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AN INVESTIGATION ON DEVELOPMENT OF A PREDICTION MODEL FOR FATIGUE LIFE OF OPEN HOLE SPECIMENS WITH DOUBLE THROUGH THE THICKNESS CRACKS USING RESPONSE SURFACE METHODOLOGY

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ABSTRACT

In this study, a model for predicting the life of open hole specimens with a double through the thickness fatigue cracks emanating from the fastener hole walls is suggested. The model predicts the life of 2024-T3 aluminum alloy under constant amplitude loading for varying geometries and is valuable for basic experimental evaluations dealing with crack growth from fastener holes. For the experimental verification, experimental test data under constant amplitude loading with the load ratio R=0 was extracted from the work of Crews et al. [Crews and White, 1972] published in NASA Technical Reports Server. In the experimental tests, specimens were prepared from 2024-T3 aluminum alloy plate for double through the thickness cracks embedded in an open circular hole. Stress intensity factors for different crack lengths have been calculated using the Bowie's [Bowie, 1967] analytical solution for the available fatigue lifes in the Crew's report. Experimental data is fitted to the FORMAN equation [Forman et al, 1967] and material constants are extracted accordingly. Afterwards, using the calculated Forman equation constants of the material, the same geometry is modeled in AFGROW. Variable parameters tensile stress (σ), the radius of the rivet hole (r), and crack length (c) are considered as the parameters affecting the fatigue and faced central composite design of experiments using the Response Surface Methodology (RSM) is implemented. Finally, analysis of variance (ANOVA) of the RSM designs led to a regression model with a good correlation to AFGROW and experimental results.

INTRODUCTION

Riveted joints play an important role in many fields specifically in the aerospace industry. 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 the joints and the 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

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experimental setup, one may observe significant differences between the life 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 root from the above-mentioned reasons. In the experimental fatigue test studies, researchers either report averaged lifes [Hudson, 1969; Hudson et al, 1973] or detailed life history for each specimen [Crews et al, 1973; Sow et al, 1976]. In this study, experimental data for the 2024-T3 aluminum alloy extracted from Crews´ report [Crews and White, 1973] for a double through the thickness crack (DTC) 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 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. Using the calculated material constants for the Forman equation, the same geometry is modeled in AFGROW [Harter, 1999] to verify the results. To investigate the relationship of the parameters with the fatigue life under constant amplitude loading, Response Surface Methodology has been employed to arrange a set of experiments to be analyzed in AFGROW. Finally, ANOVA analysis of the RSM designs led to a regression model for the life prediction of open hole specimens with 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 the maintenance and repair inspections with a good correlation to AFGROW predictions of life.

MATERIALS AND METHODS

Experimental Data

One of the most chronic reported failures in aero- structures 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 [Harter, 1999; Sidhar, 2017]. 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 Crew´s report[1]. 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 1 illustrates the specimen and Figure 2 gives the loading condition for the experimental test. The specimens were tested in an axial-load testing machine which operated at two frequencies, 0.25 Hz and 13.3 Hz. They were cyclically loaded at 13.3 Hz during the slow initial stage of crack growth; later they were loaded at 0.25 Hz during the higher growth rates. Experimental data shown in Table 1 gives the crack propagation rate after the crack length of 0.76 mm. These tests are conducted under load control conditions and therefore the strain rate of the tests are not reported. A constant amplitude loading of magnitude 115 MPa at R=0 is applied to the specimen (Figure 2). Fatigue life for different crack lengths and the corresponding ΔK values taken from the Crews`s work are presented in Table 1. It should be noted that in the experimental results given in Crews' report there is too much scatter among the cycles for the three specimens. The reason for this is the difficulties associated with the measurement of the crack lengths with the technology of the 1970s when this work was conducted.

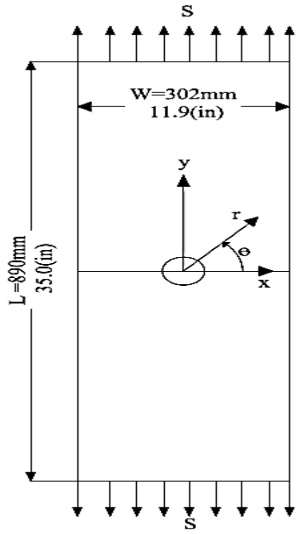

Figure 1: Representation of the experimental specimen

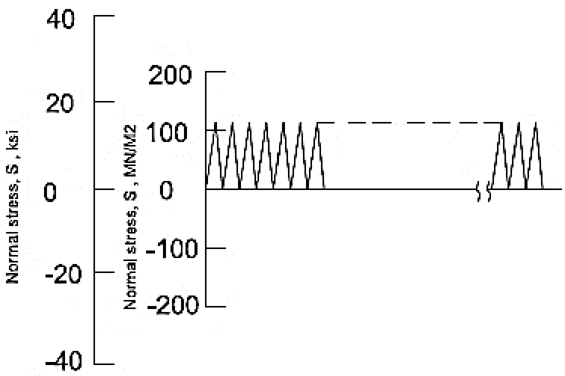

Figure 2: Loading condition for the experimental test

Table 1: Experimental test data from crews' report [1]

	Crack Propagation Rate (Cycles)		
Crack Length (mm)	N1	N2	N3
0.76	0	0	0
1.02	978	1003	452
1.27	1310	1675	1060
1.52	1660	2185	1787
1.78	1832	2550	2425
2.03	1932	2760	2557
2.29	2009	3012	2891
2.54	2069	3214	3545
3.05	2172	3424	3910
3.56	2246	3574	4083
4.06	2300	3664	4369
4.57	-	3730	4499
5.08	2416	3790	4595

5.59	2444	3860	-
6.1	2499	3937	-
6.6	2556	3983	-
7.11	2601	4033	-
7.62	2647	4073	4873
10.15	2827	4251	5051
12.7	2973	4407	5189
15.24	3116	4538	5312
17.78	3222	4652	5438
20.32	3323	4758	5541
22.86	3410	4850	5634
25.4	3491	4923	5711
30.48	3611	5055	-
35.56	3704	5153	-
40.64	3776	5225	-
45.72	3826	5274	-
50.8	3858	5313	6162
55.88	3880	5338	-
60.96	3897	5354	-
66.04	3905	5364	-
71.12	-	5367	-
76.2	-	-	6263

Calculation of the Stress Intensity Factor (SIF)

In order to calculate fatigue lifes**,** ΔK for every crack length should be calculated analytically. In this study, AFGROW method is applied [Bowie, 1969] as the reference. For a DTC geometry under tensile loading, Equation 1 and Equation 2 are used to calculate the ΔK in each loading cycle (Figure 3). Since the load ratio R is zero, ΔK is calculated as in Equation 4.

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

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

where F_W is the finite width correction factor given by:

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

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

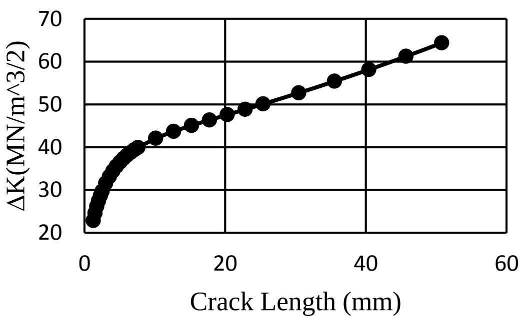

Figure 3: Calculated Stress Intensity Factors

Forman Constants

Forman model for the load ratio of R=0 (Equation 5) is used to fit the fatigue data for life prediction in this study. To this end, Forman constants are obtained by plotting log-log scale of $\Delta\mathrm{K}$ versus $\frac{\mathrm{da}}{\mathrm{dN}}(\mathrm{Kc}-\Delta\mathrm{K})$ by fitting the experimental data into Equation 5. Log-log plot of $\Delta\mathrm{K}$ versus $\frac{\mathrm{da}}{\mathrm{dN}}(\mathrm{Kc}-\Delta\mathrm{K})$ for each specimen is depicted in Figure 4. A linear fit of the data gives the Forman constants as shown in Equations 6 and 7. Table 2 gives the Forman constants for each specimen and also averaged constants used in the rest of this study.

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

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

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

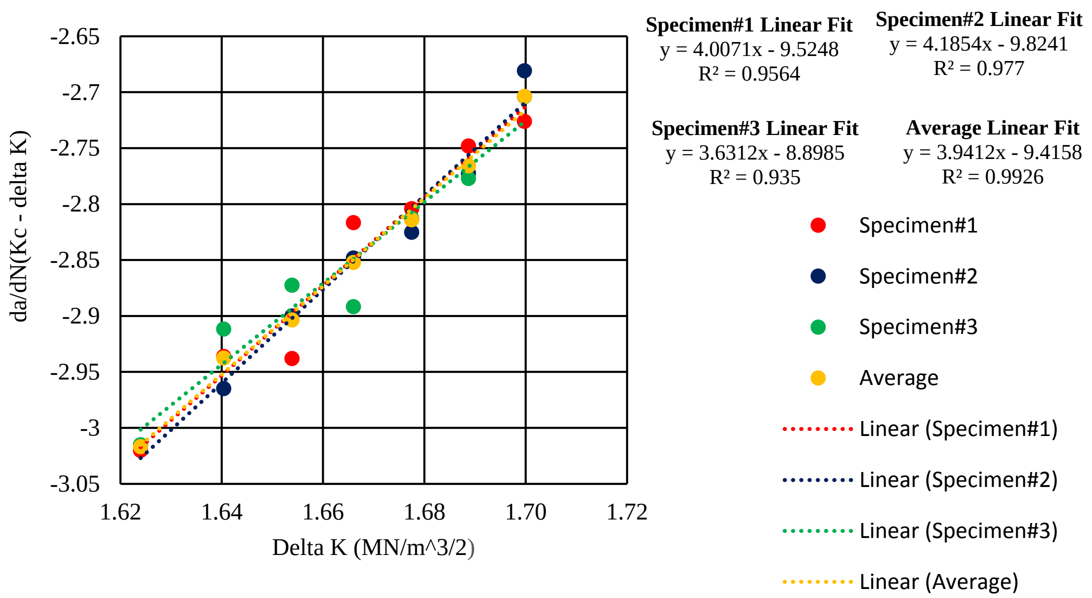

Figure 4: Linear fit of experimental data on log-log scale

Table 2: Forman Constants

Specimen ID#	C $\frac{m/cycle}{(MPa\sqrt{m})^m}$	m	K_c $MPa\sqrt{m}$
1	2.986E-10	4	110
2	1.499E-10	4.18	110
3	1.263E-9	3.63	110
Average	3.838E-10	3.94	110

Moedel Validation in AFGROW

AFGROW is a Damage Tolerance Analysis (DTA) framework that allows users to analyze crack initiation, fatigue crack growth, and the fracture to predict the life of metallic structures. AFGROW implements five different crack growth rate models (Forman Equation, Walker Equation, Tabular lookup, Harter-T Method and the NASGRO Equation) to determine crack growth per applied loading cycle [Forman rt al, 1969]. Understudy crack geometry (Figure 1) is modeled in AFGROW (Figure 5) and the Forman model is used utilizing the constants given in Table 2 to obtain the crack length versus cycle curve (Figure 6). Crack length versus the cycle variations of all specimens are compared in Figure 7. It is to be noted that AFGROW analyses are based on linear elastic fracture mechanics and crack tip plasticity effect is not taken into account.

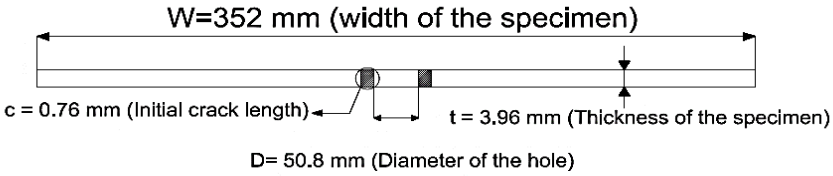

Figure 5: DTC Geometry Modeled in AFGROW

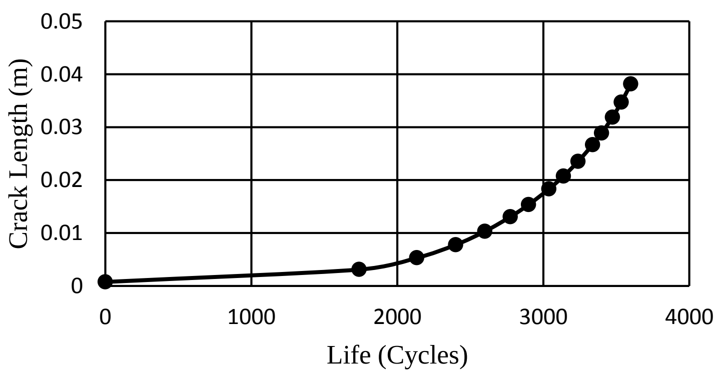

Figure 6: Crack length versus fatigue life obtained by AFGROW

As can be seen in Figure 7, there are significant differences in the crack lengths corresponding to cycles and vice versa for the experimental test specimens. This variation is attributed different treatments and conditions of preparation of the specimens but more importantly to the measurement techniques of the crack length at the time of the experimental study conducted in the early 1970s. Compared to the today's techniques, crack length measurement was not very accurate at that time. However, average crack length versus cycle data of the test still lays far from the predicted life obtained via AFGROW. The main cause of this difference roots from the plasticity phenomena. Plastic zone at the crack tip affects the crack growth due to crack retardation, hence a certain crack size is reached in higher number of cycles compared to the situation when crack retardation is not taken into account due to the plastic zone in the crack tip. Notwithstanding, in this study, the effect of plasticity on the retardation of crack growth is not considered, and LEFM is employed throughout the work.

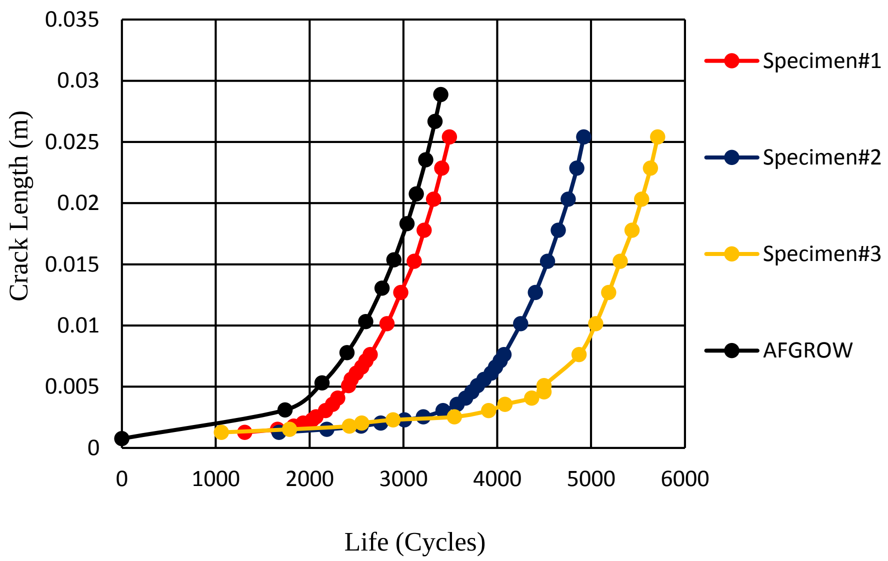

Figure 7: Crack length versus cycles comparison of experimental tests

Design of Experiments (DOE)

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 conducted in the AFGROW 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 are transformed by the natural logarithm (LN(N)) and ANOVA analysis has been conducted to obtain the regression model.

Table 3: RSM design 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 estimation of curvature. High level and low level values define the design field or the region of operability of the model.

Design Field

A space in which the model is valid throughout is called a design field. Thus, 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 mmin all of the analyses. The reason to choose an specific crack length as a criterion to cease the crack propagation instead of using the growth rate is that, the permissible length of crack which can propagate in a riveted structure is limited to spacing of two rivets in a row. Moreover, dependency of the specimen to initial conditions such as initial crack length, preparation method of specimen and etc. affects the growth rate. Nevertheless, choosing an specific crack length to stop crack propagation makes the prediction model less sensitive to unwanted factors affecting the regression model.Thus,crack propagation limit is assumed to be 20 mm. Table 4 defines the range of the parameters in the design field.

Table 4: Design field range of factors, valid for regression model criteria

Factor	Lower Limit	Upper Limit
σ(Mpa)	60	150
c(mm)	1	5
r(mm)	1	5

FCC DESIGN

As seen in Table 3, all factors have two extreme levels. In this design the star points are at the center of each face of the factorial space, so $\alpha = \pm 1$.Table 5 shows the FCC experiment configurations conducted in AFGROW and the calculated fatigue lifes obtained at the final crack length of 30 mm.

Table 5: FCC design of experiments and the response

Run	σ (MPa)	r(mm)	c(mm)	Life (Cycles)
1	105	3	3	28000
2	105	3	1	44700
3	150	5	1	6000
4	105	3	3	28000
5	105	1	3	36400
6	150	5	5	2900
7	105	3	3	28000
8	105	5	3	18000
9	150	3	3	6385
10	150	1	1	25300
11	105	3	5	18800
12	150	1	5	6400
13	105	3	3	28000
14	60	1	1	1035000
15	60	3	3	275800
16	60	5	1	261800
17	105	3	3	28000
18	60	1	5	275900
19	105	3	3	28000
20	60	5	5	134200

ANOVA analysis

Statistical analysis of the results are performed using ANOVA in MINITAB [MINITAB software] statistical software for the 95% confidence level. ANOVA is a general technique that can be used to test the hypothesis 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, natural logarithm transformation on the response is applied. After the transformation, the model adequacy assumptions are met for the fatigue life response. Table 6 presents the ANOVA output of the MINITAB for fatigue life. The first column in Table 6 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 is 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. σ * σ) can be seen; rows ten through thirteen gives the overall two-way interaction of 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.

Table 6: ANOVA for the transformed response

Source	Adj SS	F-Value	P-Value
Model	42.1415	567.45	0
Linear	40.5254	1637.08	0
σ	35.537	4306.69	0
r	2.5302	306.63	0
c	2.4582	297.91	0
Square	1.4005	56.58	0
σ * σ	0.6169	74.76	0
r*r	0.0012	0.14	0.713
c*c	0.0296	3.59	0.088
2-Way Interaction	0.2155	8.71	0.004
σ *r	0.0023	0.28	0.61
σ *c	0.0015	0.19	0.674
r*c	0.2117	25.65	0

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 6, c*c , σ *r and r*r terms in the regression model have the least effect on the response. Main and interaction effect plots are given in Figures 8-10.

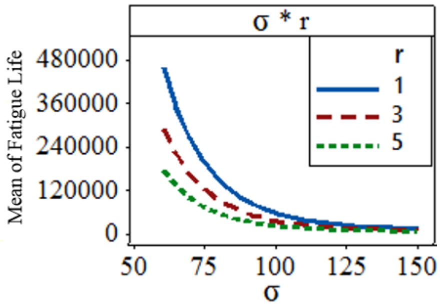

FIGURE 8: TWO-WAY INTERACTION EFFECT OF LOAd σ) AND RIVET HOLE RADIUS (r) ON THEFATIGUE LIFE (N).

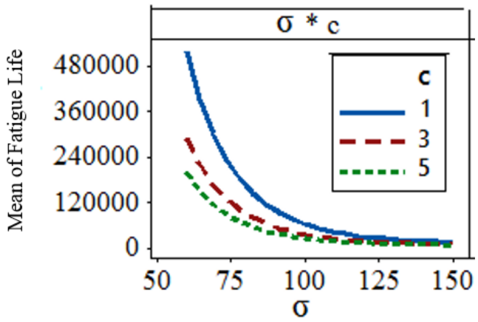

FIGURE 9: TWO-WAY INTERACTION OF LOAD (σ) AND INITIAL CRACK LENGTH (c) ONTO FATIGUE LIFE (N).

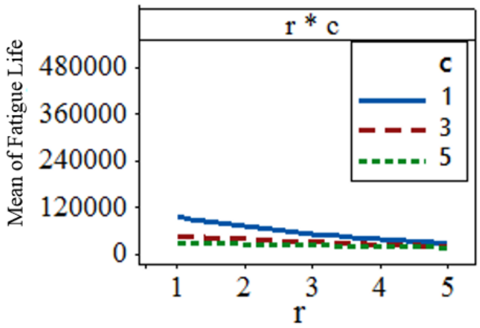

FIGURE 10: TWO-WAY INTERACTION OF RIVET HOLE RADIUS (r) AND INITIAL CRACK LENGTH (c) ONTO FATIGUE LIFE (N).

The effects of each parameter in Table 6 on the fatigue life may described as:

1.Main interactions (i.e. only one parameter independent of the other variable) affecting the response is also called as the linear effect.

2. Interaction effect (i.e. parameters affect the response two by two) is also called as the two-way interaction.Two way interaction is simply the effect of multiplication of two parameters on the response (Fatigue Life). For instance, r*c , is the effect of r*c term in the regression model on the Fatigue Life. In Figures 8-10 interaction effects of the parameters on the response are given. As can be seen from Figure 8, by increasing the radius of the rivet hole and the tensile load (σ) fatigue life drops. Furthermore, in Figure 9 again, an increase in the initial crack length (c) and the tensile load (σ) results in poor fatigue life. Nevertheless, two-way interaction of the radius of the hole (r) and the initial crack length (c) does not significantly affect the fatigue life as depicted in Figure 10.

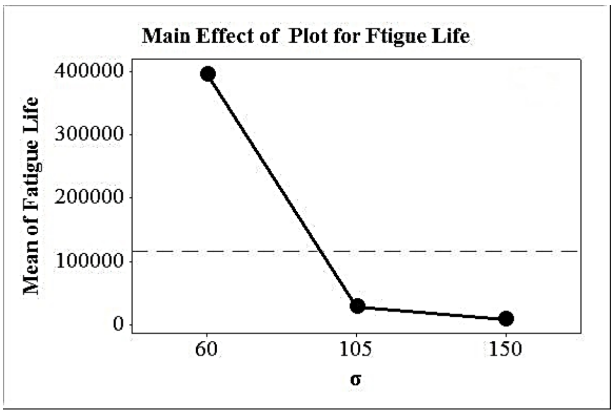

FIGURE 11: MAIN INTERACTION EFFECT OF LOAD (σ) ON THE FATIGUE LIFE (N).

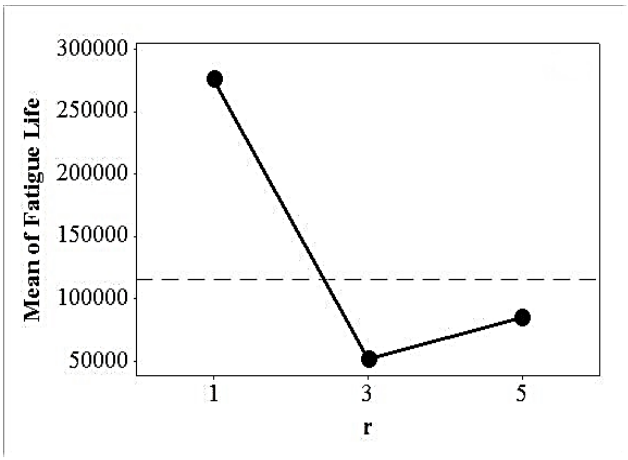

FIGURE 12: MAIN INTERACTION EFFECT OF RIVET HOLE RADIUS (r) ON THE FATIGUE LIFE (N).

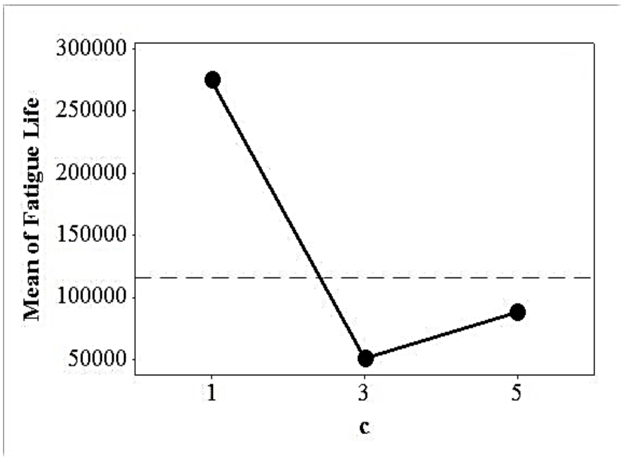

FIGURE 13: MAIN INTERACTION EFFECT OF CRACK LENGTH (c) ON THE FATIGUE LIFE (N).

On the other hand, main effects of the parameters are shown in Figures11-1313. As seen in Figure 11, increase in the tensile load (σ) results in a continuous drop of the fatigue life while, as shown in Figure 12 and Figure 13 decrease in initial crack length and the rivet hole radius does not always result in the drop in the fatigue life, and above certain values of the initial crack length and the rivet hole radius, fatigue life again increases.

Regression Function

Regression analysis is a statistical tool for the investigation of relationships between the output and the input variables. Usually, one seeks to ascertain the causal effect of one variable on another. To explore such issues, the investigator assembles the data on the underlying variables of interest and employs regression to estimate the quantitative effect of the causal variables on the variable that they influence. In a regression function, the coefficient of determination - R^2 provides a measure of how well outputs are likely to be predicted by the regression model. The bigger the value, the better fit the model is. However, only considering R^2 is not adequate to evaluate a regression function because the R^2 value always increases with the addition of a new input variable to the function, even if it is not significant. Therefore, usually the adjusted R^2 and ${R_{adj}}^2$ value is used for evaluating a regression function. If the ${R_{adj}}^2$ value is significantly lower, then it normally means that one or more explanatory variables are missing. So, for a good fit, it is preferred for ${R_{adj}}^2$ to be big and close enough to R^2. We also check whether or not the regression model adequacy is met.

In this study, the regression model in terms of natural logharitm function (*Ln(Fatigue Life))* of the fatigue life is obtained by Minitab as given in Equation 8.

$$\text{Ln (Fatigue Life)} = 19.133 - 0.08998\,\sigma - 0.3227\,r - 0.5093\,c + 0.000234\,\sigma * \sigma - 0.0052\,r*r + 0.0259\,c*c - 0.000188\,\sigma *r - 0.000154\,\sigma *c + 0.04067\,r*c \quad (8)$$

R^2	${R_{adj}}^2$
99.80%	99.63%

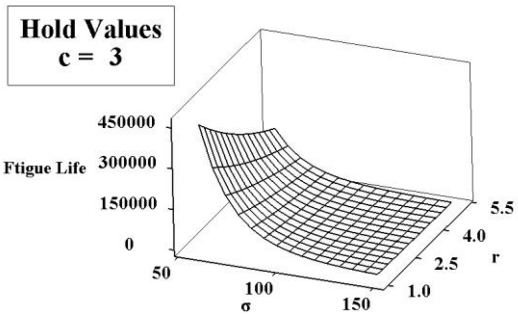

FIGURE 14: SURFACE PLOT OF FATIGUE LIFE VS r & σ

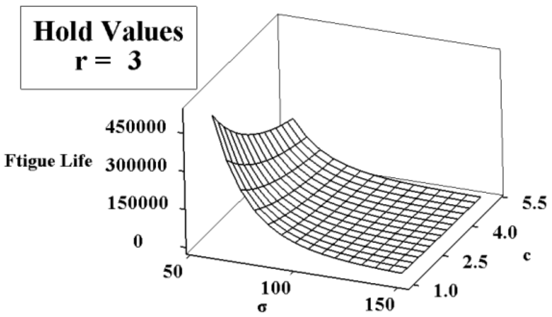

FIGURE 15: SURFACE PLOT OF FATIGUE LIFE VS c & σ

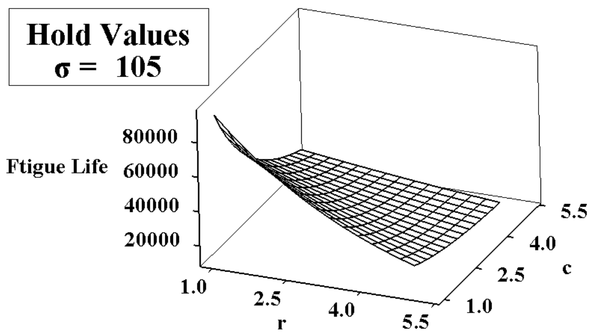

FIGURE 16: SURFACE PLOT OF FATIGUE LIFE VS c & r

Developed regression model for fatigue life in Equation 8 is also presented as response surface plots for variables and shown in Figures 14-16. In these plots, one variable is kept constant and the other two variables are fed into Equation 8 from the design field to draw response surfaces.

Verification of the Regression Model

In order to verify the developed regression model, some random selections from the design field are made to compare fatigue lifes with those predicted by the AFGROW (Table 7). Difference column in the Table below indicates the regression model variation from AFGROW.

TABLE 7: VERIFICATION OF THE DEVELOPED MODEL WITH AFGROW

σ (MPa)	r (mm)	c (mm)	AFGROW Prediction (Cycles)	Reg. Model (Cycles)	Difference. (%)
133	2.6	1.5	17388	17778	2.24
133	2.6	2.25	14444	13913	-3.67
133	2.6	3.9	9180	8991	-2.02
99	1.55	4.7	32810	32180	-1.92
99	2.55	4.7	27323	27111	-0.77
99	4.55	4.7	18832	18654	-0.94
83	2	3.5	84180	85242	1.26
113	2	3.5	22355	22061	-1.31
147	2	3.5	7826	7932	1.35
105	3	3	28000	27270	2.6
105	3	1	44700	45670	-2.17
150	5	1	6000	6069	-1.15
60	1	1	1035000	1040380	-0.52
60	5	1	261800	262941	-0.43
150	1	5	6400	6294	1.65

Results obtained for the random design points from the design field show that the developed regression model produces fatigue life resultsMachinery which are very close to the AFGROW results.

CONCLUSION

In this paper, a regression model for double through the thickness cracks emanating from fastener holes is developed successfully by using the response surface methodology and the analysis of variance. Acquisition of the material constants needed to calculate the fatigue lifes using the Forman model is done using the experimental results of Crews [Crews and White, 1973] prior to the analysis of the experimental model using AFGROW. A series of experiments is designed according to the response surface methodology to investigate the fatigue lifes using AFGROW. Finally, by means of ANOVA statistical analysis a regression model is determined to predict the fatigue life of open-hole specimens with DTC. The developed regression model gives fatigue lifes which are very close to the AFGROW predictions for the random selections from the design field. Hence, the developed model is deemed to be a useful tool for fast prediction of the fatigue life of panels with cracked fastener holes in either the design phase or for maintenance operations.

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