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Probabilistic assessment of creep-fatigue crack propagation in austenitic stainless steel cracked plates

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ABSTRACT

This study investigates the effects of uncertainties in the prediction of creep-fatigue crack propagation in 316L(N) austenitic stainless steel plates containing a semi-elliptical surface defect. Different parameters in geometry, material behavior and test condition are considered as random variables in probabilistic assessments. Monte-Carlo sampling method is employed to estimate the probability distribution of desired outputs such as propagated crack sizes, stress intensity factors and creep rupture life. It is shown that, the standard deviation of the predicted crack sizes in both through-wall direction and along the surface of the plate will be increased by increasing the time (hence the crack size). It is observed also that, the uncertainty in the prediction of the half-surface crack lengths, c_i, is significantly more than that of crack depths, a_i. Furthermore, probabilistic evaluations are performed using different reliability methods to calculate the probabilities of exceedance of available experimental results. These evaluations clarified the importance of consideration of uncertainties in creep-fatigue crack growth prediction. Sensitivity analyses are carried out to provide useful information about the order of importance of random variables associated to the different limit state functions. It is found that, the CoV (Coefficient of Variation) of the initial crack size, a_0 and c_0/a_0 has a significant role on the importance of these parameters; and therefore they may be important random variables in such probabilistic assessments, based on their CoV and defined limit state functions.

1. Introduction

For defective components, which operate under the combination of static and cyclic loading at elevated temperatures, an assessment of creep-fatigue crack growth may be necessary in order to demonstrate the integrity of these components. Various deterministic studies carried out to investigate the behavior of creep-fatigue crack propagation [1–6]. Li et al. [1] employed the Cohesive Zone Model (CZM) to numerically simulate the crack growth. A trinomial superposition model has been proposed by Liu et al. [2] to predict creep-fatigue crack growth rates. Mehmanparast et al. analyzed the creep and creep-fatigue crack growth results for a range of steels taken from the HIDA collaborative project, and identified the interactive creep-fatigue behavior of these steels. They used ASTM E2760-10 creep-fatigue crack growth testing standard, as guideline to analyze the results [3]. A presentation has been published by Nikbin [4] about testing, modeling and component life assessment of welds under creep-fatigue crack growth condition. Saxena [5] presented the progress made in the field of time-dependent fracture mechanics. A creep-fatigue interaction

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damage model has been proposed by Xu et al. [6] in order to evaluate damage evolution and crack growth behavior in creep-fatigue regime. Although these studies provide valuable information, they do not address the issue of the effect of uncertainties on the response of defective components. In reality, there are different sources of uncertainty in the areas of "material behavior", "operating (test) conditions", "geometry parameters", "evaluation models" and "inspection methods and data", which considering them in probabilistic assessments leads to a more comprehensive understanding of the remaining life of a cracked component.

Probabilistic investigations and reliability analysis of creep-fatigue behavior, have been performed by other researchers on either crack initiation (damage accumulation) or crack growth. Mao and Mahadevan [7] proposed a probabilistic approach for creep-fatigue reliability analysis, which consists of a failure function that models the effects of creep-fatigue interaction without symmetry assumptions. Uncertainties in creep and fatigue life, creep and fatigue loading cycles, and limitation of test data are included in this study. A method has been outlined by Harlow and Delph [8] in order to incorporate the scatter bands in fatigue cycles-to-failure and creep rupture times-to-failure into a probabilistic creep-fatigue failure model. Their study has been conducted in the context of the well-known damage fraction summation rule for creep and fatigue damage. Probabilistic life models have been derived by Ibisoglu and Modarres [9] based on the creep rupture behavior of 316FR austenitic stainless steel. A standard Bayesian regression approach was used to estimate the parameters of the proposed creep-fatigue model. Hu et al. [10] conducted experimental study on a nickel-based super alloy in order to investigate the effects of dwell times on the creep-fatigue behavior. Also, they established a probabilistic model based on the applied mechanical work density (AMWD) method, to describe the scattering in creep-fatigue life-times.

Relatively few studies performed on statistical and probabilistic assessment of creep-fatigue crack growth. A study reported by Dogan et al. [11] has been focused on the life assessment approaches and the sources of scatter in creep-fatigue crack growth data. Different sources of scatter due to test equipment, testing procedures, data analysis method and creep-fatigue interaction, are explained in this work. Furthermore, they describe sensitivity analysis of high-temperature crack growth data, including probabilistic and deterministic methods. Probabilistic analysis of crack growth, based on the damage accumulation mechanisms have been done in the research of Wei et al. [12]. In this paper, a deterministic creep-fatigue accumulation model has been developed, and Monte-Carlo simulation method is used to investigate the probabilistic behavior of the derived deterministic model. In the study performed by Wei et al. [13], a linear superposition theory is proposed to model the creep-fatigue-oxidation crack growth. Monte-Carlo simulation has been implemented into creep-fatigue-oxidation model, by introducing the uncertainties of parameters in creep, fatigue and oxidation crack growth laws.

Several experimental and deterministic investigations have been carried out to describe the behavior of semi-elliptical defect in austenitic stainless steel plates subjected to creep-fatigue loading condition [14–20]. Although, deterministic studies provide worthy information about the creep-fatigue crack propagation in the cracked plates, they do not address the effects of the indeterminacy of the various input parameters, on the prediction of creep-fatigue crack growth. The present study evaluates the probabilistic behavior of such specimens, considering the sources of uncertainty in "test condition", "material behavior", and "geometry parameters". The areas covered in this study are as follows:

I. *Estimation of probability distribution of the results:* in this phase, Monte-Carlo sampling method has been applied in order to estimate the probability distribution of desired outputs, i.e. propagated crack sizes, initial and final stress intensity factors, and creep rupture life.
II. *Calculation of probabilities of exceedance of experimental results:* in the second phase, probabilistic assessments have been performed in conjunction with experimental results [20] utilizing different reliability methods (e.g. FORM, Sampling, etc.). Assessments have been carried out with two aims: first, for understanding the influence of uncertainties on the creep-fatigue crack growth prediction, in comparison with available experimental data; and second, for investigating the importance of random variables corresponding to each of the defined limit state functions.
III. *Sensitivity analysis:* in the last phase, the order of importance of the random variables corresponds to the different limit state functions have been extracted as a by-product of the previously performed FORM analysis. The γ importance vector has been used to investigate the relative importance of the random variables.

2. Deterministic assessment

Probabilistic investigations in present study have been implemented on a benchmark problem, which its experimental background is reported by Poussard and Moulin [20] (see Section 2.1). It should be noted that deterministic calculations are at the heart of the probabilistic assessments. The deterministic approach used in the present study for prediction of the creep-fatigue crack propagation of the benchmark problem, is adapted from the procedures employed by Baker et al. [14], based on the R5, Volume 4/5 procedure [21] (see Section 2.2).

2.1. Overview of experiment

The benchmark problem consists of a 316 L(N) austenitic stainless steel plate containing a semi-elliptical surface crack, subjected to a set of fatigue and creep-fatigue loadings at 650 °C [20]. Plate geometry, test configuration, and location of the defect are shown in Fig. 1. The plate has a thickness of $t = 24.5$ mm, and a width of $w = 350$ mm, loaded through an arm with a length of $l = 350$ mm. Initial surface crack of depth, $a_0 = 7.9$ mm and width, $2c_0 = 87.2$ mm, is achieved after high temperature fatigue pre-cracking (Fig. 2).

Loading conditions, along with the experimental results are summarized in Table 1. Creep-fatigue cycles consist of a dwell of one