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Development of a regression model for the life assessment of open-hole specimens with double through cracks utilizing stress intensity factor calculations via XFEM

S.Sohrab Heidari Shabestari[a, b]* and Altan Kayran[a]

[a]Department of Aerospace Engineering,Middle East Technical University, Ankara 06800, Turkey
[b]Barida Engineering and Automation Solutions, Bursa 16280, Turkey

Abstract

In this study, a regression analysis model has been developed to calculate the fatigue life of open-hole specimens with a double through cracks without significantly compromising on the accuracy. In the first phase of the study, experimental fatigue life data for open-hole 2024-T3 aluminum specimens with double through the thickness cracks is extracted from experimental test data. Life assessment model corresponding to the experimental data is generated using the Forman equation to fit the da/dN vs delta K crack growth data, and material constants and plane stress intensity factor of 2024-T3 alloy in the Forman equation are obtained. Extended finite element method (XFEM) has then been employed to model the same open-hole specimen geometry with a double through the thickness cracks to check the accuracy of the XFEM results with the experimental fatigue life data. XFEM simulation for the crack growth and determination of the stress intensity factor during the crack propagation has been performed for different combinations of the initial crack length, rivet hole diameter and applied far field stress utilizing design of experiments based on Response Surface (RS) method. Utilizing the transformed fatigue life results obtained by the XFEM method, a regression analysis of the RS experiments has been performed and a regression model capable of acceptable life prediction of open hole specimens with DTC has been developed.

Keywords: Fatigue Life Assessment, Regression Model, XFEM, Double Through the Thickness Cracks

* Corresponding author. Tel.: +90-553-714-2990;
E-mail address: e199369@metu.edu.tr

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1. Introduction

Riveted joints play an important role in many fields specifically in aerospace industries. Load-carrying panels in several parts of aircraft such as fuselage and wings are bonded together using riveted joints. Prediction of crack growth under cyclic loadings is very crucial in the design phase and also in the maintenance and repair of the fleet to ensure the safety and reliability of joints and load-carrying panels to prevent catastrophic accidents. For this, tedious experiments should be carried out to be able to predict the crack growth behavior under different loadings and boundary conditions which necessitate expending a considerable amount of resources. Experimental tests also may show a large variation from specimen to specimen according to how they have been prepared, methodology in the experimental setup, boundary conditions, and even with the same conditions of the experimental setup, one may observe significant differences between the lifes of identical specimens. As recommended by the ASTM E647 standard, replicate or repeat tests should be conducted to monitor life variation for the same test conditions which roots from the above-mentioned reasons. In the experimental fatigue test studies, researchers either report averaged lifes or detailed life history for each specimen. In this study, experimental data for the 2024-T3 aluminum alloy extracted from the report of Crews and White (1972) for double through the thickness crack (DTC) configuration emanating from an open circular hole is used to define the material constants needed in Forman´s equation. There are several life prediction models available such as Paris, NASGRO, Walker, etc. with specific pros and cons for each. The reasons to choose the Forman model to predict fatigue life in this work can be listed as 1- recommendation of the experimentalist (Crews and White, 1972) in their report; the Forman model fits well with experimental data 2- pressurized cabin in aircraft undergoes very small and near-zero load ratio, hence, the effect of r on the crack growth data shift would be negligible 3- Forman equation also attempts to model region III as Δk approaches Kc. XFEM method for crack growth problems shows a good agreement with analytical and experimental studies. For instance, Dirik and Yalcinkaya (2018), evaluated the crack path and life prediction under mixed-mode cyclic variable amplitude loading through XFEM and experimental studies. They developed an algorithm using ABAQUS to compare XFEM solutions with the experimental data. Good agreement is observed between numerical and experimental results. Kastratovic et al. (2018) studied stress intensity factors for a multi-site damaged problem with 11 holes and 22 cracks emanating from holes using XFEM and approximate method based on superposition. Dirik and Yalcinkaya (2016) compared the overload and overload-underload effects on life cycles using XFEM with NASGRO. Their developed ABAQUS algorithm for XFEM solution resulted in good correlation with NASGRO predictions.

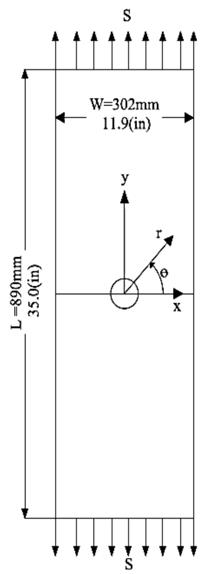
In this study, by using the calculated material constants for the forman equation, the same geometry in the report of crews and white (1972) is modeled in ansys by employing the xfem method. following the convergence analysis, the optimal mesh size and the enrichment characteristics needed for XFEM analysis have been ascertained. good agreement has been obtained between the Δk values calculated by xfem and the analytical results with less than 5%variation. To investigate the relationship of the parameters with the fatigue life under constant amplitude loading, Response Surface Methodology (RSM) has been employed to arrange a set of experiments to be analyzed in ansys. A design field for significant variables are defined and the experiments are designed according to the faced central composite method for the response surface. Then, all cases of the designed faced central composite experiments are investigated utilizing the XFEM to extract SIFs using the maximum crack length failure criterion. Moreover, obtained SIFs are utilized to assess the life prediction by employing the Forman equation and experimental material constants obtained beforehand, via Vroman integration. In order to identify the main and interaction effects, the significance levels of crucial crack parameters (such as applied stress, initial crack length, hole radius), and to obtain the regression model, analysis of variance (ANOVA) is conducted for the designed experiments. Finally, ANOVA analysis of the RSM designs led to a regression model for the life prediction of open-hole specimens with a double through the thickness cracks emanating from open rivet hole edges. The developed model is a handy tool to be used in the preliminary design phase and also in maintenance and repair inspections with a good correlation to XFEM predictions of life.

Nomenclature

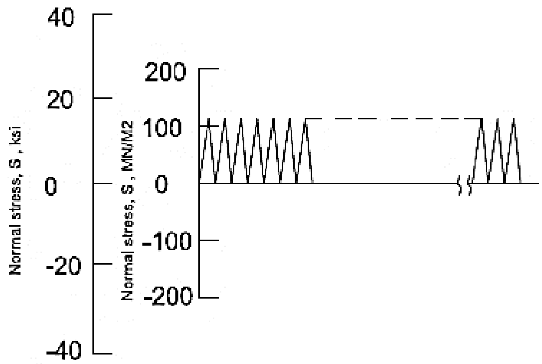
σ Tensile remote stress (MPa)
β Geometry correction factor
r Radius of the rivet hole (mm)
c Pre-crack length (mm)
K_I Mode I stress Intensity factor
K_c Plane stress fracture thoughness
C Forman Model Constant
m Forman Model Constant
N Fatigue Life (Cycles)
R Load Ratio

2. Methods and Materials

One of the most chronic reported failures in aerostructures are the cracks emanating from discontinues such as rivet holes. There are several aluminum alloys developed with high tensile strength and low density and high toughness to be used in load-carrying structures like fuselage and wings and among them, one of the most widely used aluminum alloys in the aerospace industry is 2024-T3 (Paris (1964)). To study fatigue the crack growth behavior of this alloy for open-hole double through the thickness crack (DTC) geometry, experiments were conducted and reported in Crews and White (1972) report. Three different specimens were prepared and tested under constant amplitude loading with R=0. A predefined crack of length 0.76 mm was embedded in all three specimens. Figure 1a illustrates the specimen and Figure 1b gives the loading condition for the experimental test.



a)



b)

Figure 1. a) Experimental Specimen b) Loading Condition in the experimental tests [1]

2.1. Calculation of Forman model Constants

In order to calculate fatigue lifes, ΔK for every crack length should be calculated analytically. In this study, Bowie (1956) method is applied as a reference. For a DTC geometry under tensile loading, Equations 1 and 2 are used to calculate the ΔK in each loading cycle.

$$K_I = \sigma\sqrt{\pi c}\beta \tag{1}$$

$$\beta = 0.5\left(3.0 - \frac{c}{r+c}\right)\left(1.0 + 1.243\left(1.0 - \frac{c}{r+c}\right)^3\right) * F_W \tag{2}$$

where F_W is the finite width correction factor given by:

$$F_W = \sqrt{\sec\left(\frac{\pi r}{W}\right)\sec\left(\frac{\pi(r+c)}{W}\right)} \tag{3}$$

Since the load ratio R is zero, ΔK is calculated as in Equation 4. Forman model (Equation 5) is used to fit the fatigue data for life prediction in the study. Forman constants are obtained by plotting log-log scale of ΔK versus $da/dN(\mathrm{Kc} - \Delta\mathrm{K})$ by fitting the experimental data into Equation 5. Log-log plot of ΔK versus da/dN(Kc − ΔK) for each specimen is depicted in Figure 2. A linear fit of the data, gives the Forman constants as shown in Equation 6 and 7. Table 1 gives the Forman constants for each specimen and also averaged constants used in the rest of this study.

$$\Delta K = (K_{max}) - (K_{min} = 0) \tag{4}$$

$$\frac{da}{dN} = \frac{C\Delta K^m}{Kc - \Delta K} \tag{5}$$

$$\frac{da}{dN}(K_c - \Delta K) = C.\Delta K^m \tag{6}$$

$$\mathrm{Log}\left(\frac{da}{dN}(K_c - \Delta K)\right) = Log(C) + mLog(\Delta K) \tag{7}$$

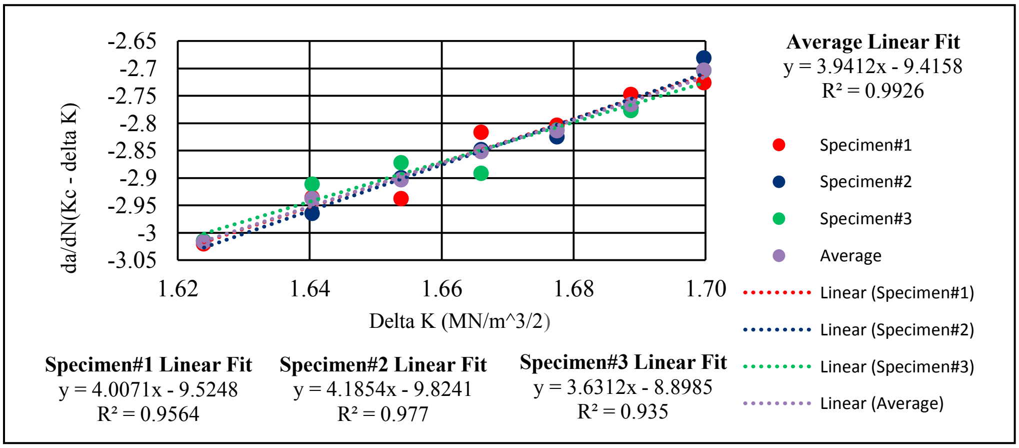


Figure 2. Linear Fit of the Experimental Data on LOG-LOG Scale

Table 1: Forman Model Constants

Specimen ID#	C $\frac{m/cycle}{(MPa\sqrt{m})^{m}}$	m	K_c $MPa\sqrt{m}$
1	2.986^{-10}	4	110
2	1.499^{-10}	4.18	110
3	1.263^{-10}	3.63	110
Average	3.838^{-10}	3.94	110

2.2. XFEM Modelling of Double Through the Thickness Cracks

Prior to XFEM in conventional finite element method (FEM), cracks are modeled explicitly as part of the understudy geometry definition. When the crack grows based on some fracture criterion, the mesh must be suitably updated using features such as morphing and re-meshing so that the analysis can continue. The extended finite element method (XFEM), introduced by Belytschko and Black (1999), overcomes the requirements of updating the mesh as the crack grows.

In this study, XFEM analysis is conducted using the ANSYS Parametric Design Language (APDL). The geometry of the double through the thickness crack problem as presented in the experimental test described in Crews and White (1972) report is modeled using the developed code in APDL. The developed code is capable of perfectly modelling the geometry as well as the loading and the boundary conditions and defining the required parameters for the XFEM analysis.

The geometry is modeled with two nodes at the left most and the right most of the crack plane fixed in the y-direction due to the symmetry of the geometry. To prevent the rigid body motion, there should exist two fixed nodes in the x-direction. Two nodes at the middle of the model located in the upper and lower edges are considered as fixed nodes in the x-direction (Figure 3). In the modeled geometry pressure loads of 115 MPa are applied to the upper and the lower (y=890 mm and y=0) boundaries of the model to simulate the fatigue loading under cyclic constant amplitude load (Figure 3). The load ratio (R) is also set to zero to stimulate the zero-based constant amplitude loading.

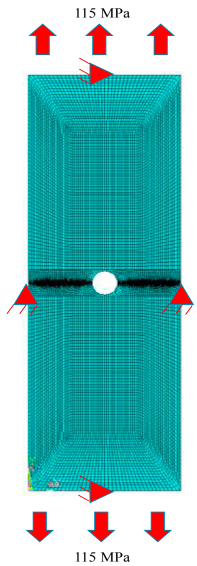


Figure 3. Modelled geometry for the XFEM analysis

The variation of stress intensity factor from the analytical method is observed by changing the mesh size along the crack surface and the enrichment region. For convergence analysis, three different mesh sizes are tested to assure the accuracy of the results. Table 2 shows the details of element sizing and meshing for these tests. A representing figure for meshed model, enrichment field mesh and the initial crack definition in the model are given in Figure 4.

Table 2: Meshing Details of the Convergence Analysis

	Mesh#3	Mesh#2	Mesh#1
Crack Plane Element Size (mm)	0.25	0.38	0.75
Number of Elements around the Hole Circumference	108	80	44
Total number of elements	80051	43292	14427
Enrichment region element size (mm)	1.5	2	4
Out of Enrichment element size (mm)	4.5	6	8
Total Number of Nodes	80372	43538	14597
Meshing Time (s)	25	13	6

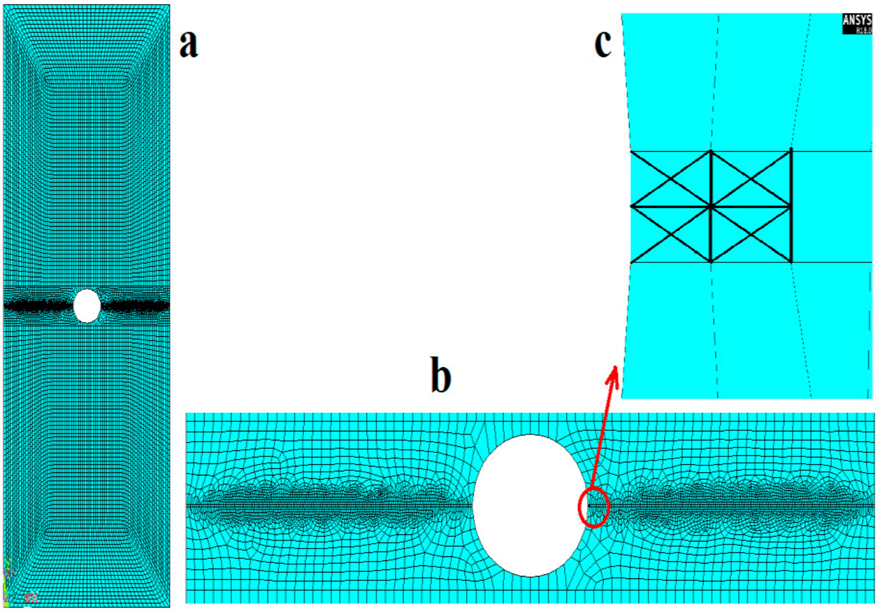


Figure 4. a) Meshed model using Mesh#2 b) Enrichment field c) Initial crack definition in XFEM

To compare different mesh size effect on the stress intensity factor with the analytical results, graphs of crack length versus ΔK are depicted for all mesh cases and also for the analytical method with finite width correction factor in Figure 5. As can be understood from Figure 5, crack plane mesh size of 0.38 mm shows a good convergence to Bowie solution even at the short crack lengths. Further refinement of mesh size in the crack plane gives no more significant enhancement to the calculated SIFs. It should be noted that XFEM analyses are used to calculate the stress intensity factors for 0.38 mm crack increments up to 30 mm of crack length. Extracted stress intensity factors then are used to put in Forman model to calculate fatigue life of the specimens. In order to compare SIFs obtained from XFEM, Bowie analytical solution with finite width correction factor used to calculate analytical stress intensity factors for each crack length. Formulation of Bowie solution and finite width correction factor is given in section 2.1 in Equation 1 through Equation 3.

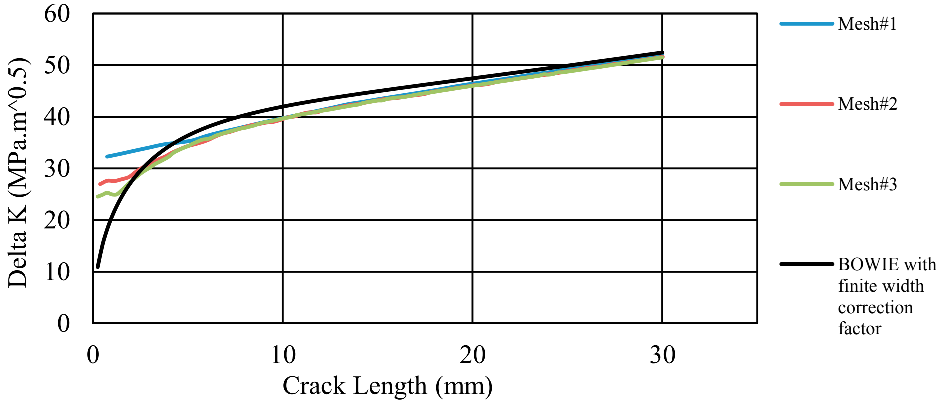


Figure 5. Comparison of XFEM mesh sensitivity

2.3. Response Surface Methodology

Design of experiments (DOE) is a design tool that makes changes to the independent (input) variables to determine their effect on the dependent (output) variable. It not only identifies the significant factors (independent variables) that affect the response (dependent variable) but also how these factors affect the response. Thus, the objective of this study is not only to investigate how the life of a DTC specimen is affected by the pre-defined factors, but also to predict the fatigue in the design field. The term “Experiments” in the Design of Experiments refers to conducting experiments with a specific configuration of independents variables to extract the response; however, in this study, these experiments are coded in the Ansys Parametric Design Language environment. The response considered in DOE is the fatigue life in cycles. Factors that are likely to affect the response (Fatigue Life) are the initial crack length (c), rivet hole radius (r), and the remote tensile stress (σ). In this section, first, a Faced Central Composite (FCC) DOE, based on three factors and three levels (Table 3) is conducted. Then, FCC DOE is analyzed using the analysis of variance (ANOVA) to determine the main and interaction effects of the factors. Lastly, the response of the FCC designs in terms of fatigue life cycles is transformed and ANOVA analysis has been conducted to obtain the regression model.

Table 3: RSM parameters levels in FCC design

Factor	High Level	Star point	Low Level
σ (MPa)	150	105	60
c (mm)	5	3	1
r (mm)	5	3	1

It should be noticed that, in Table 3, there exist three values for each factor. Star point values come from factorial designs. Composite designs contain an imbedded factorial or fractional factorial design with center points that is augmented with a group of 'star points' that allow the estimation of curvature. High level and low level values define the design field or the region of operability of the model. The range of the independent variables should be defined to develop a regression model. Since the hoop stress in pressurized cabins of aircraft rarely exceeds 150 MPa and drops below 60 MPa, in this study tensile stress range has been chosen between 60 MPa and 150 MPa. The rivet hole radius (r) is chosen between 1 mm and 5 mm as mentioned in the FAR maintenance and repair handbook. Rivet joint pattern dictates the spacing between two rivets. Hence, maximum crack propagation length is taken as 30 mm in all of the analyses. As seen in Table 3, all factors have two extreme levels. Table 4 shows the FCC experiment configurations conducted using XFEM and the calculated fatigue lifes obtained at the final crack length of 30 mm.

Table 4: FCC design of experiments and the related response

Run #	σ (MPa)	c (mm)	r (mm)	Life (Cycles)
1	60	1	1	**1172540**
2	105	5	3	**18780**
3	105	3	3	**28417**
4	150	3	3	**6356**
5	105	3	3	**28417**
6	150	1	5	**5901**
7	105	1	3	**47868**
8	105	3	1	**53714**
9	60	3	3	**277468**
10	150	5	1	**6912**
11	60	5	5	**120307**
12	105	3	3	**28417**
13	105	3	3	**28417**
14	150	5	5	**2570**
15	60	1	5	**258723**
16	60	5	1	**258723**
17	150	1	1	**29313**
18	105	3	5	**16964**
19	105	3	3	**28417**
20	105	3	3	**28417**

2.4. Analysis of Variance (ANOVA)

Statistical analysis of the results are performed using ANOVA in MINITAB [11] statistical software for the 95% confidence level. ANOVA is a general technique that can be used to test the hypothesis such that the means of two or more groups are equal. ANOVA assumes that the sampled populations are normally distributed. To be able to interpret the ANOVA results, there are other assumptions that must be met. This is also referred to as the model adequacy check. The model adequacy requires that residuals must be normally and independently distributed, have a mean of zero, and have a constant variance. If one of these assumptions is not met, a suitable transformation such as, inverse log, natural logarithm, square root, inverse square root, etc. should be applied on the response to achieve the model adequacy. In the current model, because the ANOVA assumptions are not met for the life, transformation on the response is applied. After the transformation, the model adequacy assumptions are met for the fatigue life response. Table 5 presents the ANOVA output of the MINITAB for the fatigue life. The first column in Table 5 represents the source of statistical parameters (such as Adj SS, F-Value and P-Value). In the first row, values of these parameters for entire the regression model are shown; in the second row calculated statistical parameters for the linear part of the predictors in the regression model are presented and in the following three rows main effects of each parameter are considered separately. Furthermore, again in row six through nine overall square interaction effects of parameters on the response (Fatigue Life) and for each parameter separately (e.g. $\sigma*\sigma$) can be seen; rows ten through thirteen give the overall two-way interaction of the parameters on the response. Adjusted sums of squares (Adj- SS) are measures of variation for different components of the model. The order of the predictors in the model does not affect the calculation of the adjusted sum of squares. In the Analysis of Variance table, Minitab separates the sums of squares into different components that describe the variation due to different sources.

In ANOVA, the *F*-test is used to compare the variances. The bigger the *F,* the more likely it is that the factor is significant. In the ANOVA table, probability (P-value) indicates whether or not the factor affects the fatigue life. The factor having small P value (e.g, $P<0.05$) means that this factor has a significant effect on this response. As it can be noted from Table 5, $c*c$, $\sigma*r$ and $r*r$ terms in the regression model have the least effect on the response.

Table 5: ANOVA results of RSM experiments

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	0.047336	0.005260	3883.17	0.000
Linear	3	0.046292	0.015431	11392.55	0.000
σ	1	0.038967	0.038967	28769.79	0.000
r	1	0.004195	0.004195	3097.32	0.000
c	1	0.003130	0.003130	2310.55	0.000
Square	3	0.000739	0.000246	181.76	0.000
σ*σ	1	0.000244	0.000244	180.10	0.000
r*r	1	0.000012	0.000012	**8.75**	**0.014**
c*c	1	0.000011	0.000011	**7.96**	**0.018**
2-Way Interaction	3	0.000306	0.000102	75.20	0.000
σ*r	1	0.000092	0.000092	68.01	0.000
σ*c	1	0.000070	0.000070	51.96	0.000
r*c	1	0.000143	0.000143	105.63	0.000
Error	10	0.000014	0.000001		
Lack-of-Fit	5	0.000014	0.000003	*	*
Pure Error	5	0.000000	0.000000		
Total	19	0.047349			

In Table 5, DF stands for the degree of freedom. Degree of freedom encompasses the notion of limits on the estimation of the parameters. Typically, the degree of freedom is equal to sample size (in this study there are 20 cases) minus 1. By increasing the sample size, more information about the population will be provided and this increases the total DF. On the other hand, increasing the number of terms in the model uses more information, and this decreases the total DF available to estimate the variability of the parameter estimates. Minitab partitions the DF for the error if two conditions are satisfied. In the first condition, there should exist terms in which the data can be fit with the data that are not included in the current model. For instance, having a regressor with two or more distinct values, one may estimate a quadratic term for that predictor. If the model does not consist of any quadratic term, then there is no term to fit data in the model which results in satisfying the first condition. Existence of replicates in the data introduces the second condition. For example, if there exist three observations for which the value of predictors are same in all of the three observations, then those three observations are replicates. If the two conditions mentioned above are met, then DF partitions into two parts for the error, the lack-of-fit and pure error. The DF for the lack-of-fit allows a test used to decide if the model form is adequate or not. The lack-of-fit test uses the degrees of freedom for the lack-of-fit. The more the DF for pure error, the greater the power of the lack-of-fit test. Existence of the lack of fit term in the source column in Table 5 means that the regression model fails to adequately describe some of the data. Lack of fit occurs in two cases. When important terms such as interactions or quadratic terms are not included in the model and if several unusually large residuals appear by fitting the model to the data. In case of existing lack of fit in ANOVA analysis, to check the accuracy of the model, P-value of individual terms of the model according to the analysis significant value (α) may be checked. If the P-value falls smaller than the significance value, then it means that the relevant term is significant. As can be seen in Table 5 (bold P-values), c*c and r*r terms are less significant in the regression model. Moreover, F-value is closely related to the P-value. The F-value is the statistic test used to determine whether a term in the regression model is associated with the response. Minitab uses the F-value to calculate the P-value, which helps to make a decision about the statistical significance of the terms and model. In brief, a sufficiently large F-value indicates that the effect of the term on the model is significant. Generally, minimum F-value is unity and bigger F-value shows higher contribution of a term to the model. Insignificant terms according to F-value are in bold character in Table 5. To check the normality assumption, least square residuals plot should form an approximately straight line. Figure 6 shows the normal probability plot and residuals occurrence histogram respectively. Figure 7 illustrates the residuals per each experiment.

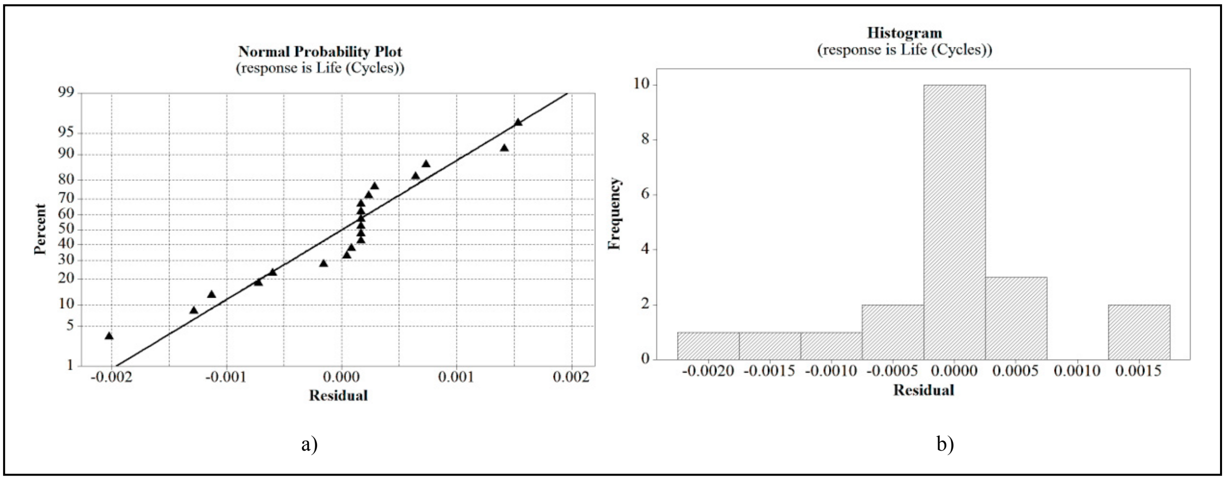


Figure 6. a)Normal Probability Plot. b) Residuals Histogram

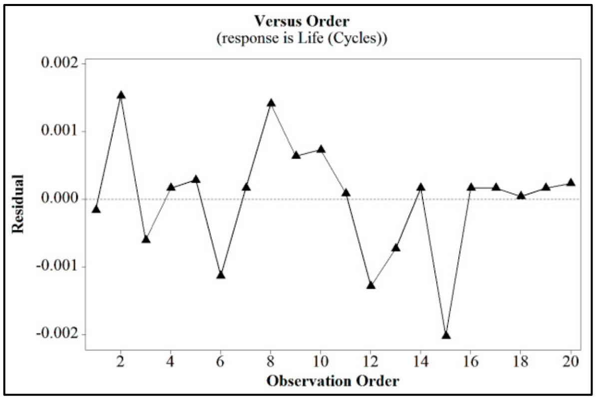


Figure 7. Residuals of each experiment

By considering the normal probability in Figure 6a, it can be clearly observed that a linear distribution of residuals exists and this confirms the normality assumption of the ANOVA analysis. Furthermore, histogram of the residuals in Figure 6b also shows a well-balanced distribution of residuals around zero. Figures 6 and 7 show a well-established regression model. It should be noted that there are three outliers in the residual plot which belong to experiments 8, 11 and 17. These three outliers introduce lack of fit to the model. Table 6 shows the related experiments in which lack of fit arises and Table 7 shows the residual characteristics of unusual observations.

Developed regression model for prediction of fatigue lifes of specimens double through the thickness cracks emanating from rivet holes under constantant amplitude loading is given by Equation 8. In order to check the accuracy of the model, some random configurations from the region of operability of the variables are selected to compare with the fatigue life results obtained by XFEM analysis of SIFs and fatigue life evaluation via Forman's equation. Table 8 shows the comparison of the regression model with the XFEM based analysis. Moreover, other points are selected randomly from the design field to verify the model with XFEM results. Table 9 gives the response of the developed regression model to ten different randomly selected points in the design space. Both results show that the regression model accurately predicts the fatigue lifes of specimens with DTC emanating from the rivet holes.

Table 6: Unusual Observation in the fitted data

Experiment #	Life (Cycles)	Fit	$\left[1-\frac{Fit}{XFEM}\right]*100$
17	29313	28124	4.0
11	120307	125445	-4.2
8	47868	50911	-6.35

Table 7: Residual characteristics of Unusual Observations

Experiment #	$-Life\ (Cycles)^{-00699432}$	Fit	Residual	Std Residual
17	-0.487034	-0.488447	0.001413	2.67
11	-0.441233	-0.439945	-0.001289	-2.43
8	-0.470612	-0.468587	-0.002024	-2.44

$$-Life\ (Cycles)^{(-0.0699432)} = \begin{array}{c} -0.23768 - 0.002152\ \sigma - 0.01257\ r - \\ 0.01153\ c + 0.000005\ \sigma*\sigma \\ + 0.000519\ r*r + 0.000495\ c*c - \\ 0.000038\ \sigma*r - 0.000033\ \sigma*c \\ + 0.001057\ r*c \end{array} \tag{8}$$

Table 8: Verification of the regression model with selected designed experiments

Verification case#	σ (MPa)	r (mm)	c (mm)	Model (Cycles)	XFEM (Cycles)	Difference (%) $(1-\frac{Model}{XFEM})100$
1	105	5	3	16861	16964	0.60
2	150	3	3	6409	6356	-0.83
3	150	1	5	7023	6912	-1.60
4	60	3	3	275255	277468	0.79
5	150	5	1	5925	5901	-0.40
6	60	5	5	121445	120307	-0.94
7	150	5	5	2564	2570	0.23
8	60	1	5	296823	299747	0.97
9	60	5	1	257879	258723	0.32
10	150	1	1	29189	29313	0.43

Table 9: Verification of the regression model with randomly selected points in the design field

Verification case#	σ (MPa)	c (mm)	r (mm)	Model (Cycles)	XFEM (Cycles)	Difference (%) $(1-\frac{Model}{XFEM})100$
1	65	2	1.5	464459	457600	-1.49
2	85	2.5	1.75	120801	119000	-1.51
3	105	3	2	38890	38707	-0.47
4	125	3.5	2.5	13791	13953	1.16
5	145	4	3	5724	5888	2.78
6	75	2	1.5	263526	262840	-0.26
7	100	2.5	1.75	60989	61123	0.21
8	95	3	2	59440	58738	-1.19
9	115	3.5	2.5	19592	19447	-0.74
10	135	4	3	7647	7711	0.83

3. Conclusion

This work is dedicated to one of the on-demand problems of fatigue crack growth in the aerospace industry; specifically to indigenous approaches to investigate different damage scenarios to establish new models and predictive tools that result in the enhancement and acceleration of on-demand design and revisions in the industry. Another outcome of this work is concerned with the maintenance and repair routines of the fleet. By employing the results of this work, it is conveniently possible to predict the remaining life of the damaged panels with DTC emanating from the rivet holes. Nevertheless, the extension of this work to cover more damage cases is of crucial importance for the widespread use of the predictive models. Through this study, XFEM method is used for the crack growth analysis to determine the stress intensity factors. It is shown that the XFEM results are in good correlation with the analytical results of Bowie for the DTC problem. The developed regression model using the response surface methodology at the end of this study shows an acceptable agreement with XFEM results. This model is advantageous as it eliminates the tedious task of model preparation and solving of the problem using FEA software for different configurations of the same problem.

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