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Study on life and path of fatigue cracks in multiple site damage plates

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ABSTRACT

This paper presents experimental and numerical study of the fatigue crack growth of hollowed pre-notched plates with multiple site damages (MSD). The numerical analyses were performed using finite element method. Experiments were carried out to validate the numerical results. Fatigue tests of aluminum sheets with MSD cracks were conducted to evaluate the effects of some parameters such as the thickness, hole diameter and central distance of the holes. The results show that the distance of the holes has greatest and size of the hole has little effects on the fatigue lives. Nucleation of cracks strongly depends on the thickness, distance and hole size.

1. Introduction

The Aloha accident in 1988 attracted the attention of the fracture mechanics research community to issue of multiple site damage (MSD) phenomenon. MSD is a typical problem for ageing aircraft, starting when the fuselage pressure cycling fatigue loads lead to crack initiation and propagation at multiple riveted locations. When a critical situation is reached, MSD cracks may interact and sudden cracks link-up may occur which reducing the overall structural integrity of the structure [1]. Structural components are generally subjected to a wide stress spectrums over their lifetime. Service loads are accentuated at the areas of stress concentration, mainly at the connections of components. When there is a critical level of MSD at connections, the cracks link up to form a larger crack which abruptly reduces the residual strength of the damaged member. Therefore, it is important to estimate the fatigue life before the cracks link up due to critical MSD [2]. In order to assess the crack link-up with a leading crack which interacting with one or more MSD cracks, experimental tests have been performed on flat panels [1].

Dawicke and Newman developed a method to calculate the stress intensity factor for multiple interacting cracks [3]. This technique was implemented in the fatigue crack growth study of MSD in a riveted flat plate. Pyo et al. used an extended formulation of *J*-integral to predict the stable fatigue crack growth of lead crack in the presence of MSD cracks [4]. Combination of the finite element results for uncracked elastic material and analytical solution for multiple cracks was used to study the residual strength reduction of a material with MSD cracks. Fatigue lives of unstiffened aluminum plates with MSD cracks were predicted by using the numerical and experimental methods [5]. Cracks initiation, interaction and coalescence were considered in this study. Combination of strain-life method, Neuber's and Miner's rules provide a good estimation of crack initiation around the hole in a panel contain MSD.

Cherry et al. investigated the residual strength of unstiffened aluminum panels containing MSD and by using five different failure criteria, they predicted the residual strength (failure load) for different specimen geometry [6]. Wang et al. studied the residual strength of an aircraft fuselage with MSD [7]. They simulated full scale fuselage panels using the elastic–plastic finite element method and investigated the effects of the interactions between multiple lead cracks in the panels with MSD cracks. Their results show a noticeable reduction in the residual strength by considering the MSD cracks. Pidaparti and Palakal used an optimization-based neural network method to predicting the crack growth and fatigue lives of MSD panels in aging aircraft [8]. Optimization solutions were applied to calculation of the cracks path based on the initial configuration of panels and cracks. Interactive effects of crack tip plastic zones for adjacent cracks in collinear symmetric MSD were studied by Kuang and Chen [9]. They showed that the calculation of the plastic zone by using Dugdale method and considering the interactivity give numerical results which have good consistency with experiments. Jones et al. used simplistic specimen of unreinforced lap joints to study the MSD behavior of pressurized fuselage lap joints [10]. The obtained results on the crack growth rates were consistent with fleet data. They proposed using thermal emission

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techniques for optimizing the fastener patterns of mechanical repairs in aging fuselages.

The fatigue loading of MSD cracks in the mechanical joints shows that the variations of the stresses and strains at the critical locations of the joint may reach a saturated linear state depending on the sequence and level of loads [11]. Here, the behavior of stress–strain may be linear after initial plastic yield with the stress concentration range smaller than the elastic value. Silva et al. done fatigue tests on the riveted lap-joints under the constant amplitude load [12]. Test results of the initiation and growth of cracks and residual static strength were used to assess the predictive model based on the finite element method. Galatolo and Nilsson investigated the residual strength reduction of a butt-joint panel with MSD by experimental and computational methods [13]. An adaptive multi-modal importance sampling technique has been developed for efficiency and accuracy in probabilistic life estimation under the MSD due to corrosion fatigue [14]. Jones et al. demonstrated that the crack growth from edge of a hole in riveted fuselage lap joint reveals a near linear relationship between the logarithm of distance of crack tip from hole center versus the number of load cycle. This relation is consistent with simple test specimens as well as with real fuselage lap joint tests [15].

Labeas developed a link-up criterion for the MSD cracks by using magnitude of the strain energy increasing during the fracture process of the ligament between two adjacent cracks [16]. In other paper, Labeas and Diamantakos proposed an analytical method for predicting the condition of coalescence of the interacting cracks and estimation of the residual strength under MSD situations [17]. Kebir et al. developed a simplified quasi 2D stress analysis, using the boundary element method to evaluate the stress intensity factors for through cracks emanating from holes in several double shear lap joint configurations [18].

Quantitative risk assessment based on the accurate modelling of fracture mechanics of the MSD cracks is necessary for evaluation of structural integrity of most components [19]. These simplified methods use analytical and numerical methods such as finite element for calculation of mechanical and fracture parameters. Wu and Xu presented an analytical method based on the Dugdale strip yield model for MSD problems by using the weight function method [20]. The MSD problems are usually analyzed by using numerical methods rather than the theoretical ones because of the complicated interactions between multiple cracks [2]. Newman Jr. and Ramakrishnan demonstrated that the fatigue life prediction methods based on the fatigue crack growth alone can be used adequately to calculating the life of the fuselage riveted lap joints [21].

This article describes a procedure for predicting the fatigue crack growth, interaction effects of MSD cracks and fatigue lives through the study of a simplified scenario. Experimental tests were conducted to evaluate the accuracy of the numerical results for predicting the fatigue lives of the panels with MSD cracks. In continue, we performed fracture experiments for the crack propagation rate and path in these specimens. The validity of the analysis for the crack path of multiple site damage could be identified by comparison with the experiments.

2. Experimental setup

A testing program was conducted to evaluate the accuracy of numerical results in predicting the fatigue lives of the panels with MSD cracks. The experimental investigations were performed with the different types of specimens in order to study the effects of the various parameters. The 8 series of specimens were tested. Samples were made by aluminum with height and width, respectively as 200 mm and 50 mm and thickness as 1.0 or 2.0 mm. The sheets were analyzed using direct-reading spectrometer device. Chemical compositions of these alloys are indicated in Table 1. Based on the standard of BS EN 573-3:2013, these alloys can be considered as AA5050-H34 and AA5052-H32.

Stress–strain curves of these alloys were determined by using universal tensile tests based on ASTM-E8 and illustrated in Fig. 1. Mechanical properties are also depicted in Table 2.

Specimens had different size of holes, distances between the holes, alloy types and thickness values. Details are illustrated in Table 3. Cracks were created by spark method using copper electrodes in desired length and direction as displaced in Fig. 2, for instance. Maximum radius of induced crack tips were 0.15 mm.

Fatigue tests were conducted by using Instron-8502 servo-hydraulic test machine as shown in Fig. 3. Constant amplitude loads with the stress ratio of 0.01 were applied. Maximum values of the applied loads were chose in a way that the tensile average stress in the net cross section area on the cracks line becomes 100 MPa. The loading frequency was 15 Hz.

3. FEM modeling of the fatigue crack growth

We used the franc2d software for calculation of fracture parameters. The FEM modeling and meshing were done in casca program. These free softwares are developed by Cornell Fracture Group at Cornell University. The model was imported to franc2d environment and pre-cracks were created. Specimens with multiple cracks were clamped at upper edge and tensile stresses applied at bottom edge. It must be noted that this conditions are only for prepared samples. For real structures such as riveted fuselage with MSD cracks, the rivets location is usually stiffened and also have a proper fastener so axial loads and sometimes bindings are supplied by rivets on the plates.

The stress intensity factors were extracted versus crack length (a) for all cracks. The SIFs can be obtained by using three methods: displacement correlation technique, modified crack closure and J-integral method. We used the J-integral method, although its results had not considerable difference with displacement correlation results due to fine meshing the crack tip regions.

Variation of the cracks length versus number of load cycles were determined by using the Paris model. The FEM model of sample 4-10-1 with fine elements in the near of crack tips is depicted in Fig. 4. In this sample, initial FEM model (without cracks) has 1706 nodes and 516 8-node biquadratic plane elements. Each crack was induced in the model with fine 6-node triangular elements along its length and 8 elements around the tip.

4. Experimental data and numerical results

In this section, we compare the experimental data with the results of the numerical analyses.

During the last five decades, numerous mathematical models for predicting the fatigue crack growth have been proposed and most of them validated by referencing to some experimental results. Under the conditions of linear-elastic fracture, the most widely used and recognized empirical law is the classical Paris model [22]. This model is chosen as a starting point to developing a simulation model for the structural damages or cracks growth. This model relates the rate of change of crack size (length), da/dN to stress intensity factor (SIF) range, ΔK in the following form:

$$da/dN = C(\Delta K)^m \quad (1)$$

where C and m are material constants. The stress intensity factor range is calculated as