were held constant while different values of pit volume were analyzed. The results show there exists little variation of SCF with different pit volumes; the SCF remains relatively steady at around 2.3 for most pit volumes. However, at higher pit volumes between 1.2-1.5, the SCF values seem to jump above 2.5. The higher values seem to correspond to pit depths >27% of the plate thickness, as depicted in Fig. 7.

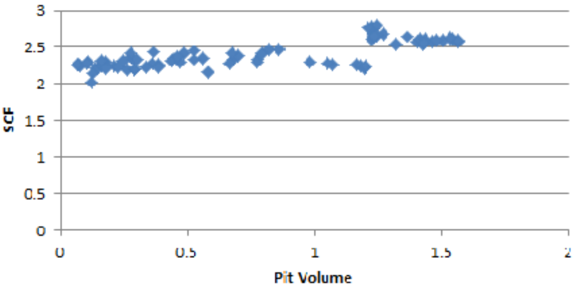

Fig. 6. SCF vs changing pit volume

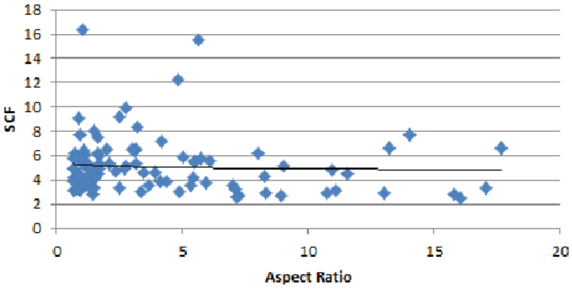

Fig. 7. SCF vs AR for 20 pits.

Simulations were performed with collusion allowed, per-pit volume constrained to a fixed value. Thus, the key variables used for these simulations were the number of pits and their distribution on the plate. The results show that with an increase in pit density, the trendline for the SCF becomes more ambiguous. While the case for 2 pits shows a clear trendline in the SCF, the number of anomalous points lying well outside the trendline increases with pit density; this can be due to collusion between pits. An example of this is shown in Fig. 8.

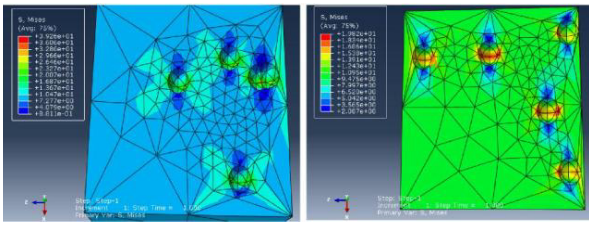

Fig. 8. Comparison of high (left) and low (right) SCF cases for 5 low aspect ratio pits

Pitting severity can be characterised by both the total pitted volume and number of pits. An increase in these values can be considered an increase in pitting intensity. Probabilistic simulations were conducted wherein considering all important parameters - including pit aspect ratios, volumes, pitting density were randomised, unlike in previous simulations wherein certain parameters were fixed to conduct sensitivity tests. Due to the significant impact of collusion, the simulations were conducted separately for both collusion and non-collusion cases. Fig. 9 shows the distribution of SCF relative to pit numbers.

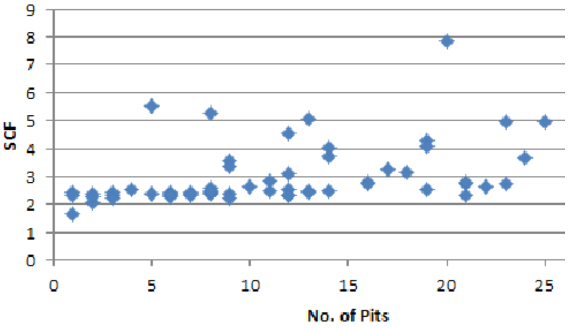

Fig. 9. SCF relative to pit numbers

5. Model Validation

The numerical approach used in this study was validated analytically; an acceptable correlation can be deduced by comparing a basic FE model with a suitable analytical case. The analytical formula used in this case is that for an infinitesimally thin 2-D plate with a notch subjected to a tensile load through the central axis of the plate [10].

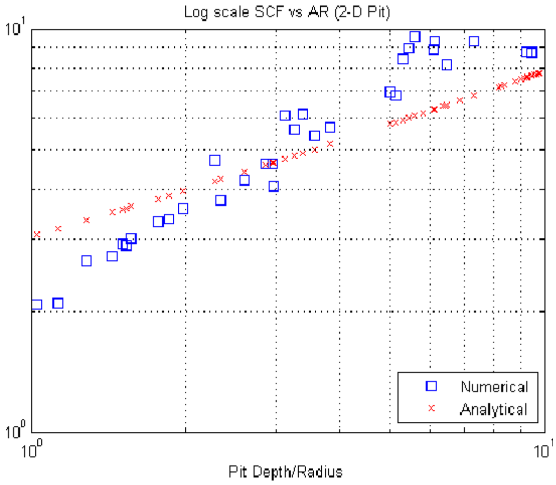

Fig. 10. Comparing the analytical plot with results obtained from a 2-D numerical analysis

In Fig. 10 the corresponding result from a 2-D simulation alongside the plot obtained from the analytical formula is shown. It can be seen that the numerical result also follows a roughly linear trend in the logarithmic scale. Comparing the numerical and analytical datasets, the two are markedly different in their gradients and points of intersection with the Y-axis. However it can be noted that they appear to follow an acceptably similar trend.

6. Conclusion

This paper has presented a validation of FEA-based methods for corrosion characterization and assessment based on the stress concentration approach through a series of deterministic and stochastic simulations. Surface conditions of a specimen were found to play a very important role in determining its fatigue life. From a stress concentration perspective, geometry and relative distribution of corrosion pits plays the most important role in affecting the strength of a specimen, while collusion of pits adds several layers of complexity to any pitting corrosion simulation. Expansion of this work can consider non normal distributions for the pit dimensions as suggested in relevant literature. Additionally, time-dependent simulation can be introduced to the parametric model, which is also a highly important parameter in the study of corrosion as well as check additional measures of pitting intensity such as the total pitted surface area.

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