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Fatigue Life Prediction of Rivet Joints

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ABSTRACT

Strength reduction in structures like an aircraft could be resulted as cyclic loads over a period of time and is an important factor for structural life prediction. Service loads are emphasized at the regions of stress concentration, mostly at the connection of components. The initial flaw prompting the service life was expected by using the Equivalent Initial Flaw Size (EIFS), which has been recognized as a powerful design tool for life prediction of engineering structures. This method was introduced 30 years ago in an attempt to study the initial quality of structural details. In this paper, the prediction of life based on failure mechanics in a riveted joint has been addressed through the concept of EIFS. For estimation of initial crack length by EIFS, extrapolation method has been used. The EIFS value is estimated using the coefficient of cyclic intensity (ΔK) and using the cyclic integral (ΔJ), and the results are compared with each other. The simulation results show that the if the coefficient of tension been used in EIFS estimation, which based on the Paris law, the EIFS value will be dependent on the loading domain, while the use of the *J*-Cyclic integral in the EIFS decrease its dependence on the load domain dramatically.

Keywords : Fatigue; Riveted joints; Life prediction; Fracture.

1 INTRODUCTION

THE prediction of fatigue life is of great importance to the safety and reliability of structural components in numerous engineering jobs. Many methods have been suggested for the prediction of fatigue life [1]. As the damage tolerance theory is broadly recognized, the growth of fatigue crack method, based on Linear Elastic Fracture Mechanics (LEFM), is becoming increasingly significant [2]. In 1963, Paris and Erdogan interrelated the crack growth rate with the range of SIF and proposed the famous Paris law, which is known for the fatigue life prediction of materials [3]. So far, many equations have been proposed modification of Paris law, for example, the fracture toughness and the stress ratio be able to be encompassed as the modification coefficients in Forman's equation [4], which is thought to be a possible approach to handle the experimental data of numerous materials.

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Many components of aerospace structures are subject to fatigue loading. There are many different criteria for predicting fatigue life. Fig. (1) shows a sample of the failure of a rod due to fatigue crack growth:

Fig.1
Failure in fatigue crack growth.

In general, methods for predicting fatigue life are divided into two main categories; first one is safe-life and second one is Damage Tolerance. The first category itself is a traditional approach, which is divided into three basic sub categories: 1- stresses based analysis, 2- strain-based analysis and 3- energy based analysis [5]. The second category is the mechanical failure method, which based on the growth of fatigue crack growth. There are several theories for estimating the fatigue life of a component. Selection of a suitable method is a function of component geometry and loading conditions. The theory of crack growth can establish a link between a Safe-Life approach and a Fracture Mechanics-Based Life prediction. Integrating these two approaches will provide an integrated approach for life prediction in the industry. Therefore, life expectancy based on fracture mechanics is a very useful and useful method in industries, especially in the oil industry [6]. In this way, it is always assumed that there is an initial crack in the specimen. The length of this initial crack is estimated from the concept of EIFS (Equivalent Initial Flaw Size).

It should be known that EIFS is not a physical quantity. It is a quantity extrapolated from experimental data to facilitate life prediction by means of long crack growth analysis and preventing the solution from difficulties of short crack growth modeling, as the mechanism of small-crack growth has not been clearly found out. The other problem is that small-crack growth intensely depends on the material microstructure and has extensive uncertainties initiated accidentally from size of grain, grain direction and initial flaw form [7].

Another important issue in the fracture mechanics-based life prediction is the accidental nature of applied load [8]. It is known that the crack growing mechanism is affected by the stress order and interaction associated with the arrangement of the load ranges.

Given that crack growth is calculated by stress intensity factor (SIF), the initial flaw size is important to influence crack growth because SIF increases as flaw size rises. For example the main problems of aeronautical structures are damages due to fatigue, which accentuated in areas of stress concentration, like fuselage panels joints, which usually done by riveting [9]. Shahani and Moayeri [10] estimated ΔK_{th} by both *K*-increasing and *K*-decreasing methods. The experimental results showed that the value of ΔK_{th} estimated by the *K*-increasing method is lower than that estimated by *K*-decreasing method. Suna et al. [11] proposed two methods which were evaluated in the aspects of crack developing history and validation of corrosion fatigue life prediction. The crack developing history derived by the two methods reflected the same trend as the fatigue test results. The fatigue life predicted by both two proposed methods was in acceptable agreement with the experimental data. Gallagher and Molent [12] summarized the equivalent initial flaw size (EIFS) results (based on the fits from four da/dt fitting approaches) and compared the EIFS values to the corresponding equivalent pre-crack size (EPS) values based on a back extrapolation of the ln(a) vs. Flight Hour fit to 0.0 flight hours. They concluded that EIFS and EPS values compared very well.

In this paper, the prediction of life based on failure mechanics in a riveted edge joint has been studied by means of EIFS method. 3D model of the fatigue crack growth was performed in a riveted lap joint and the crack growth profiles were predicted. Afterwards, the fracture mechanics-based life prediction of the riveted lap joint was considered by means of EIFS concept. Back extrapolation method was used for estimating EIFS by both cyclic stress intensity factor (ΔK) and cyclic *J* integral (ΔJ). Then, the results were compared. Finally the results are compared with each other. The simulation results showed that in Paris law along with the use of EIFS estimation method, when cyclic stress intensity factor is utilized the EIFS value is dependent on loading domain while the use of *J*-Cyclic integral in the EIFS estimation reduce its dependency on load domain dramatically.

2 A FRACTURE MECHANICS APPROACH TO FATIGUE LIFE PREDICTION

In this perspective, it is always assumed that there is an initial crack in the specimen. Of course, this assumption is not far from reality for many industrial parts that were defected during construction or containing cracks. Number of cycles is calculated by Paris law as stated below (1).

$$\frac{da}{dN} = \bar{C}\left(\Delta K\right)^{m} \tag{1}$$

where:

a= Crack length (*m*)
N= Number of cycles
$\bar{C}$ = Constant
K= Stress intensity factor
m= Constant

In this regard, the upper limit of the integral (a_f) can be calculated with respect to the fracture toughness of the material and the critical crack length, but one of the main problems of this method is to calculate the initial crack length (a_i). The initial crack length can be obtained by using non-destructive tests, but due to the lack of technology in the discovery of small cracks, this method may be very conservative. On the other hand, the growth behaviour of small cracks is very complex and depends on the microstructure of material. Therefore, two modes can be considered. The first mode is when the lower integral domain be equal to internal flow length; in this case the complex small growth cracks should be used. Nevertheless, the second mode is that, instead of using the complex curve of small cracks growth, the same well-known curve of large cracks be used, and the lower domain of the integral be equal to the EIFS initial crack length. The first mode is the method established by Newman. He also provided a code called Fastran [13] and predicted the life of many tactile parts using that code, but this method, due to the complexity of the theory of small cracks, did not make significant progress. The second method is a widespread method that has attracted the attention of many industries and scientists. A lot of work has been done in this regard [14]. Due to the complexity of the small-cracks growth curve, the EIFS concept avoids the analysis of small-cracks growth and in return, uses an equivalent initial crack length for growth curve of the large cracks in such a way that the same fatigue life be made such as previous state. However, in order to equate lower areas of these two curves, more data of small cracks growth curve is required. In order to avoid this, instead of matching the "Large Crack Growth" curves with the "Small Crack Growth", EIFS could be derived from the match between "Large Crack Growth Analysis" and "S-N Graph" [15]. There are several methods for calculating the EIFS value; the most widely used ones can be referred to as Back-Extrapolation. This method uses a fatigue crawl growth analysis, considering the length and the initial shape of the virtual crack, attempts to reconcile life with the S-N graph. The algorithm of this method is shown in Fig. 2. According to this method, the life of a piece is firstly determined by performing laboratory tests, then finite element modelling and considering a basic initial length, the life expectancy of the segment is predicted. By comparing the calculated lifetime of the piece in the laboratory with the predicted life, the virtual initial crack length be corrected continue this cycle to the certain extent to obtain an appropriate error.

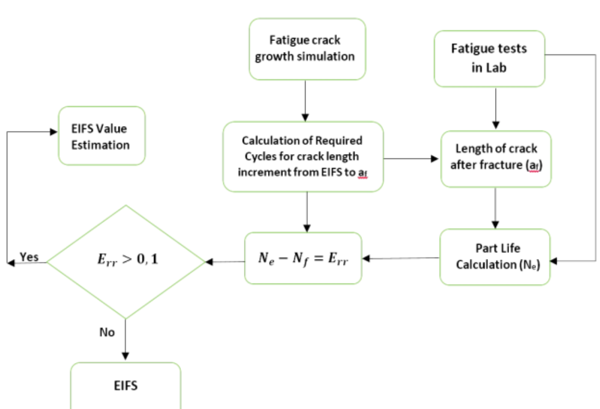

Fig.2
Extrapolation method for EIFS calculation.

One of the major problems in this method is the dependence of the EIFS amount on the applied load. By changing the load range, the estimated EIFS value will be variable. In this paper, the EIFS value is calculated using both the cyclic stress intensity coefficient and the *J*-cyclic integral. Its dependency on the load level in both cases will be discussed later in this paper.

3 FINITE ELEMENT MODELING

Rivet joints with the same hole spacing are very common in aerospace industries. Due to the concentration of high tension in the area around the holes of the rivets, the cracks usually form and grow from the corners of the holes. The growth of the cracks in this area can lead to the total dislocation of the structure. In this study, an edge-to-face connection with a triangle and a riveting column, as shown in Fig. 3, has been investigated. The first and last rivets are supporting main load, and it was also observed in the experiments that the cracks presented in the cross section containing rivet 1 of the upper plate and rivet 3 of the lower one.

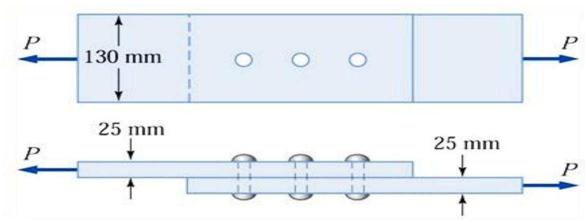

Fig.3
Rivet Plate Joints.

The sheets are made of aluminium T3-2024 with mechanical properties as stated in Table 1, and the rivets are from this NASA 1097 AD4 with a diameter of 3.2 *mm* and a length of 7 *mm* whose mechanical properties are provided in Table 2.

Table 1
Mechanical properties of aluminium 2024-T3.

Density	2.75 gr/cm^3
Modulus of elasticity	73.1 *GPa*
Poisson's ratio	0.33
Submit tension	345 *MPa*

Table 2
Mechanical properties of aluminium 2117-T4.

Density	2.75 gr/cm^3
Modulus of elasticity	71 *GPa*
Poisson's ratio	0.33
Submit tension	165 *MPa*

3D simulation of the problem was performed in ABAQUS software. Fig. 4 represents the meshed model, including 22230 second-order quadratic elements (C3D22R) of 20 nodes.

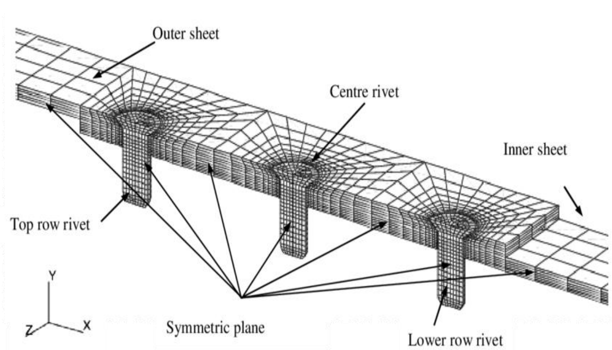

Fig.4
The finite element model of the problem.

Between contacting surfaces, 13 contact pairs have been considered. The remote load was applied to section A of the top plate (Fig. 5). All of the nodes of the section B were constrained in all three degrees of freedom. The applied load was equal to 90, 120, and 160 (*MPa*) with the stress ratio of *R*= 0.05.

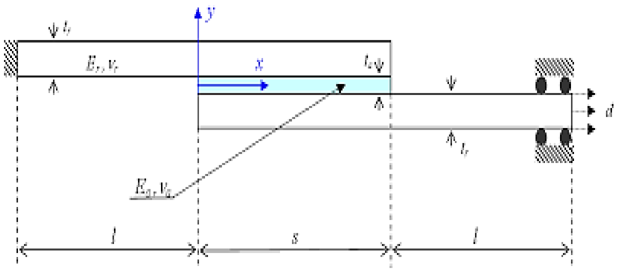

Fig.5
Boundary conditions and loading.

As shown in Fig. 6, the problem has been analyzed for 5 different crack lengths. In order to increase accuracy, the crack tip element were used at the tip of the crack.

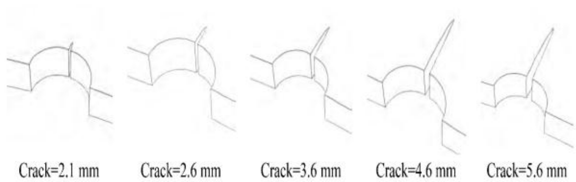

Fig.6
Problem analysis for 5 different cracks lengths.

4 CALCULATE THE COEFFICIENT OF STRESS INTENSITY FACTOR AND INTEGRAL *J*

As shown in Fig. 7, due to the application of tensile loading, the sheets were bended; therefore, there were combined loading conditions around the rivets holes.

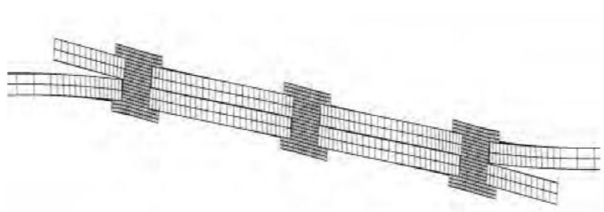

Fig.7
Bending the sheets after loading.

Distribution of stress intensity factor along the thickness of the sheet is shown in Fig. 8. As represented in Fig. 9 it is noticeable that the highest amount of tensile strength coefficient occurs at the upper surface of the sheet due to the bending.

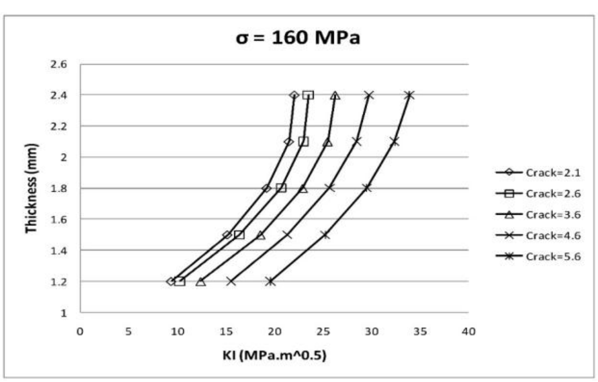

Fig.8
Stress intensity factor along the thickness for different cracks (loading 160 *MPa*).

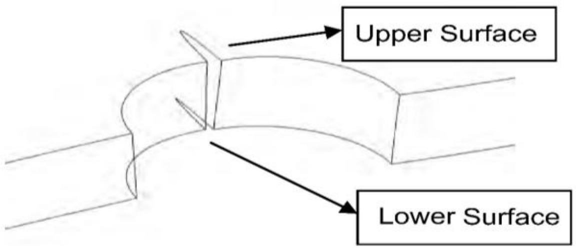

Fig.9
Crack opening at the top of the sheet (tension surface).

In Fig. 10, the values of stress intensity factor were compared in the first three modes with each other. It is observed that the stress intensity factor in the first mode is larger than that of other modes. Therefore, only the first mode is included in EIFS calculation.

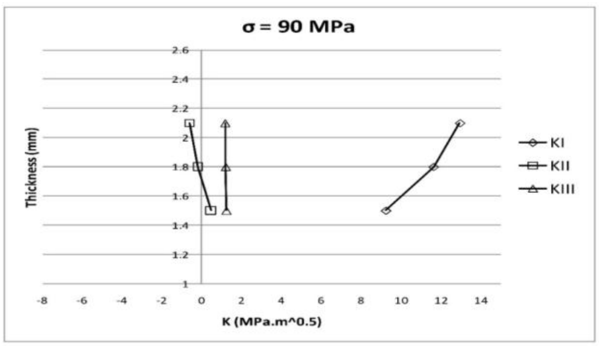

Fig.10
Comparison of stress intensity factor in three modes (loading 90 *MPa*).

In order to calculate the number of cycles using the Paris law, the relationship between the stress intensity factor and the length of the crack is required which is shown in Fig. 11, and the relation between the integral with the crack length, was calculated according to Fig. 12 with a second order polynomial. The calculation is based on the fact that the values of stress intensity factor at the upper surface of the sheet are larger than the lower surface,

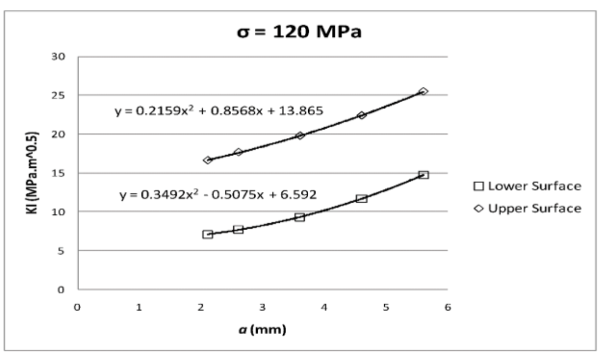

Fig.11
Relationship of stress intensity factor in terms of crack length (loading 120 *MPa*).

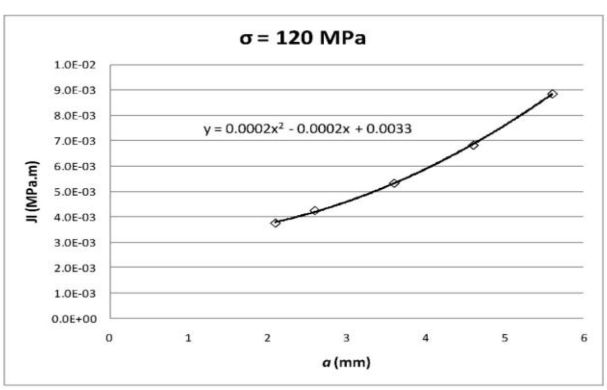

Fig.12
The J integral in terms of the length of the crack at the upper surface of the sheet (loading 120 *MPa*).

5 EIFS (EQUIVALENT INITIAL FLAW SIZE)

5.1 By means of cyclic stress intensity factor

In this section, EIFS has been calculated using the Paris equation, taking into account its coefficients m = 3.3736 and C = 5.0227E-11 [13]. For this purpose, according to the algorithm presented in Fig. 3, and lifetime values in Table 3, obtained from the results of the fatigue test [13], we estimated the initial crack length in a way that the number of required cycles for growth the crack completely be equal to predicted fatigue life via tests. The initial crack length was assumed to be $a_i = 1.8(mm)$ (note that a (*mm*) includes hole radius). According to experimental observations, the final crack length is 4 *mm* in the upper surface of the sheet [13].

Table 3
Lifetime of the riveted edge for different loading values [16].

Lifetime	Loads
700000 *Cycles*	90 *MPa*
240000 *Cycles*	120 *MPa*
80000 *Cycles*	160 *MPa*

Estimated values for EIFS are presented in Table 4. It is seen that the EIFS value is variable for different loading values.

Table 4
Estimated EIFS values by ΔK.

EIFS	Loading Values
3.7079 *mm*	90 *MPa*
3.7342 *mm*	120 *MPa*
3.7647 *mm*	160 *MPa*

5.2 Using the J Cycle integral

Similarly, in this section, we want to use the integral J in accordance with Eq. (2) in the EIFS estimation. The relation between the constants of this equation and Paris law is in the form of relation (3) [14]:

$$\dot{m} = \frac{m}{2} \tag{2}$$

$$\dot{C} = \left[\frac{E(1-R)}{(1+R)}\right]^{\frac{m}{2}} \tag{3}$$

Estimated values for EIFS are presented in Table 5. It is noticeable that in this case, EIFS variations have dropped dramatically for different load values.

Table 5
Estimated EIFS values by ΔJ.

EIFS	Loading Values
3.7688 *mm*	90 *MPa*
3.7666 *mm*	120 *MPa*
3.7651 *mm*	160 *MPa*

6 CONCLUSION

Fatigue tests were conducted on small rivet specimens. To calculate the value of EIFS, the Paris equation and back extrapolation techniques are used in final crack size distribution derived from single crack growth length data. The simulation results showed that the EIFS value is dependent on the loading domain when using cyclic stress intensity factor used along with Paris law, while using the *J*-cyclic integral in the EIFS estimation, decrease its dependence on the load domain significantly. Fig. 13 shows that how we can consider its value as a constant value.

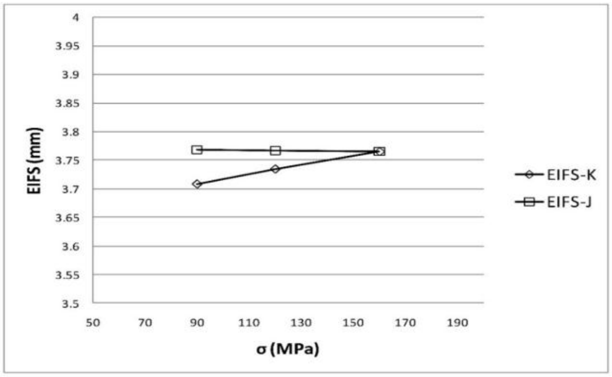

Fig.13
Estimation of EIFS using stress intensity factor and integral *J*.

Considering calculation of EIFS on the one hand, and the relationship between the growth rate of fatigue cracking (the relationship between Paris law and relation (3)), on the other hand, the lifetime of a specimen under different loading can be calculated based on failure mechanics.

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