FATIGUE LIFE PREDICTION OF EDGE CRACKED ALUMINUM PANEL: XFEM AND DIC

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ABSTRACT

Extended finite element method (XFEM) is a special kind of numerical method which enables the approximation of non-smooth solutions such as jumps, kinks, singularities or general high gradients with optimal accuracy. Since the crack possesses both singularity and jump, XFEM is indispensable for modeling crack. In the present work, we investigate the crack growth rate of straight and inclined edge crack in Aluminum plate, subjected to constant amplitude cyclic loading, both numerically using XFEM and experimentally through digital image correlation (DIC). Camera triggering controller is used to correlate between DIC images and the number of loading cycles. Commercially available software ABAQUS 6.9 with inbuilt XFEM is used for numerical analysis. The life estimated using XFEM is showing a maximum of 4% deviation from the experimental result.

Keywords—*Aluminum panel, Digital Image Correlation, Edge crack, Extended Finite Element Method, Fatigue life*

I. INTRODUCTION

Fatigue is one of the primary damage mechanisms of structural components. Fatigue failure results from cyclic stresses that are well below the yield stress of the material. The fatigue life of a cracked component can be expressed as the number of loading cycles required for the crack to propagate to the critical size. Fatigue failure occurs in three stages: crack initiation; slow and stable crack growth; and rapid fracture. Fatigue lifing for the structural components are generally ignored if the stress level is very high or the critical flaw size is too small. In all other cases the crack growth life will be substantial portion of the total life of the component and hence fatigue lifing should be duely considered. In a cracked structure, due to application of repeated loads this crack grows with time. The residual strength of the structure decreases progressively with increasing crack length and eventually goes below the designed service load [1] rendering the component unusable for the intended service. Hence the life estimation of crack under fatigue loading has a key role in designing of structural components

There are two major aspects in crack growth: crack growth direction and crack growth rate. Various criteria for the crack growth direction have been proposed. Some of them are Maximum tangential stress criteria (MTS) [2], strain energy density criteria [3, 4], dilatational strain energy density criterion [5], vector crack tip displacement (CTD) criterion [6], tangential stress factor and tangential strain factor and maximum tangential strain criteria [7]. Among all these, MTS criterion is widely used and we are using it in our work. The application of this criterion can be found from the works by several authors [8, 9]. Secondly, to correlate fatigue crack growth rates under mixed mode loading Tanaka et al. [10] used a Paris type equation as a function of an effective stress intensity factor.

Similarly, many experimental methods are in use for monitoring crack growth behavior. ASTM E647 [11] suggests two methods for measuring crack length. Compliance gauge method and electrical potential difference method. The compliance gauges are only useful for the straight cracks. Ali Kha Soh et al. [12] used crack micro-gauge to monitor crack growth during the test. All the above methods uses electrical signals and need gauges to be attached with the specimen. Borrego et al. [13] used traveling microscopes to measure crack length. All the above setups are tedious to handle and requires frequent stoppages in fatigue tests to monitor crack growth at regular intervals. Hence we make use of Digital image correlations (DIC) to monitor the crack growth. In DIC the objects in subset windows are compared before and after the deformation to get displacement field.

Finite element method (FEM) is widely used for fracture problems from several decades even though some numerical difficulties are present. To list a few, to represent the crack tip singularity, re-meshing with the advancing crack, crack branching and etc. are the common difficulties with the Galerkin finite element methods. Mesh refinement is usually necessary near the crack tips in order to represent the asymptotic fields associated with the crack tips. And for propagating crack re-meshing is necessary. Using XFEM the above mentioned problems can be avoided. The extended finite element (XFEM) is a special kind of numerical method to handle discontinuities and singularities [14]. In XFEM the standard displacement based approximations is enriched near a crack by incorporating both discontinuous fields and the near tip asymptotic fields through a partition of unity method. XFEM allows the entire crack to be represented independent of the mesh.

Giner et al [15] implemented XFEM through user subroutines in ABAQUS and evaluated SIFs for several cracked specimen configurations. I V Singh et al. [16] evaluated the fatigue life of homogeneous plate containing multiple discontinuities (holes, minor cracks and inclusions) by using extended finite element method (XFEM). In this paper we are investigating crack growth and life of edge cracked Aluminum specimens using XFEM and comparing it with the experimental results which is obtained using digital images.

II. MATERIALS AND SPECIMEN PREPARATION

Experiments are conducted on the test specimens machined from 3 mm thick sheets of Al 2014-T6. Its materials properties and Paris law coefficients are obtained from the Ref. [17] and are listed out in the Table 1 and Table 2 respectively. Two configurations of crack are considered in the present study they are as follows:

1) Side Edge Notched specimen (SEN)
2) Edge Slant Cracked specimen (ESC)

SEN and ESC specimens represents mode 1 and mixed mode crack growth behavior respectively. These specimens were obtained using wire cut EDM for creating initial crack. The dimensions of the SEN and ESC specimens used in our study is shown in the Fig 1.

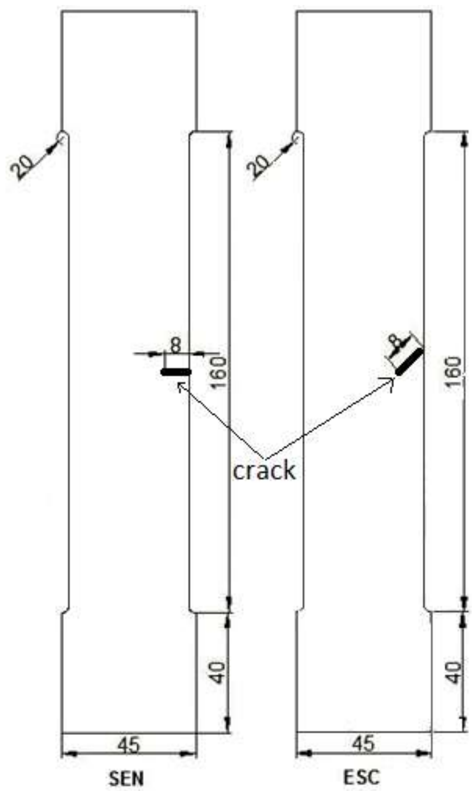

Figure 1: Specimen Dimensions

The surface of the specimens is prepared for DIC experiments by coating it with thin layer of white acrylic paint and over it sprayed with carbon black paint using an airbrush to obtain a random black-and white speckle pattern.

Table 1: Material properties of Al 2014-T6

Property	Value
Young's Modulus, GPa	73.1
Poisson's Ratio	0.33

Table 2: Paris law constants of Al 2014-T6

Property	Value
C, $mm/(cycle*MPa\sqrt{mm})$	5.57e-13
M	3.37

III. CRACK MONITORING: DIC SETUP

DIC is established in the field of experimental mechanics as an effective and flexible tool for the full field measurement of shape and deformation. It offers range of advantages over the other experimental techniques such as simple optical set up, ease of specimen preparation, relatively less stringent requirements on measurement conditions and wide range of sensitivity of measurement. Fig. 2 shows the typical 2D DIC experimental setup. The hardware for the optical setup of 2D-DIC system comprises a CCD camera (of 2448*2048 spatial resolution with 8 bit intensity resolution and frame rate of 15 fps), Tamron lens with 180mm focal length, a portable computer system with image acquisition card and LED lighting to ensure adequate image contrast. All the experiments are performed using a computer-controlled MTS Landmark® servo-hydraulic cyclic testing machine of 100 KN capacity with a computer data acquisition system. Self-adjusting hydraulic test fixtures are used to grip the specimens.

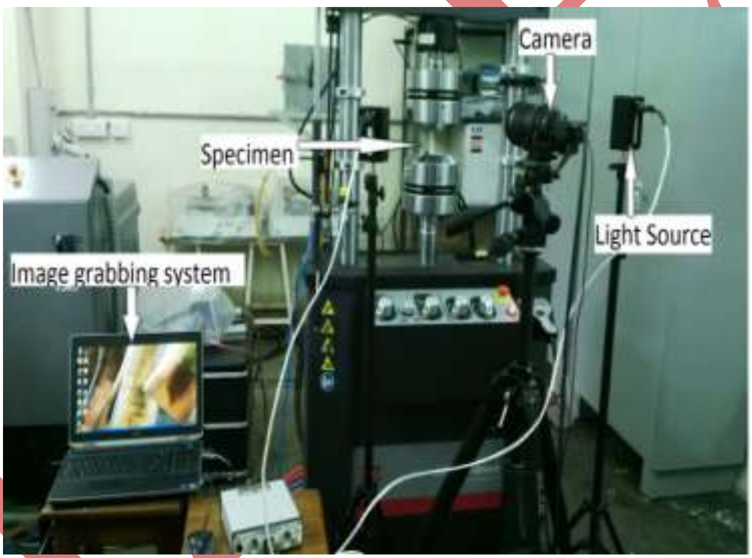

Figure 2: Experimental Setup

In order to get exact correlation between the images and number of cycle, a camera triggering controller is used to trigger the camera in equal intervals of cycles at specified phase angles. In the present analysis the images were captured at every twenty cycles at 90 degree phase angle. While grabbing the images the output from the load cell is synchronized with image for obtaining the number of cycles using data acquisition system. The reference image is calibrated for a known distance to get coordinates of pixels' in mm. This capability of image correlation is used for obtaining the crack advancement distance from the crack tip. Post processing of the captured images are done using VIC-2D 2010 software acquired from Correlated Solutions. Region of interest (ROI) is selected and the subset sizes are chosen as 35x35 and a step size of 5 is taken. The x and y coordinate plots are used for measuring crack length and propagation angle. The crack length and the propagation direction is calculated using Eqs.1 and 2 respectively.

$$\Delta a = \sqrt{(x_{ci} - x_c)^2 + (y_{ci} - y_c)^2} \quad \textbf{(1)}$$

$$\theta = \arctan\frac{y_c - y_{ci}}{x_c - x_{ci}} \quad \textbf{(2)}$$

Where

Θ is crack propagation direction

x_{ci} and y_{ci} are the coordinates of the initial crack tip

x_c and y_c are the current tip coordinates

IV. FATIGUE CRACK GROWTH: NUMERICAL MODELING

In the present work, the fatigue crack growth simulations are performed in ABAQUS 6.9 with inbuilt XFEM module. As discussed earlier in introduction (see Sec. 1) crack growth direction and crack growth rate are key aspects even in fatigue crack growth. Crack tip characteristic parameter that is stress intensity factor dictates the crack growth phenomenon. We obtain the stress intensity factor using J-integrals numerically through FEA simulations in ABAQUS.

The direction of crack propagation is established to be a function of the mixed-mode stress intensity factor at the crack tip. Maximum tangential stress criterion [2] is adopted to calculate the crack propagation direction. In this criterion, the deflection angle of crack growth defined to be perpendicular to the maximum tangential stress at the crack tip. The crack propagation angle Θ is given by the Eq. 3. Where the crack propagation angle Θ is measured with respect to the crack plane Θ=0 which represents the crack propagation in the straight-ahead direction. The direction of crack propagation is taken according to sign of K_2. If $K_2<0$ crack propagation angle Θ is taken as positive and vice versa.

$$\theta = \arccos\left(\frac{3K_2^2 + \sqrt{K_1^4 + 8K_1^2 + K_2^2}}{K_1^2 + 9K_2^2}\right) \quad \textbf{(3)}$$

Where K_1 and K_2 are mode 1 and mode 2 stress intensity factors respectively.

For mixed mode crack growth problems we use equivalent mode 1 SIF for the life calculations. Tanank et al [10] proposed a relationship for the equivalent SIF based on curve fitting data.

$$\Delta K_{eq} = \sqrt[4]{\Delta K_1^4 + 8\Delta K_2^4} \quad \textbf{(4)}$$

Where

$$\Delta K_1 = K_{1\max} - K_{1\min}$$

$$\Delta K_2 = K_{2\max} - K_{2\min}$$

For stable crack propagation, the generalized Paris law is described as

$$\frac{da}{dN} = C(\Delta K_{eq})^m \quad \textbf{(5)}$$

Where *a* is the crack length, N is the number of loading cycles and K_{eq} is obtained by with ΔK_1 and ΔK_2, C and m are material properties. The loading cycles required to extend the crack from initial length to final failure length are evaluated by Eq. 5. A compromise must be made regarding the value of the linear extension length Δa, if crack increment is too small, then very fine meshing is required at the crack tip so that crack tip should fall in new element after each step. If increment is too long, the piecewise linear path cannot precisely represent the real crack path [16]. The problems having single crack, Δa is kept constant.

V. EXPERIMENTAL AND NUMERICAL EVALUATION

1.1 Problem Definition

In this work we are investigating the crack growth behavior of thin edge cracked Al 2014-T6 panels. The dimensions of the SEN and ESC specimen is shown in the Section 2. A sinusoidal fatigue load is applied to the specimens. The specifications of loads are given in the Table 3. The crack behavior is investigated using DIC and XFEM.

Table 3: Fatigue Load

Property	Value/Type
Mean Load, kN	5
Amplitude, kN	3.5
Frequency, Hz	10
Applied Form	Sinusoidal

5.2 Experimental evaluation: DIC

The wire cut notched specimen is subjected to fatigue loading till the fatigue crack initiates. This instance the image taken by the DIC is considered as first image. This first image is used later to correlate the subsequent image for crack tip monitoring. The crack growth and number of cycles are extracted at increments in crack length Δa is less than 2 mm. As the crack grows it tends to follows the path perpendicular to the loading axis. So we consider $y_{ci} = y_c$, hence $\Delta a = x_{ci} - x_c$ and $\Theta = 0$ in global coordinates.

5.3 Numerical Evaluation: XFEM

In the present work, ABAQUS 6.9 which has inbuilt XFEM module in it is used for numerical simulations. 3-D finite element model is used to extract SIFs. XFEM module for modeling crack enables us to create the crack geometry separately and assemble the crack to the plate. Plate is meshed with two elements along the thickness. SIF and crack propagation direction is evaluated from the mid-plane of the model. The life for the crack increment is calculated using Paris law. The crack length is incremented by 0.5 mm in the crack propagation direction and the new SIF and crack propagation direction are extracted. This process continued until plates fails.

VI. RESULTS AND DISCUSSIONS

Experimental and numerical study of straight (SEN) and inclined (ESC) edge cracked specimens are carried out as explained in Section 3 and 4.

The life diagram obtained for the SEN specimen is shown in the Fig. 3. In here, blue line represents numerically obtained curve and green line represents the experimental one. For SEN specimen, the life estimated through the XFEM is 7360 and that of from experiment is 7670. The result obtained from numerical method is conservative in nature and shows 4% error from the experimental results. Similarly, the fatigue life diagram of ESC specimen is shown in the Fig. 4. The fatigue life obtained using XFEM and experiments is found to be 19790 and 19533 respectively. The numerical result shows 1% error from the experimental results.

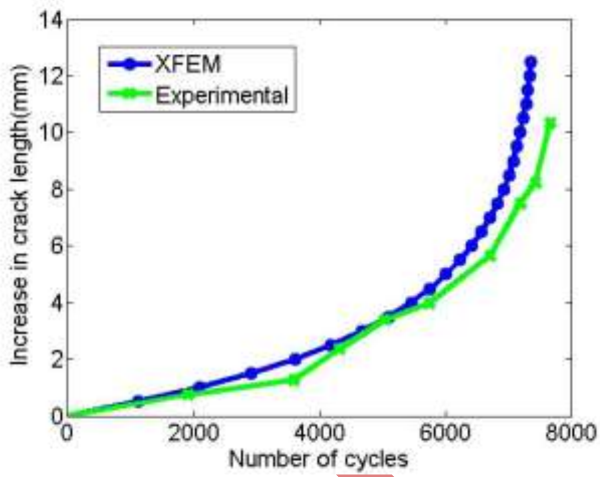

Figure 3: Life diagram of SEN specimen

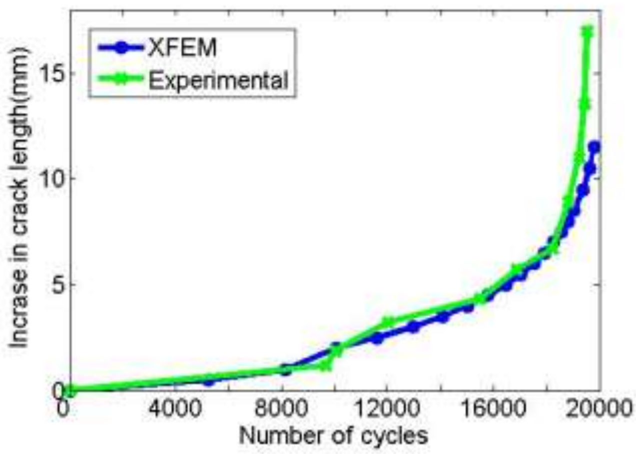

Figure 4: Life diagram of ESC specimen

Even though we used same loads and crack length the life of ESC specimen is 153% more that of SEN specimen. For ESC specimen the perpendicular component of force (with respect to crack plane), which is responsible for the crack opening, is less than that of SEN specimen. So the ESC crack grows slowly as compared to SEN specimen (see Table 4).

Table 4: Life of various specimens

Specimen Type	Experimental	XFEM	Percentage error
SEN	7670	7360	-4%
ESC	19533	19790	+1%

During crack monitoring, it is little difficult to identify the crack tip precisely from the images. So we used paint in the crack, which helped us to trace the crack as it grows.

While using a moving microscope [14], it is necessary to stop the experiment to measure the crack length. For accurate monitoring of crack, loading cycle has to be stopped in order to take measurements. However, in DIC with a trigger controller the images are taken at regular interval of cycles. And the crack length can be measured very easily from that images during post processing, without interrupting loading cycle. So the down time for measuring crack can be avoided for measuring the crack length. Furthermore, the experimental set up does not contains any component which is directly attached to the specimen. Hence the setting up of experiment is relatively easy as compared with other experiments such as compliance gauge method and electrical potential difference method. Due to above mentioned advantageous, the crack monitoring using DIC is found to be easy and useful.

VII. CONCLUSION

The key findings from our study on fatigue life predictions using XFEM and DIC are as follows:

- Fatigue life is experimentally measured for ESC and SEN Al 2014-T6 specimens using DIC. The fatigue testing time is reduced significantly by usage of DIC without making any compromise in monitoring crack growth.
- The fatigue life is estimated using maximum tangential crack propagation criteria and Paris law for ESC and SEN specimens numerically using XFEM in ABAQUS.
- Fatigue life of SEN specimen is 154% more than the ESC specimen.
- The presence of mixed mode crack significantly affect the fatigue life
- The numerical prediction of fatigue life is within 4% error as compared to experimental estimates.
- We demonstrated that XFEM is valuable tool in predicting fatigue life.

VIII. ACKNOWLEDGEMENT

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