Research article

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A fatigue crack initiation and growth life estimation method in single bolted connections

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Abstract:

Fatigue Life estimation accuracy of mechanical parts and assemblies has always been the source of concern in different industries. The main contribution of this paper lies in a study on the accuracy of different multi-axial fatigue criteria, proposing and investigating the accuracy of four optimized fatigue crack initiation life estimation methods- volume, weighted volume, surface and point, thereby improving the multi-axial fatigue life estimation accuracy. In order to achieve the goal, the fatigue lives of bolt clamped specimens, previously tested under defined experimental conditions, were estimated in both fatigue crack initiation and fatigue crack growth steps and then summed together. In the fatigue crack initiation part, a code was written and used in the MATLAB software environment based on critical plane approach and different multi-axial fatigue criteria. In the fatigue crack growth part, the AFGROW software was utilized to estimate the crack growth share of fatigue life. Experimental and numerical results showed to be in agreement. Furthermore, detailed study and comparison of the results with the available experimental data showed that a combination of SWT approach and volume method results in lower error values; while, a combination of Fatemi-Socie criterion and surface or point method presents estimated lives with lower error values. In addition, the numerical proposed procedure resulted in a good prediction of the location of fatigue crack initiation.

Keywords: Fatigue life, Finite element, Fatigue crack growth, crack nucleation, Bolted joints

Nomenclatures

$3D$	Three dimensional	N_p	Predicted fatigue life
a	Crack length (in A direction)	S_{max}	Maximum applied remote stress
a_0	Initial crack length	$S.W.T$	Smith–Watson–Topper
a_i	Initial flaw size for the AFGROW software	t	Plate thickness
A	Crack propagation direction	t_0	Reference thickness (plane strain condition)
A_k	Fit parameter of the NASGRO equation	T	Applied torque
b	Fatigue strength exponent	ΔK	Stress intensity range
B_k	Fit parameter of the NASGRO equation	ΔK_0	Threshold stress intensity range at $R = 0$
c	Crack length (in C direction)	$\Delta \varepsilon/2$	Maximum principal strain amplitude (local)
c_i	Initial Flaw size for the AFGROW software	$\Delta \varepsilon_n$	the range of normal strain
C	Crack propagation direction	$\Delta \sigma_n$	the range of normal stress
C_{th}	Threshold coefficient	$\Delta \gamma$	range of shear strain
E	Elastic modulus	$\Delta \tau$	the range of shear stress
ER	Error index	ε	Strain (local)
FCG	Fatigue crack growth	ε'_f	Fatigue ductility coefficient
FCI	Fatigue crack initiation	σ_0	Flow stress
F_{cl}	Clamping force	σ_n	local normal stress
K	material parameter in the multiaxial fatigue criteria	σ'_f	Fatigue strength coefficient
K_{Ic}	Plane strain fracture toughness (Mode I)	σ_y	yield stress
N_e	experimental fatigue life	σ_{max}	Maximum tensile stress (local)
N_f	crack nucleation number of cycles	τ'_f	Fatigue strength coefficient
		μ	Friction coefficient

1. Introduction

Fatigue life of mechanical parts and connections is one of the most important factors, in the design of the aerospace vehicles, as well as the maintenance of them. Each year a huge portion of the aerospace vehicle failures happens due to fatigue, thereby making it the most dominant form of aerospace structure failure. Therefore, the fatigue life estimation of them and its accuracy is of paramount importance. However, the absence of a unique criterion and method, which leads to low orders of error in this life estimation field, for different loading conditions, is evident. Fatigue life of the mechanical parts includes the fatigue crack initiation period and the fatigue crack growth life. Therefore, to assess the fatigue life of a part, a precise and low error estimation of the lives in both of the periods is required.

Fatigue crack initiation in mechanical parts of different materials, and the life for a crack until it initiates have been the source of study for over decades, both numerically and experimentally [1-

7]. As a result, several fatigue life estimation criteria have been developed and presented, including the multiaxial fatigue criteria, for which there are several formulas. Due to the nature of the application of mechanical parts, they are used mostly in the environments exposed to stresses and strains in different directions, or in other words multiaxial states of stresses and strains. This has caused the multiaxial fatigue criteria to become vastly useful and important. In one hand, the multiaxial fatigue criteria can be classified into three groups of stress based criteria such as Sines [8][9], Findley [10-13], Mc Diarmid [14][15], and Dang van [16-19]; strain based such as Fatemi-Socie [20], Li Zhang et al [21] and Wang Yao [22]; energy based ones like SWT [23], Glinka [24], Varani-Farahani [25], Morrow [26] and Garud [27]. On the other hand, they can be classified as the ones which are based on critical plane approach and those which are not. The critical plane approach has proved its validity so far up to a good extent for the multiaxial cases of loading. This approach takes a plane as the critical plane (for example the plane of maximum normal stress), and the other variables of the formula are calculated in this plane based on the damage model; the Glinka, SWT, Fatemi-Socie and Findley multiaxial fatigue life and damage assessment formula are capable of being integrated with the critical plane approach.

Fatigue crack growth life (FCG), the life of a crack from the moment of initiation to reaching a critical length, is usually estimated using different models including Paris [28], Forman [29], Walker [30], and NASGRO [31]. Due to the credibility of them, the two FCG life prediction codes of FASTRAN and AFGROW, which are modified using the enhanced partial crack closure model [32-38], are widely utilized. Data presented in the aforementioned sources demonstrate the reasonable FCG life estimation of AFGROW [39].

In the previous studies, the investigations on multiaxial fatigue life have been carried out both experimentally and numerically. However, the numerical ones still lack a high degree of accuracy to make them so reliable that one can fully depend on them like the stress analysis fields. Therefore, there is still an ongoing effort to improve the available ones, by proposing either new models or new procedures.

In this study, a finite element model of the whole assembly is drawn in the ANSYS Workbench software environment, simulated completely based on the real test condition, and solved under different loading conditions. Fatigue crack initiation (FCI) and FCG lives are calculated using a written code by the authors and the AFGROW software, respectively. The numerical results agree with the experimental ones. Four optimized methods of volume, weighted volume, surface and point are proposed and evaluated. These methods present a more optimized procedure for using the different multiaxial fatigue criteria. In addition, the code, integrated with the four mentioned methods predicts the crack initiation location with a good accuracy, compared to the experimental fractographic results.

2. Experimental test summary

The details of the experiment were previously reported in the Ref. [40]. However, to provide the reader with an overview, a brief description of the experimental procedure and steps is presented. Four batches of specimens (Fig. 1), made from aluminum alloy 7075-T6 material, were utilized due to their availability, comparability to the other research work, their clear and trending behavior under fatigue, and most importantly widespread use in different mechanical and aerospace industry. One batch of the specimens was fatigued in an open hole condition while the other three batches were bolt clamped and fatigued. The mechanical properties of the material were derived by conducting simple tensile tests (Fig. 2).

Figure 1. The dimensions of the fatigue specimen [39].

Figure 2. The true stress–strain diagram for Al-alloy 7075-T6 [40].

The bolted specimens were loaded with clamping force, to be put under preloading. In order to apply the clamping force, using a steel hexagonal bolt and nut, and a set of steel washers, the hole on the specimen was bolted. It is worth mentioning that $M5 \times 0.8$ bolt and nut type, of 8.8 material class, and based on ASME B18.2.3.5M were used.

While tightening the nut over the bolt, three different torques of $T=0.25, 3.5, 7 \text{ N.m}$ were applied. To measure the corresponding clamping force resulted from each applied torque, a steel bush was placed between the plate and the nut, which itself was connected to a strain gauge. Then, by measuring the axial strain in the bush and knowing its mechanical material properties, the magnitude of the applied stress and the resulting clamping force as a result, were calculated using the Eq. (1).

$$F_{cl} = E_{bush} A_{bush} \varepsilon_m \quad (1)$$

Using Eq. (1) and through the aforementioned procedure, the corresponding clamping forces to the torque values were calculated as $F_{cl} = 244, 3409, 6818 \text{ N}$, respectively. After applying the preload on the specimens, fatigue tests were performed on them with different amplitudes ranging from 55MPa to 120MPa, while $R=0$, $P_{min}=0$, and the frequency of the test was set to 15 Hz.

3. Finite element simulation

To achieve an accurate solution to the problem, the assembly parts and the loading condition were all modeled, exactly the same as the real test conditions, without any simplification. The assembly consists of an aluminum plate, a steel bolt, a steel nut and two steel washers.

The ANSYS Workbench finite element software was used to model, mesh and solve it. The material type and the mechanical behavior were set in the material library based on the data from the experimental results, as given in Table 1 and Fig. 2. The material behavior of the aluminum plate was set based on a kinematic hardening model. However, the mechanical behavior of the other components was set based on a linear elastic model, with the Young's modulus of 207 GPa and the Poisson's ratio of 0.30, since they all remain elastic during the experiment.

Table 1. Mechanical material properties

	Al 7075-T6	Steel
E (GPa)	71.5	207
ν	0.33	0.33

To mesh the modeled assembly, ANSYS Workbench meshing was used. The behavior of the interacting surfaces between the components was modeled utilizing ANSYS WORKBENCH frictional contacts, which allow the surfaces to slide, but not to penetrate. It is worth mentioning that the approximate frictional coefficients were derived using a numerical trial and error method, which is discussed separately in the Ref. [41]. ANSYS (3D) solid element type of SOLID185 was chosen and used, to make a well-mapped mesh. However, in the regions where the two components touch each other, like the one between the aluminum specimen and the washer, CONTA174 and TARGE170 element types were used by ANSYS. This element is used to represent contact and sliding between 3-D "target" surfaces (TARGE170) and a deformable surface, defined by it [42][43].

In addition analysis was performed to maintain a solution independent of mesh size, thereby generating a number of 119221 elements. It is worth mentioning that a biased mesh type was generated in areas that were anticipated to have more intense stress gradients. This eliminated the need to fine the elements in the regions which were not of interest and did not have stress concentration.

Figure 3. FE model of the assembly

In order to simulate the loading conditions, corresponding to the model real conditions, at first two tangential forces in cylindrical coordinates, with respect to the central axis of the nut, were applied on the two opposite hexagonal sides of the nut. This generated the required torque to tighten the nut, thereby simulating the preload or clamping force effect, the accuracy of which was verified by matching the resulting strains with the experimental results. Then, in the second step of the solution, a fixed constraint was applied on one side of the specimen. Finally, in the third step of the solution, longitudinal loads in the direction of the length of the specimen were applied cyclically to investigate fatigue life under clamp condition.

consequently, the results and output of the finite element analysis were used to form the stress and strain tensors for being used in fatigue life section. The choice of the critical points and the procedure to use them for fatigue crack initiation and growth analysis is described in the following sections.

4. FCI formulation theory and methodology

Fatigue crack initiation life, FCI, is the life of a mechanical part or the specimen under cyclic loading until a crack with a specific size is initiated in it. To investigate this life using several multiaxial fatigue FCI criteria, a MATLAB code was written and used to estimate FCI life.

It is worth noting that the critical plane approach is integrated with all of the models, while doing the calculations. Based on the critical plane approach, the variations of stress and strain- normal or shear depending on the model type that is used- is calculated along with some other variables or parameters. The plane with the most critical and largest value of damage- as defined by each model- is called the critical plane and the corresponding damage value is chosen as the damage for fatigue life calculations [44].

4.1 FCI formulation theory

Since the loading case in the experiment is a multiaxial state of loading, considering the preload direction and the cyclic longitudinal loading, different multiaxial fatigue criteria were used to investigate and compare the proposed method and its effect on the models. The four models of Findley, Smith-Watson-Topper (S.W.T), Fatemi-Socie and Glinka were used in this study, due to their well-publicity and good correspondence to multiaxial loading state of stress.

The Findley model defines damage in terms of a linear combination of shear stress and the maximum normal stress [12]. Therefore, as described in the definition of the critical plane approach, the left hand side of the Eq. 2 has to reach its maximum value on a specific plane, in order to be taken as the damage value corresponding for FCI.

$$\left(\frac{\Delta\tau}{2} + K\sigma_n\right)_{max} = \tau^*(N_f)^b$$

$$\tau^* = \sqrt{1 + K^2}\tau'_f \quad (2)$$

The K constant is declared to be 0.3 for metals, making the $\sqrt{1 + K^2}$ term to become 1.04 approximately [45]. This model is usually used in the cases of high fatigue life.

The S.W.T model, can be used both in proportional and non-proportional loading states of loading, and specifically the case in which the mode I crack is the dominant type mechanism of cracking [23]. This model considers the plane of the maximum normal strain range as the critical plane.

$$\sigma_{n, max} \frac{\Delta\varepsilon_1}{2} = \frac{\sigma_f'^2}{E} (2N_f)^{2b} + \sigma_f' \varepsilon_f' (2N_f)^{b+c} \quad (3)$$

The Fatemi-Socie model defines the damage resulting from fatigue in terms of shear strain range and maximum normal stress. It takes the plane of the maximum shear strain as the critical plane [20]. It is worth noting that the K parameter is a material property and represents the effect of normal stress on crack propagation.

$$\frac{\Delta\gamma}{2} \left(1 + K \frac{\sigma_{n, max}}{\sigma_y}\right) = \frac{\tau_f'^2}{G} (2N_f)^{b_\gamma} + \gamma_f' (2N_f)^{c_\gamma} \quad (4)$$

$$\tau_f' = \frac{\sigma_f'}{\sqrt{3}}, \gamma_f' = \sqrt{3}\varepsilon_f' \quad (5)$$

$$b_\gamma = b \quad c_\gamma = c \quad (6)$$

The Glinka model is a combination of energy and critical plane approach [24]. It takes the plane with the maximum shear work as the critical plane. In other words, this model considers the plane with the maximum value of the product of shear stress and shear strain range as the critical plane.

$$\frac{\Delta\gamma}{2} \times \frac{\Delta\tau}{2} + \frac{\Delta\varepsilon_n}{2} \times \frac{\Delta\sigma_n}{2} = \frac{\sigma_f'^2}{2E} (2N_f)^{2b} + \frac{\sigma_f' \varepsilon_f'}{2} (2N_f)^{b+c} \quad (7)$$

4.2 FCI life estimation methodology

Having applied the critical plane approach, multiaxial FCI life estimation codes were written in MATLAB environment to get the stress and strain tensors from the FEM analysis- for different combinations and cases of loading- and calculate the life portion of crack initiation.

Therefore, the first step is to extract data from the solved finite element model in the ANSYS Workbench software. In this part, only the points with the maximum stress on the drawn stress contour for each loading case are chosen. This includes an approximate number of 200 points, half of which has been chosen from the parallel plane to the edge of the hole, where it has shown to carry the most critical points, in all the loading cases. Because, for a point to become a site for crack initiation, not only the condition of itself matters, but also the points in the vicinity should have the similar potential condition. In other words, fatigue is a local phenomenon in the material, not a point one. This is illustrated in Fig. 4, to help for better visualization.

Figure 4. The critical regions on the edge of the hole, in red (on the left), the points on nodes from the red region in 2 parallel planes (on the right).

After calculating the damage value for all of the data points and deriving the most critical ones, the corresponding initiation life based on the different aforementioned criteria and the four methods of point, surface, volume and wieghted volume were calculated.

It is worth mentioning that they were also found to be on the edge of the hole plane and the plane behind it in parllel, but moving up and down based on the loading case. This is depicted in Fig. 5.

Figure 5. A stress contour showing the critical points on the edge of the hole.

The four proposed methods are defined as follows:

- The point method simply considers the point with the most critical damage value as the base for life calculations. This means that the most damaged point's data, based on the utilized multiaxial model definition, is used to calculate the FCI life of the specimen under a specific loading condition.
- The surface method takes the average life of the points in the vicinity of the most critical point, but in the same plane, i.e. the plane at the hole edge.
- The volume method, not only considers the role of the neighboring points in the same plane, but also takes into account the effect of the points in the plane preceding to the hole edge plane by including them in the averaging procedure.
- The weighted volume method uses a weighted average method to calculate the FCI life. In other words, it gives more weight to the points on the plane at the edge of the hole by a factor of 2, while the ones in the back plane take a factor of one. The idea and formulation is backed up by the fact that the points in the same plane should have more significant effect on the generated damage compared to the ones in the other plane.

The constants of the formula were found in the similar research and work, which are a material property [39][46].

Table 2. Mechanical properties of AL-alloy 7075-T6

K constant	τ'_f	b_y	$\sigma_{yield}(Pa)$	C_y	γ'_f	G (Pa)	ϵ'_f	$\sigma'_f(Pa)$	E(Pa)
0.3	8.46E+08	-0.143	5.03E+08	-0.619	0.454	7.00E+10	0.262	1.47E+09	7.15E+10

5. FCG formulation theory and methodology

Fatigue crack growth life, FCG life, is the life spent from the first moment that a crack is initiated until it propagates to a critical value, in which the component fails. To calculate the fatigue crack growth life, the AFGROW software was used. This software is developed by Harter and uses linear elastic fracture mechanics [31][47].

5.1 FCG formulation theory

To move forward with the process of fatigue crack growth life estimation in the software, it was assumed that the crack is planar and semicircular at the hole edge. This is also proved independently in the results of the FCI life investigations (See section 7.2). Moreover, the dimensions of the specimen, material properties and the loading conditions were given as reported in the experimental section and the rest of the paper.

Figure 6. Orientation of the defined cracks for FCG analysis in the AFGROW software

In using the AFGROW software, the NASGRO model was used [47]. The model parameters were used as defined in the software library [31]. Because of its capability to account for the effects of stress ratio, stress intensity range and threshold stress intensity range, it was preferred over the other available models of the field. In addition, since the analysis contains hole in its geometry and stress intensity around the hole, this one is a more appropriate FCG model for the study. This model obeys the following formula:

$$\frac{da}{dN} = C \left[\left(\frac{1-f}{1-r} \right) \Delta K \right]^n \frac{\left(1 - \frac{\Delta K_{th}}{\Delta K} \right)^p}{\left(1 - \frac{K_{max}}{K_{crit}} \right)^q} \quad (8)$$

$$f = \frac{K_{op}}{K_{max}} = \begin{cases} \max(R \cdot A_0 + A_1 R + A_2 R^2 + A_3 R^3) & \text{for } R \geq 0 \\ A_0 + A_1 R & \text{for } -2 \leq R < 0 \\ A_0 - 2A_1 & \text{for } R < -2 \end{cases} \quad (9)$$

$$\begin{aligned} A_0 &= (0.825 - 0.34\alpha + 0.05\alpha^2) \left[\cos\left(\frac{\pi S_{max}}{2 \sigma_0}\right) \right]^{\frac{1}{\alpha}} \\ A_1 &= (0.415 - 0.071\alpha) \frac{S_{max}}{\sigma_0} \\ A_2 &= 1 - A_0 - A_1 - A_3 \\ A_3 &= 2A_0 + A_1 - 1 \end{aligned} \quad (10)$$

$$\Delta K_{th} = \frac{\Delta K_0 \left(\frac{a}{a+a_0} \right)^{1/2}}{\left(\frac{1-f}{(1-A_0)(1-R)} \right)^{(1+C_{th}R)}} \quad (11)$$

$$\frac{K_{crit}}{K_{Ic}} = 1 + B_k e^{-(A_K \frac{t}{t_0})^2} \quad (12)$$

Where t_0 is the plane strain condition and defined by Eq. 13.

$$t_0 = 2.5 \left(\frac{K_{Ic}}{\sigma_{ys}} \right)^2 \quad (13)$$

The required constants already exist in the material library as general fatigue material constants [31], and have been used for this study.

5.2 FCG life estimation methodology

To perform a FCG analysis, the material type and dimensions of the specimen were given, for which the required material property of the formula was available in the library. Furthermore, the value of ΔK_0 was chosen based on the given value in the library data of the software, for aluminum 7075 T-6.

$$\Delta K_0 = 3.297 MPa\sqrt{m} \quad (14)$$

6. Fatigue life

The sum of the lives spent on FCI and FCG is the fatigue life of the specimens. Therefore, the fatigue lives of the specimens under different loading conditions were estimated by this procedure, and compared to the available experimentally obtained lives. In addition, the following error function was used to calculate the deviation from the experimental results.

$$ER = \log \left(\frac{N_p}{N_e} \right) \quad (15)$$

$$\overline{ER}\% = \left(\frac{1}{n} \sum_{i=1}^n |ER_i| \right) \times 100 \quad (16)$$

7. Results and discussion

Using the procedures described above, separately for each section, the results for different cases of loading were derived and recorded as follows.

7.1 Finite element simulations and analyses

The finite element model was solved under four clamping conditions of $F_{cl} = 0, 244, 3409, 6818$ N, together with the longitudinal cyclic loads of $S_{max} = 110, 190, 240$ MPa. In other words, the combination of each of the two sets was solved for.

To better visualize the effects of the two types of loadings, the combination of maximum longitudinal load in the different clamping forces, from the above combination are chosen to be shown in this section, in Figs. 9-12.

Figure 7. Longitudinal stress distribution contour (MPa), X direction, after applying a 240MPa remote stress in open-hole condition

Figure 8. Longitudinal stress distribution contour (MPa), X direction, after applying a 240MPa remote stress, with a clamping force of $F_{cl}=244$ N

Figure 9. Longitudinal stress distribution contour (MPa), X direction, after applying a 240MPa remote stress, with a clamping force of $F_{cl}=3409$ N

Fig. 10. Longitudinal stress distribution contour (MPa), X direction, after applying a 240MPa remote stress, with a clamping force of $F_{cl}=6818$ N

It can be seen that with a higher clamping force or preload, both the magnitude and the distribution of unfavorable resultant tensile stresses around the hole is reduced. In other words, the more clamping force or favorable compressive stresses around the hole, the less the likelihood of fracture and reaching to the threshold resistance of the structure for rupture.

7.2 FCI

The stress-life or S-N diagrams for FCI life portion is plotted, to interpret and compare different models and methods. The diagrams based on the four chosen models, along with the proposed life estimation methods, for the highest clamping force is presented in Figures 13-16.

Fig. 11. The FCI life graph variations based on the Fatemi-Socie criterion and the four proposed methods

Fig. 12. The FCI life graph variations based on the Glinka criterion and the four proposed methods

Fig. 13. The FCI life graph variations based on the S.W.T criterion and the four proposed methods

Fig. 14. The FCI life graph variations based on the Findley criterion and the four proposed methods

It can be seen that the predictions based on the volume and weighted-volume method present more optimistic values, compared to the point and surface methods, and just by considering FCI life, because their graphs fall on top of the methods of point and surface. Moreover, the results of

fractographic investigations, taken from the Ref. [39], and depicted in Fig. 15, show that for most of the loading cases the point of crack initiation is located close to the middle part of the thickness of the specimen, while with reducing the clamping force and the cyclic loading amplitude it might move downwards, for some cases. This matches with the numerical predictions. To show the correspondence between the experimental results of crack initiation and the numerical ones predicted by the analysis, the predicted crack initiation region shown by green dots in Fig.16, is plotted for different clamping and longitudinal loads. The red colored regions are the maximum stress areas in the figures. Therefore, the proposed methods nonetheless have resulted in good approximation of the point for the onset of crack or crack initiation location. The finding is also obvious from the stress contours of finite element solution in Figs. 9-12.

In the derived stress contours under different loading conditions it is obvious that the magnitude and distribution of the desirable compressive stresses around the hole, which delay the fracture under the fatigue loading, are more in the top or the surface of the specimen compared to the middle plane. This means that the final resultant stress that appears after applying the cyclic or fatigue longitudinal loading becomes greater in the middle regions of the thickness of the plate, and makes that region a more potential site for the initiation of the fatigue crack. This further approves the aforementioned analysis and conclusion in the previous paragraph.

Fig. 15. Results of the fractography for different clamping force and remote stress [39].

Fig. 16. The results of fatigue crack initiation location prediction via the applied method

7.3 FCG

The results of the FCG analysis are observable in the Fig.17 for the crack propagation in the C direction, and in the Fig.18 for the crack in the A direction. Furthermore, the graphs represent crack length-FCG life graphs for the cyclic stress amplitudes of 110, 190 and 240 respectively. The increase in the FCG life with an increase in the clamping force was expected and is observable in life graphs in both of the directions. However, the influence tends to alleviate, as a higher cyclic stress is applied on the specimen. In addition, the comparison between the growth rates in A and C direction shows that a higher crack growth rate exists in the A direction. Considering this and knowing that there is a smaller size in this direction, the smaller FCG life in this direction becomes justified.

Fig. 17. Crack length growth vs Life, in the C direction for the remote stress amplitudes of 110 MPa (left), 190 MPa (right) and 240 MPa (center)

Figure 18. Crack length growth vs Life, in the A direction for the remote stress amplitudes of 110 MPa (left), 190 MPa (right) and 240 MPa (center)

7.4 Fatigue Life

Finally, the S-N diagrams are represented together with the experimental graphs for different remote stress amplitudes in Figs.19-22. Evidently, each single diagram is represented for different models estimation with one of the four methods of volume, weighted volume, surface and point, respectively.

Figure 19. S-N diagrams based on volume method and the different multiaxial criteria, in different clamping forces

Fig. 20. S-N diagrams based on weighted volume method and the different multiaxial criteria, in different clamping forces

Fig. 21. S-N diagrams based on surface method and the different multiaxial criteria, in different clamping force

Fig. 22. S-N diagrams based on point method and the different multiaxial criteria, in different clamping forces

A single consecutive glance on the graphs will lead one to the conclusion that the Fatemi-Socie model presents generally better, at the same time optimistic approximations (non-conservative); whereas, Findley and S.W.T result in more conservative approximations of fatigue life. When considered the fatigue loading regime in the results analysis, at medium and high clamping forces, 3409 N and 6818 N, Findley and S.W.T show better results in HCF when used with the volume and weighted volume method. For this case Glinka model when used with the volume and weighted volume also shows good accuracy. However, in LCF regime Fatemi-Socie model when used with the weighted volume method predicts better at the mentioned clamping forces. At low clamping forces, open-hole and 244 N, Fatemi-Socie model shows good agreement with the experimental results both in the low cycle and high cycle fatigue regime, when used with the point or surface method.

To better comprehend the presented graphs, the error percentage for each case is calculated and shown in the following tables by using the error estimation function of Eqs. 15 and 16.

Table 2. The estimate errors for fatigue life calculations

<i>point</i>					<i>surface</i>				
	<i>open hole</i>	<i>F_{cl}=24 4N</i>	<i>F_{cl}=340 9N</i>	<i>F_{cl}=681 8N</i>		<i>open hole</i>	<i>F_{cl}=24 4N</i>	<i>F_{cl}=340 9N</i>	<i>F_{cl}=681 8N</i>
<i>Fatemi-Socie</i>	1.55	7.28	19.74	17.73	<i>Fatemi-Socie</i>	4.87	3.99	20.23	13.34
<i>Glinka</i>	34.84	25.97	17.57	18.97	<i>Glinka</i>	30.39	24.02	18.79	20.08
<i>S.W.T</i>	38.13	46.92	36.05	51.37	<i>S.W.T</i>	35.98	44.72	34.89	49.43
<i>Findeli</i>	52.29	60.05	59.81	57.83	<i>Findeli</i>	50.22	58.46	58.98	55.46

<i>volume</i>					<i>weighted volume</i>				
	<i>open hole</i>	<i>F_{cl}=24 4N</i>	<i>F_{cl}=3409 N</i>	<i>F_{cl}=6818 N</i>		<i>open hole</i>	<i>F_{cl}=24 4N</i>	<i>F_{cl}=340 9N</i>	<i>F_{cl}=681 8N</i>
<i>Fatemi-Socie</i>	53.33	45.37	34.63	39.91	<i>Fatemi-Socie</i>	42.72	34.64	20.17	28.59
<i>Glinka</i>	54.97	49.46	24.47	24.45	<i>Glinka</i>	48.29	42.66	17.25	17.29
<i>S.W.T</i>	4.07	11.61	2.84	14.87	<i>S.W.T</i>	12.13	19.89	11.02	23.47
<i>Findeli</i>	15.72	23.69	24.52	18.58	<i>Findeli</i>	24.57	32.32	32.70	27.46

A method-based analysis and zoom-in on the tables, will lead us to the conclusion that when using the Findley and S.W.T models, weight and weighted volume method result in better approximations. When using the Fatemi-Socie and Glinka model, However, the point and surface methods present better results.

In addition, discussing the tables from a preload-based point of view brings about the inference that for the high clamping force or preload, S.W.T method via the volume and weighted volume generally present low errors. For the case of lower preload nevertheless, utilizing the surface and point methods via the Fatemi-Socie model ends in lower fatigue life estimation errors.

8. Conclusion and summary

In this research the FCI and FCG lives of the clamped and longitudinally loaded bolted flat specimens, made from aluminum 7075-T6, were investigated numerically. To do so, a precise complete finite element model of the assembly was made in the ANSYS Workbench environment. The model was solved under conditions exactly simulated based on the real test situation. Then, the reasonable and precise contours and data of the stress and strain were used for FCI and FCG life estimations. FCI life was calculated using the code written in the Matlab environment. The code used the four well known multiaxial fatigue criteria and models of Fatemi-Socie, Glinka, Findley and S.W.T, while benefited from the critical plane approach. Four optimized methods of point, surface, volume and weighted volume were introduced and used in the final step of FCI life estimation, each proved to be working well with a model. FCG life was estimated using the AFGROW software. Finally, the summation of the two lives for different loading cases was compared to the available experimental data. The results showed good agreement with the experimental ones, based on the presented conclusions. Additionally, the following achievements were attained:

- Four optimized methods of numerical fatigue life estimation were proposed. The idea which is borrowed from the microstructural concepts of a crystalline material, presents a better method for applying the aforementioned models by improving the accuracy of their estimation. Furthermore, it ascertains that the derived critical point is not a singular point, coming from numerical errors, backed up by the fact that fatigue damage is rather a local and not point phenomenon.
- The estimated fatigue crack initiation life graphs exhibited the difference between the four proposed methods. The volume and weighted volume method proved to be more optimistic methods for life prediction, since their graph fall on the top of the life graphs for point and surface methods
- The method demonstrated a good accuracy in approximating the point or region of failure. It was witnessed that for most of the cases the point for the onset of crack is close to the middle of the specimen thickness, while decreasing the clamping force or the stress amplitude resulted in the movement of the point downwards, for some of the cases. This matches with the fractographic experimental results.
- The analysis of the estimated fatigue lives, from the summation of the portions for FCI and FCG, led the authors to the conclusion that the Fatemi-Socie presents better predictions and at the same time is more non-conservative; while, the Findley and S.W.T models make more conservative estimations.
- A more in-depth comparison of the results using the error index function was presented. A method-based data analysis showed that when using the Findely and S.W.T models the weighted volume and volume methods is better to be used to have lower prediction errors; while an integration of the Glinka and Fatemi-Socie models with the point and surface results in better life predictions. On the other hand, a pre-load based analysis of the error tables, demonstrates that in the case of high clamping force or pre-load, the S.W.T model with the volume and weighted volume make low error predictions; while for the cases of lower clamping force and pre-load the surface and point methods with the Fatemi-scoie model make better life estimations.

- Conclusively, *at middle to high clamping forces*, using the Findley or S.W.T models with the volume and weighted volume method is preferred when in high cycle fatigue regimes. For this case Glinka model with the volume and weighted volume also shows good accuracy. However, Fatemi-Socie model with the weighted volume method is a better choice for the low cycle fatigue regime. At *low or no clamping forces* the Fatemi-Socie model with the point or surface method is the preferred combination for both low and high cycle fatigue regime.
- The error percentage in the numerical estimations of fatigue life compared to the same ones reported in the referenced works and the ones in the field, is improved.
- The effect of precise and complete modeling on the accuracy of the results is seen both on the final results and stress contours variations.

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