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Fatigue Crack Initiation Life Prediction for a Flat Plate with a Central Hole

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ABSTRACT

This work constructs an effective procedure that combines the finite element and strain-life methods in order to accurately predict fatigue crack initiation (FCI) life and then establish an estimated schedule of fatigue life. The proposed procedure is applied to a flat plate with a central hole to obtain predicted lives. The results from the proposed method are compared with those of Juvinall's stress-life method, Socie's local strain method and Bannantine's summary experimental data. Comparative results demonstrate that the fatigue life estimated by the novel procedure closely approximates the experimental results.

Key Words: stress concentration, finite element method, crack initiation life.

圓形開孔板結構裂縫起始壽命評估

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摘 要

本文利用有限元素法與應變壽命評估方法整合後建立一有效準確的疲勞裂縫起始壽命評估程序，並針對開孔零件進行疲勞壽命評估，此外並與 Juvinall 應力壽命法、Socie 局部應變法及 Bannantine 等人所整理之實驗結果做一比較、驗證，驗證結果顯示本文建議之評估程序與實驗數據接近。

關鍵詞： 應力集中，有限元素法，裂縫起始壽命。

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Ⅰ. INTRODUCTION

Nearly all mechanical components and structures contain geometrical discontinuities and notches. For example, pressure vessels always have openings for functional requirements, while shafts contain keyways and steps. Stress concentration will be produced in these discontinuity notches as a result of external force. The stresses are generally higher than the nominal values, and if proper care is not taken, notches could be sites of crack initiation and subsequent crack propagation may cause structural elements to fail. To evaluate a notch of structure components, predicting fatigue strength in relation to design and safety considerations is relevant.

Fatigue life prediction of notched members has been extensively studied [1-18]. Fatigue life prediction for notched members may be approached from several viewpoints. For estimating fatigue crack initiation life, many researchers [1-7] have supplemented the traditional approach, which is based on nominal stresses, stress concentration factors and local stress-strain concepts. Meanwhile, many researchers employed the equivalent strain-energy density method to predict fatigue crack initiation (FCI) life. The above analyses assumed the crack propagation part of fatigue life to be extremely small. The fracture mechanics [8-12] approach is extensively applied for crack propagation. These methods integrate the crack growth rate equation from a predetermined initial size to a final crack size to estimate crack propagation life. For estimating total life, several investigators [13-16] have combined the two analyses to estimate total fatigue, by combining the estimated results for crack initiation and crack propagation. Furthermore, Haibach et al. [17] and Juvinall [18] used the concept of S-N curve to estimate fatigue life for unnotched and notched specimens.

This work constructs an effective procedure by combining the finite element and strain-life methods to predict FCI life and then establishing an estimated fatigue life schedule. The proposed procedure can obtain the complete distribution of structural strains and strain-time history at the notch by using the finite element method (FEM), and can also obtain the fatigue life at any location in the structure by smooth specimens fatigue resistance. Additionally, this investigation considers interaction between load-time history, and Miner’s rule can be used to calculate the cumulative damage in the FCI phase. The proposed procedure is then applied to a flat plate with a central hole, and the results compared with those of Juvinall’s [18] stress-life method, Socie’s [7] local strain method, and Bannantine’s summary experimental [19] data. Comparative results demonstrate that the fatigue life estimated by the novel procedure closely approximates experimental results.

Ⅱ. FATIGUE-ANALYSIS PROCEDURE

Fatigue cracks are initiated easiest at the surface of the notch, and are concentrated by material or geometric stress raisers. Therefore, care must be taken in life prediction to account for processing and other factors that alter the surface and create stress raisers. Accordingly, in this study, predicting fatigue life notched specimens involves structural and fatigue analysis of critical areas using elasto-plastic FEM analysis, as illustrated in Fig. 1.

A. Structural Analysis

The structural analysis calculated the stresses and strains in a highly stressed region where slip concentrates from the input loads for a given material and geometry. The structural analysis allows strains and stresses to be calculated at each time increment following a finite element method, in which loading history is the input of the structural model. The stress-strain field in these critical areas within the structures can also be found via the finite element method.

B. Fatigue Analysis of Critical Areas

The FCI approach involves the following technique for converting load history, structure geometry, and material cyclic properties input into a fatigue life prediction. The operations involved in the prediction must be performed sequentially, as shown in Fig. 1. First, the stress and strain at the critical site are estimated, and ‘Rainflow’ cycle counting is then used to reduce load-time history into a number of constant amplitude events. The next step is to use the elasto-plastic FEM to convert a reduced load-time history (load events) into a strain-time history (strain events) and calculate the stress and strain in the highly stressed area. Then the strain-life methods that incorporate mean stress effects are employed for predicting structural fatigue life. Following this, the simple linear damage hypothesis proposed by Palmgren and Miner is used to accumulate the fatigue damage. Finally, the stress and strain at the critical location are used to compute damage, with their historical values being summed algebraically until a critical damage sum (failure criteria) is reached. The point at which the failure criteria are met is the predicted life.

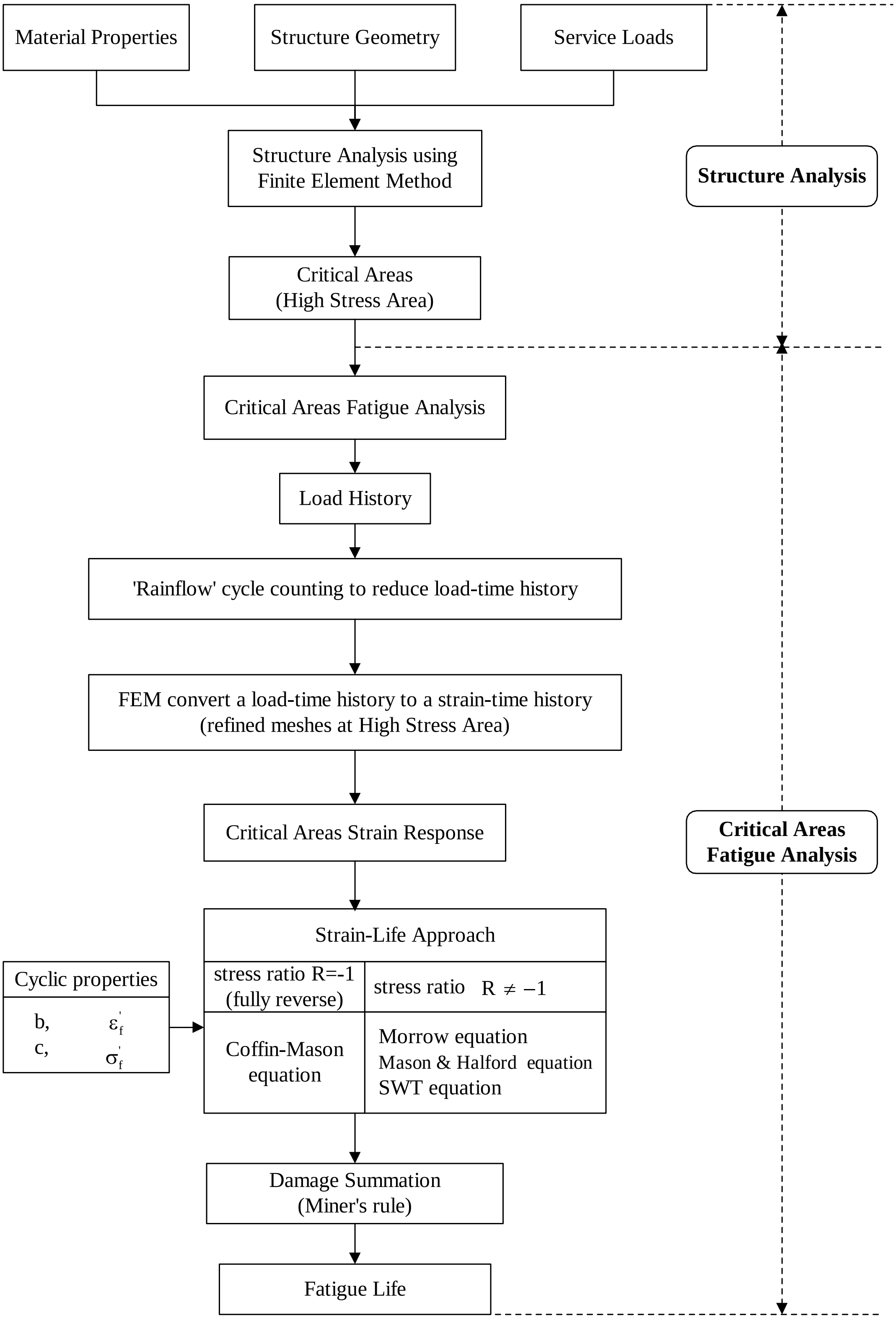


Fig. 1. Life prediction flow chart.

1. Strain-Life Properties

The fatigue resistance of metals can be characterized by a strain-life curve. These curves are derived from polished laboratory specimens that are tested under completely reversed strain control. The relationship between total strain amplitude, $\Delta\varepsilon/2$, and reversals to failure, $2N_f$, can be expressed through the following form [20,21]:

$$\frac{\Delta\varepsilon}{2}=\frac{\sigma_f^{'}}{E}(2N_f)^b+\varepsilon_f^{'}(2N_f)^c \qquad (1)$$

where $\sigma_f^{'}$ is the fatigue strength coefficient ; b is the fatigue strength exponent ; $\varepsilon_f^{'}$ is the fatigue ductility coefficient ; c is the fatigue ductility exponent.

The Strain-life equation has been modified to account for mean stress effects. Morrow [22] suggested that the mean stress effect could be taken into considered by modifying the elastic term in the strain-life equation by mean stress, σ_o.

$$\frac{\Delta\varepsilon}{2}=\frac{\sigma_f^{'}-\sigma_o}{E}(2N_f)^b+\varepsilon_f^{'}(2N_f)^c \qquad (2)$$

Mason and Halford [23] modified both the elastic and plastic terms of the strain-life equation to maintain the independence of the elastic-plastic strain ratio from mean stress.

$$\frac{\Delta\varepsilon}{2}=\frac{\sigma_f^{'}-\sigma_o}{E}(2N_f)^b+\varepsilon_f^{'}\left(\frac{\sigma_f^{'}-\sigma_o}{\sigma_f^{'}}\right)^{c/b}(2N_f)^c \qquad (3)$$

Meanwhile, Smith, Watson, and Topper (SWT) [24] have proposed another equation to represent mean stress effects.

$$\sigma_{max}\frac{\Delta\varepsilon}{2}=\frac{(\sigma_f^{'})^2}{E}(2N_f)^{2b}+\sigma_f^{'}\varepsilon_f^{'}(2N_f)^{b+c} \qquad (4)$$

where

$$\sigma_{max}=\frac{\Delta\sigma}{2}+\sigma_o \qquad (5)$$

When the fatigue properties for a given metal are known and the service environment is defined, the complex problem of fatigue-life prediction becomes a simple matter of determining the local-strain amplitude and mean stress for each reversal so that Eqs. (1) to (4) can be solved for life.

2. Cycle Counting

Currently widespread cycle counting techniques are the level-crossing method, peak counting method, range counting method, range-pair method and rainflow method. Of these various methods, the rainflow method has been shown to be superior and yields the best fatigue-life estimates. Reducing the measured history into a series of cycles and half cycles consistent with basic material behavior is critical, and ‘Rainflow’ cycle counting is established herein as the soundest technique for achieving such a reduction [25-26]. Fatigue life can then be predicted by combining the results of the cycle count with relevant basic data using the simple linear cumulative damage hypotheses.

Ⅲ. ANALYTICAL MODEL

To assess whether the use of the more accurate present calculation procedure improves fatigue-life prediction, predictions made with Juvinall's stress-life method, Socie's local strain method and the method presented herein are compared with experimental results.

Table 1. Material properties of specimen [19].

Property	*Units*	Medium strength steel (A)	Low strength steel (B)	High strength aluminum (C)
Monotonic properties				
Elastic modulus, E	GPa	208.6	208.6	698.5
Yield stress, S_y	MPa	648	351.6	537.8
Tensile stress, S_u	MPa	785.9	537.8	586
True fracture strength, σ_f	MPa	1551.2	1172	655
True fracture ductility, ε_f		1.139	1.10	0.145
Cyclic properties				
Fatigue ductility coefficient, ε_f'		1.142	0.338	0.158
Fatigue ductility exponent, c		-0.67	-0.480	-0.83
Fatigue strength coefficient, σ_f'	MPa	1165.2	1117	1661.6
Fatigue strength exponent, b		-0.081	-0.110	-0.15
Cyclic strength coefficient, K'	MPa	1061.8	1337.6	696.4
Cyclic strain hardening exponent, n'		0.123	0.226	0.040

A. Specimen and Material Properties

The materials used herein are medium strength, low strength steel and high strength aluminum, Table 1 [19] lists its basic monotonic and cyclic strain-life properties as measured during the smooth specimen tests. These data are used here for the stress-strain and fatigue analysis of the notched specimens. Figure 2 displays the geometry and dimensions of the specimens. The specimens have been constructed for constant-amplitude uniaxial loading (see Fig. 2) with a stress ratio of R= –1. Table 2 to 5 [19] list the applied load amplitude and fatigue life for the notched plates.

Table 2. Load amplitude and fatigue life for specimen A (R= -1) [19].

Specimen Number	Load Amplitude (N)	Fatigue Life (cycles)
A-1	62230.32	68
A-2	56269.73	190
A-3	53867.70	265
A-4	47373.33	1,250
A-5	40122.76	3,600
A-6	40167.25	2,400
A-7	31137.40	11,500
A-8	25265.78	55,400
A-9	23975.80	—
A-10	22018.59	160,780

Table 3.Load amplitude and fatigue life for specimen B (R=-1) [19].

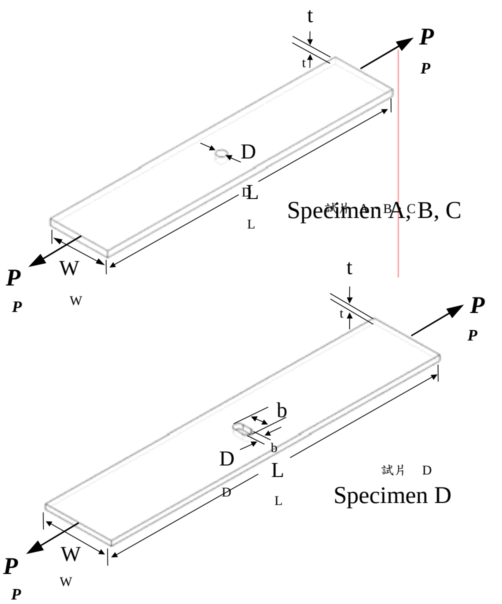
Specimen Number	Load Amplitude (N)	Fatigue Life (cycles)
B-1	78466.25	3,603
B-2	78466.25	2,800
B-3	65388.54	13,340
B-4	52310.83	51,960
B-5	47106.44	129,000
B-6	41857.56	230,460
B-7	39233.12	424,750
B-8	36653.17	589,510
B-9	34028.73	1,180,700

Table 4.Load amplitude and fatigue life for specimen C (R=0.1) [19].

Specimen Number	Maximum Load (N)	Fatigue Life (cycles)
C-1	21351.36	4,850
C-2	17792.80	8,850
C-3	14234.24	22,600
C-4	10675.68	238,000
C-5	7117.12	2,650,000

Table 5. Load amplitude and fatigue life for specimen D (R=0.1) [19].

Specimen Number	Maximum Load (N)	Fatigue Life (cycles)
D-1	21351.36	2,190
D-2	17792.80	5,900
D-3	14234.24	10,800
D-4	10675.68	27,500
D-5	7117.12	2,100,000



Specimen	t (mm)	d (mm)	L (mm)	W (mm)	b (mm)
A	7.62	12.70	254	25.40	
B	5.72	12.70	254	50.80	
C	2.03	12.70	254	50.80	
D	2.03	6.35	254	76.20	12.70

Fig. 2. Geometry of the specimens.

B. Finite Element Model for Notched Plates

This investigation develops a two-dimensional symmetrical plane stress model to find critical site and convert a load-time history into a strain-time history by using the finite element method. Two dimensional plane elements were employed in the models. The analysis assumes that symmetry exists around the centerline, accounting for why only 1/4 side of the specimen is modeled. Figure 3 displays the finite element meshes for specimen A-6, showing the refined mesh used around the stress concentration area. The symmetric model contains 520 elements and 592 nodes after meshing. In this study, the FEM analysis assumed that the material followed the von Mises yield criterion and the associated flow rules. Linear kinematic hardening was assumed.

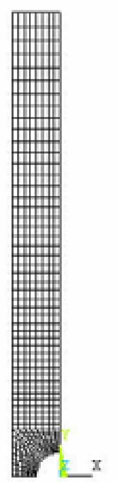


Fig. 3. The finite element mesh for the notched plates (specimen A).

C. Juvinall's Stress-Life Method

The fatigue notch factor, K_f, can be used to correct the entire S-N curve for notched members. A general trend is that the value of fatigue notch factor decreases with increasing stress level. In most design cases the fatigue notch factor needs to be correct for shorter lives. The fatigue notch factor for stresses corresponding to lives of 1000 cycles has been defined as $K_f^{'}$. Figure 4. shows an empirical relationship between the correction for $K_f^{'}$ and ultimate strength of different materials. The resulting corrected S-N curve for a notched member is show in Fig.5. This method is referred to as the Juvinall's stress-life method.

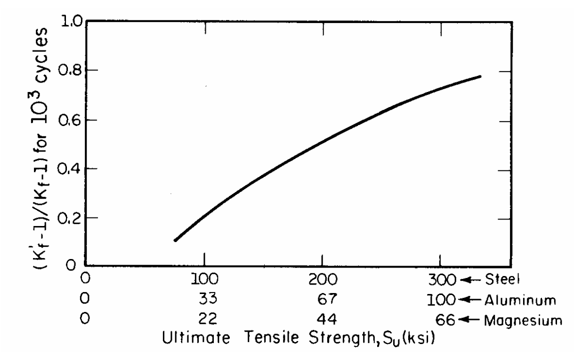


Fig. 4. Relationship between $K_f^{'}$ and K_f as a function of ultimate strength [18].

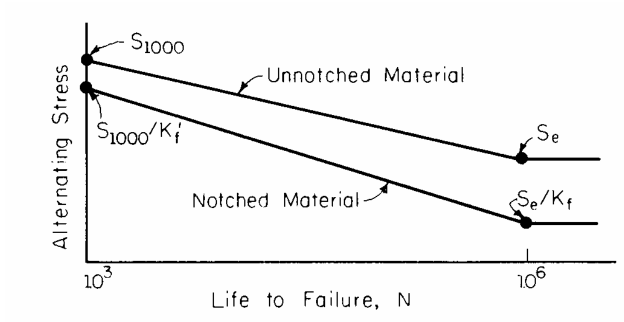


Fig. 5. Juvinall's stress-life method [19].

Ⅳ. RESULTS AND DISCUSSION

A. Verification of the Proposed Procedure

To consider the influence of stress concentrations on the predicted fatigue life of the specimens and confirm the accuracy of the present calculation procedure, the procedure proposed herein is compared with those of Juvinall's stress-life method, Socie's local strain method and experimental data of specimen A.

1. Analysis of Critical Areas

Stress acting along the loading direction is known as axial stress, and is denoted by σ_y. Figure 6 illustrates the contours of σ_y for load P = 40167.25 N of specimen A-6. The critical areas of the stress-strain field of the notched plates were found by the finite element method. As Fig. 6 displays, a high tensile stress occurred at point 'MX' along the central hole.

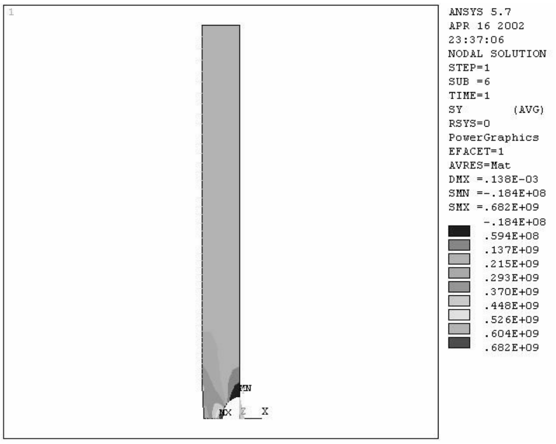


Fig. 6. Contours of σ_y

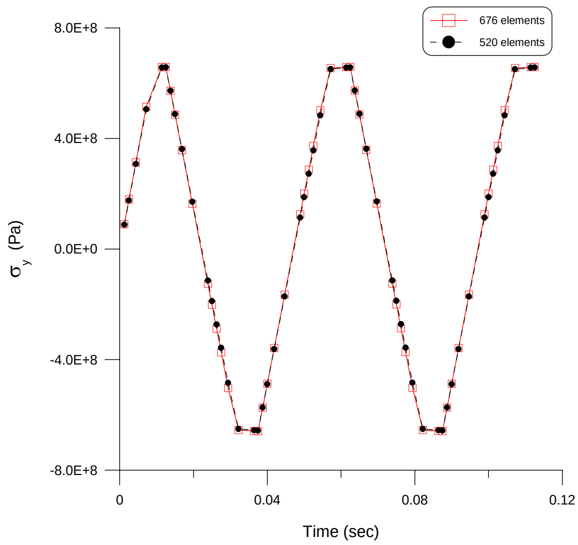


Fig.7. The stress-time history at point 'MX' for specimen A-6.

2. Mesh Sensitivity Study

The size of the finite element mesh has a great effect on the accuracy of the results and computational cost. To examine the adequacy of element size, effect of mesh refinement in the stress concentration area was studied. The refined meshes for specimen A-6 consists of 676 elements and 756 nodes. Figure 7 presents the axial stress-time history at point 'MX' for uniaxial load amplitude, $\frac{\Delta P}{2}$ = 40167.25 N with 520 and 676 finite element mesh models. Similar distributions of the results near the critical site obtained from the simulations using these two finite element meshes are observed, and we remark that the model is not sensitive to the finite element mesh refinement when the number of elements is equal to or greater than 520. Therefore, the original finite element model without mesh refinement in the butt-welded joints can be worked for this study.

3. Predicting Fatigue Life for Specimen

The proposed procedure can predict fatigue life for the specimens because the cyclic strain (stress)-time history and the strain (stress) range of the specimens on point 'MX' are determined. Following section 4.1 analysis with the finite element method, specimens A-1 to A-6 are into plastic scope while specimens A-7 to A-10 remain in elastic scope. Figure 8 presents the cyclic stress-strain curve of specimens A-1 to A-6 at point 'MX', and Fig. 9 displays the strain-time history of specimens A-7 to A-10 on point 'MX'. Owing to hysteresis loops of specimens A-1 to A-6 and the strain range of specimens A-7 to A-10 having been determined, a fatigue life analysis for the amplitude history can be performed by using a strain life equation. Figure 10 presents the results of applying various techniques to predicting the fatigue life of the notch plates (specimen A) under zero mean loads. The figure indicates that predictions of fatigue life using Socie's local strain method were conservative, while predictions by the Juvinall's stress-life method were not conservative. The closest agreement with experimental data was achieved by the procedure herein presented. Therefore, the procedure presented herein is suitable for analysis of the fatigue life of notched plates.

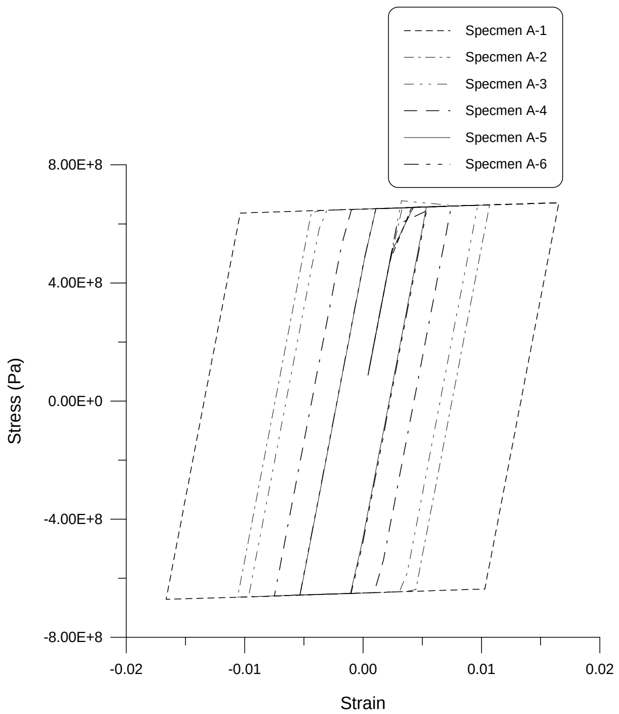


Fig. 8. Cyclic stress-strain curve of specimen A-1 to A-6.

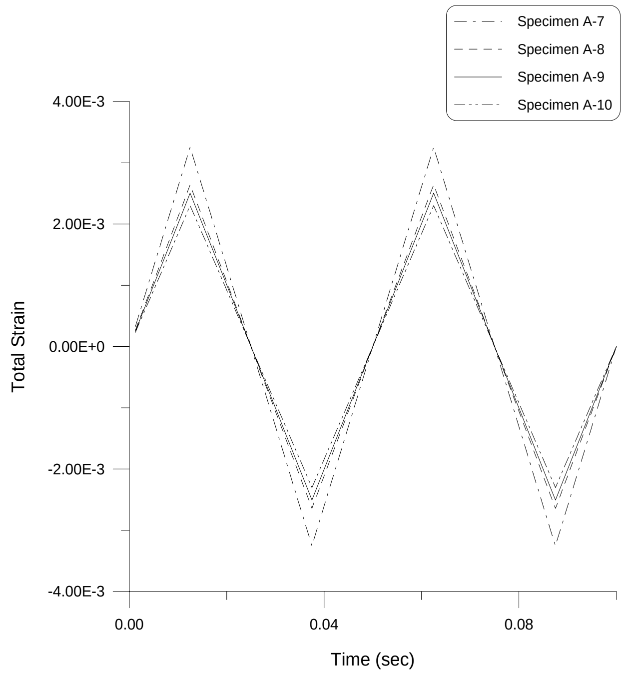


Fig. 9. Strain-time history of specimen A-7 to A-10.

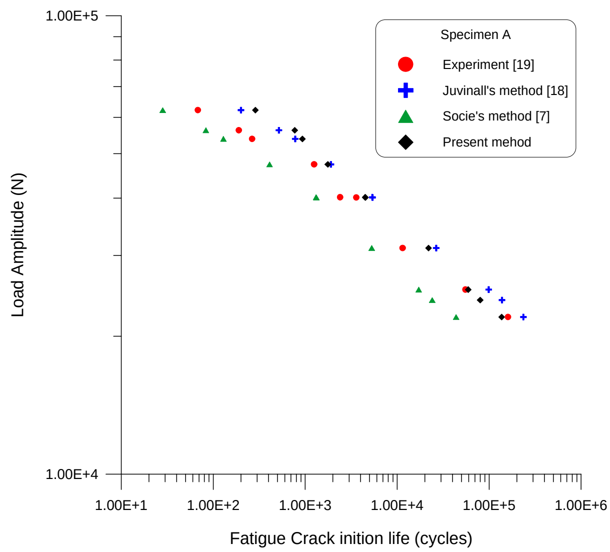


Fig.10. Various techniques for predicting the fatigue life of the notch plates (specimen A).

B. Effect of Mean Stress

Various predictions have been compared with experimental results taken from Bannaantine[19], based on different geometries, material properties, load amplitudes and stress ratios. Figure 2 illustrates the geometry and dimension of the specimens. Specimens B, C and D have been constructed for constant-amplitude uniaxial loading with a stress ratio, R, of –1, 0.1 and 0.1, respectively. Tables 3 to 5 [19] list the applied load amplitude and fatigue life for the specimens. Meanwhile, Fig. 11 presents various techniques for predicting the endurance of the notch plates (specimen B) under zero mean loads. The figure indicates that the fatigue life predictions using Socie's method were too conservative, while the predictions using Juvinall's method were conservative for high cycle regimes. The best agreement with experimental data was achieved by using the method presented herein along with the finite element method, cyclic stress-strain curve and strain-life relationship. Applying the present method rather than Socie's and Juvinall's method clearly enhances fatigue-life predictions the predictions were equally accurate for both low and high cycle fatigue-life regions. Figures 12 and 13 illustrate the fatigue life of specimens C and D for the present method combined with the Coffin-Manson, Morrow, Mason-Halford and SWT equations to account for the mean stress effect. As Figs. 12 and 13 indicate, the method presented herein combined with the SWT mean stress equation above also agrees strongly with the experimental data. Figures 14 and 15 present the predictive results of Juvinall's method and the novel method for specimens C, D under stress ratio, R, of 0.1. As Figs. 14 and 15 indicate, Juvinall's method cannot accurately predict fatigue life for mean stress effect and plastic behavior at the notch. The closest agreement with experimental data was achieved by the procedure herein presented, combined with the FEM, SWT strain-life relationship, and consideration of the effect of mean stress.

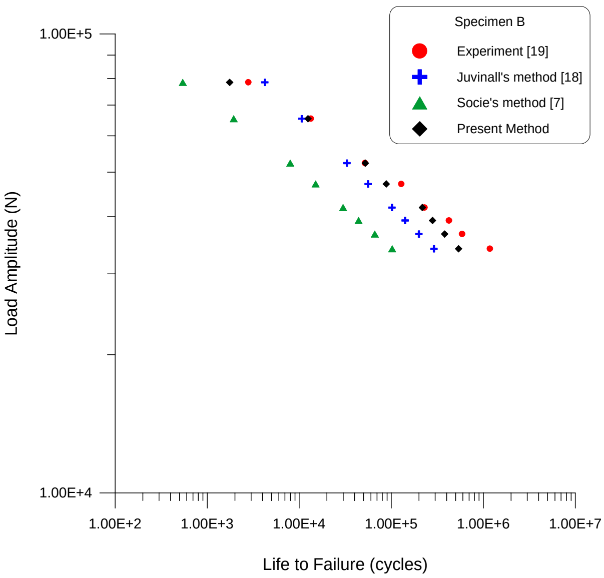


Fig.11.Various techniques for predicting the

fatigue life of the notch plates (specimen B).

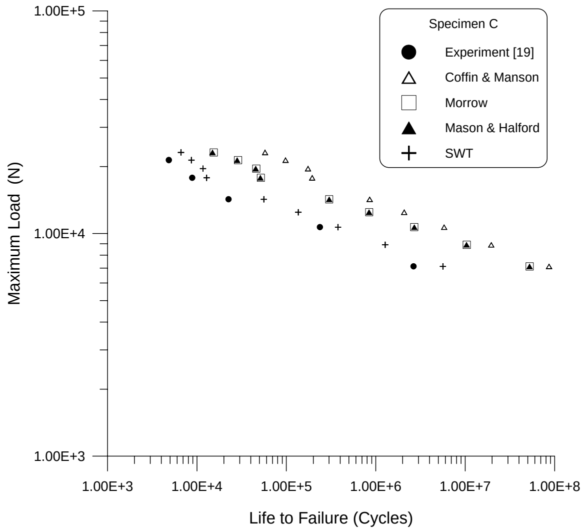


Fig.12. Fatigue life of the present method (Specimen C).

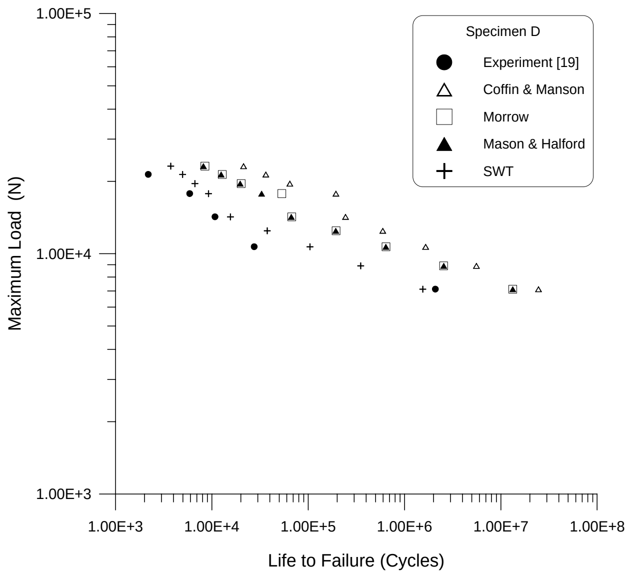


Fig. 13. Fatigue life of present method (Specimen D).

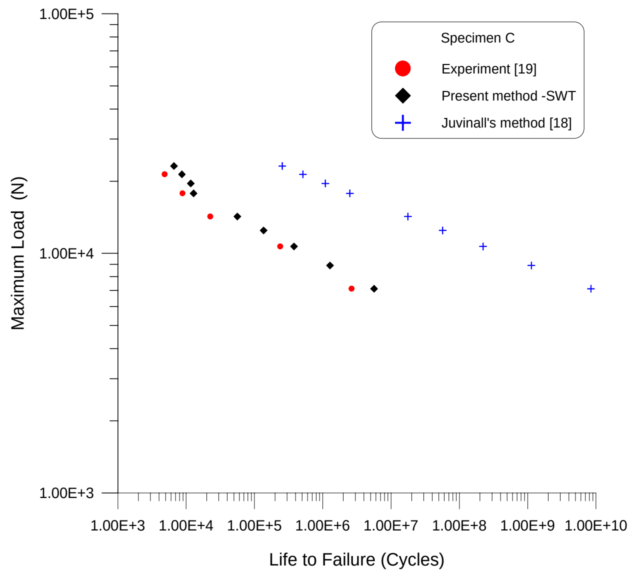


Fig.14. Fatigue life prediction of Juvinall's and the present techniques for specimen C.

Ⅴ. CONCLUSION

This study combined finite element structural analysis with strain-life equations to develop a simple and effective procedure for forecasting the fatigue crack initiation life of a flat plate with a central hole. The suggested

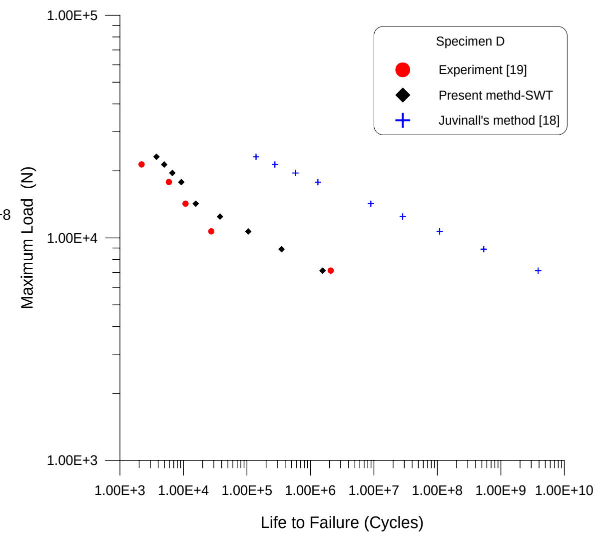


Fig. 15. Fatigue life prediction of Juvinall's and the present techniques for specimen D.

procedure is applied to various specimens with different materials, geometries, and stress ratios, and the predictive results are successfully compared with experimental data. Based on the results herein, the following conclusions are reached:

1. The Juvinall's [24] stress-life method achieves the most accurate results for high cycle fatigue (HCF), where the notch strains are predominantly elastic and loading is essentially constant. This approach does not account for inelastic behavior at the notch and cannot properly account for changes in notch mean stresses.
2. The relatively conservative fatigue life estimates yielded by Socie's local strain method (Neuber's rule) result from over prediction of the notch strain in the notch tip.
3. Applying the approach method rather than Socie's and Juvinall's method leads to an improvement in improve fatigue-life predictions, and the predictions are equally accurate for both the low and high cycle fatigue-life regions.
4. Variable amplitude loading effects are not specifically considered herein. However, the procedure suggested above provides a framework within which have been developed for handing the effects can be applied.
5. The proposed procedure, combined with three different mean stress effect equations, was used to evaluate fatigue life, revealing that the SWT equation agrees most closely with experimental data.

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