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Towards standardising the fatigue crack simulation studies on metallic materials

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Summary

Fatigue crack growth as consequence of service loads depends on many different contributing factors. This paper describes the fatigue crack growth behavior of metallic materials under cyclic loading towards standardizing the fatigue crack studies on metallic materials. For the simulation purpose, three points bend (TPB) with span to width ratio 8:1 and compact tension (CT) specimens geometry were used. There are many factors affecting the fatigue crack growth in structures, such as fatigue crack growth model, stress ratio, aspect ratio and type of geometry. The behavior of such cases is shown using different fatigue crack models (Paris, Forman and Austen). These models gave different fatigue crack growth behavior. The fatigue crack growth obtained from two specimens geometry was compared. Different values of these factors showed different effects on the fatigue crack growth. For further study need to validate the modelling procedure with experimental work as well as take into account the other factors such as; other types of geometries with fatigue crack models and environmental effects.

keywords: Cyclic loading, factors; fatigue crack growth model; geometry; simulation.

Introduction

The problem of crack growth is a major issue in the prediction and maintenance of aerospace structures, as well as other structural elements in mechanical and civil engineering projects. For the last three decades, fracture mechanics have been the main tool with which such problems have been treated. The fracture mechanics scientists and engineers have made tremendous advances, from the basic practical approach dominated by Paris–Erdogan law (1963), to more and more sophisticated crack growth models. Mathematical and metallurgical models, experimental analysis of simple models and testing of complex structures have resulted in thousands of publications, dozens of models for crack growth and life prediction. In some cases the difficulty of machining a full-size specimen has made investigators to design sub-size specimens (Jeelani, Natarajan and Reddy, 1986). There are many factors affecting the fatigue crack growth in structures, such as; stress ratio, thickness of the specimen or aspect ratio, types of specimen's geometry, fatigue crack growth model etc. A major concern of fracture mechanics is the influence of the load ratio on the behavior of cracks. This is expressed in the stress ratio (R), which is classically defined as: the ratio of minimum to maximum applied stresses (Ellyn and

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Li, 1984). To characterize the fatigue crack growth behavior of materials it is necessary to measure the fatigue crack growth curves (*da/dN–dK*) at different stress ratios (R). Many semi- empirical and empirical models for fatigue crack growth have been proposed in the literature to account for the stress ratio dependence of *da/dN–dK* curves (Forman, Kearney and Engle, 1967; Walker, 1970; Newman, 1981). It was argued that the reason for this influence is the crack closure effect. Crack closure introduced first by Elber (1970; 1971).

From previous literature on the effect of thickness on fatigue crack growth (FCGR) three different responses have been reported as follows:

1. FCGR accelerated by decreasing thickness (Tesch, Pippan and Doker, 2007);
2. FCGR decreased by decreasing thickness (Fujitiani, Sakai, Nakagawa and Tanaka, 1982; Heung, Kyung and Byong, 1996);
3. FCGR is not affected by thickness (Sullivan and Crooker, 1977).

Putatunda and Rigsby (1985) have reported that an effect of thickness and width on FCGR has not been found in tests conducted on aircraft quality AISI 4340 steel. Where Rickerby and Fenici (1984) reported an increase in *da/dN* with increase in specimen thickness in case of a 316 stainless steel in the low *dK* region. On the other hand Dover and Boutle (1978) have reported exactly the opposite findings in their work on aluminum alloys. Jack and Price (1972) have reported that the thickness effect on FCGR if any, was only above general yield but not below this level. Thus results reported by different investigators do not yield a general explanation for the thickness effect on FCGR

Due to the number and complexity of the mechanisms involved in the fatigue crack growth problem, no universal solution exists yet and there is no general agreement among researchers for any of the available models. Most of the results reported are dealing with geometry with some factors separately. In the present investigation, towards standardizing the fatigue crack studies for different geometries as well as the factors on metallic materials under cyclic loading. Tow types of specimens geometry were examined; three point bend specimen (8:1) and the compact tension shape. This study mainly focuses on the evaluating of the fatigue crack growth (FCG) with other factors. The results from TPB specimen are compared with those obtained on compact tension (CT) specimen geometry with application of the factors (initial crack length, stress ratio, aspect ratio and different fatigue crack models). All the results are compared to show their effects on FCG for the specimens.

Theoretical Background

A simple and well-known method for predicting fatigue crack propagation is a power law described by Paris and Erdogan (1963), and it is also known as the Paris

Law. The equation represents the first application of fracture mechanics to fatigue and is given by the following relationship:

$$\frac{da}{dN} = C_p (\Delta K)^{mp} \tag{1}$$

where *Cp* is the intercept and *mp* is the slope on the log-log plot of *da/dN* versus ΔK.

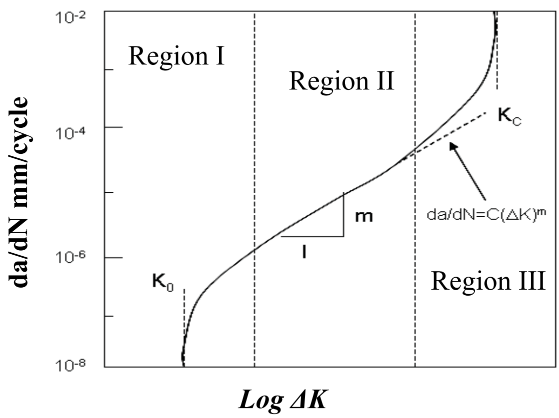

Figure 1: Typical da/dN versus ΔK curve

Eq. 1 represents a straight line on the log-log plot of *da/dN* versus ΔK and thus describes region II (Fig. 1) of the fatigue rate curve. The limitation of the Paris law is that it is only capable of describing data in region II. If the data exhibits a threshold (region I) or an accelerated growth (region III) Paris law cannot adequately describe these regions.

Although, Walker (1970) improved the Paris model by taking account of the stress ratio, neither model could account for the instability of the crack growth when the stress intensity factor approaches its critical value. Forman (1972) improved the Walker model by suggesting a new model, which is capable of describing region III of the fatigue rate curve and includes the stress ratio effect. The Forman law is given by this mathematical relationship

$$\frac{da}{dN} = \frac{C_F (\Delta K)^{m_y}}{(1-R) K_C - \Delta K} = \frac{C_F (\Delta K)^{m_y}}{(1-R)(K_C - K_{\max})} \tag{2}$$

where K_c is the fracture toughness for the material and thickness of interest. Eq. 2 indicates that as $K_{\max}$, approaches K_c & *da/dN* tends to infinity. Therefore, the Forman equation is capable of representing stable intermediate growth (region II) and the accelerated growth rates (region III). The Forman equation is capable of representing data for various stress ratios by computing the following quantity for each data point, i.e.

$$Q = \frac{da}{dN}\left[(1-R)K_C - \Delta K\right] \tag{3}$$

If the various Δ K and R combinations fall together on a straight line on a log-log plot of Q versus ΔK, the Forman equation is applicable and may be used. Comparing Eqs. 2 and 3, the Forman equation can be represented as:

$$Q = C_F\left(\Delta K\right)^{m_y} \tag{4}$$

The Austen (nCode, 2003) growth law implicitly models threshold is expressed in the following Eq.:

$$\frac{da}{dN} = C.\left(\Delta K_{eff}\right)^n \tag{5}$$

where

$$\Delta K_{eff} = \Delta K_{\max eff} - K_{\min eff}$$

$$K_{\max eff} = K_{\max} + K_{SF}$$

$$K_{\min eff} = \max(K_{\min}, K_{CL})$$

$$K_{SF} = \text{modification for static fracture}$$

$$K_{CL} = \text{stress intensity at closure}$$

Austen modeled the onset of fast fracture using the expression:

$$K_{SF} = \frac{K_{\max}}{K_{1c} - K_{\max}} \tag{6}$$

where K_{1c} is the plane strain fracture toughness.

Austen also takes account of the threshold and short cracks by applying a crack closure stress K_{CL} expressed as:

$$K_{CL} = K_{\max} = K_{\max}\cdot\sqrt{\frac{a+I_0}{a}} + \frac{\Delta K_{th}}{1-R} \tag{7}$$

The Austen model does not posses an explicit mean stress (R-ratio) correction. Austen argued the irrelevance of this and attributed it to a manifestation of crack closure and retardation.

Methodology

In this application TPB (8:1) and compact tension specimens geometry are used. The steel material selected with the mechanical and fatigue properties shown in Tab. 1. Components, structures are subjected to quite diverse load histories; their histories may be rather repetitive with different values. Constant load history used with the analysis. To account load ranges and mean of the used load history, rain flow accounting method was used. The two specimens geometry were analyzed under the constant amplitude load with different stress ratio from negative to positive shown in Tab. 2. The modeling and simulation analyzed based on nCode (Glyphwork) software (2003).

Table 1: Mechanical and fatigue properties of the material

Yield Stress (MPa) *YS*	324
Ultimate Tensile Strength (MPa) *UTS*	552
Plane Strain Fracture Toughness (MPa($m^{1/2}$)) K_{1C}	121
Plane Stress Fracture Toughness (MPa($m^{1/2}$)) K_{1D}	242
Paris Law Co-efficient (m/MPa($m^{1/2})^n$) C	3e-12
Paris law Exponent	3.43
Delta K threshold at R=0 (MPa($m^{1/2}$))m D_o	8
Delta K threshold at R>0 (MPa($m^{1/2}$))m D_1	2

Table 2: Fatigue loading of load histories with stress ratios

Stress Ratio (R)	Max. Load (KN)	Min. Load (KN)
- 0.3	146	- 44
- 0.15	165	-24
0	190	0.2
0.3	275	84
0.5	385	195

Results and Discussion

For given stress range, the number of cycles required for crack growth depends on the initial crack length. Local stress range ahead of the crack tip will be higher for a deeper crack than for shallow crack because the stress intensity factor is higher for deeper crack. This explains why the number of cycles required for crack growth in structures having a long crack would be less in comparison to the structures having a small crack. This shown clearly in the Figs. 2 and 3, and the differences between the numbers of cycles for the two specimens geometry in average are about 22%. This percentage begun with a small value at small initial crack length and increase with the increment in initial crack length, which cause a reduction in the number of cycles.

The effects of stress ratio (*R*) ranging from –0.3 to 0.5 on crack growth are

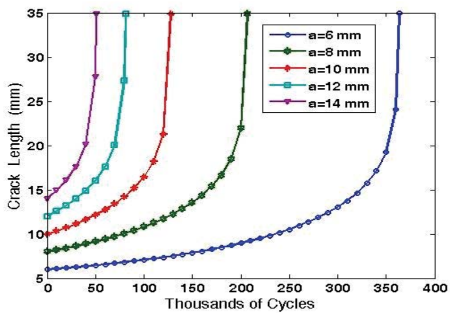

Figure 2: Effects of initial crack length on FCG for TPB

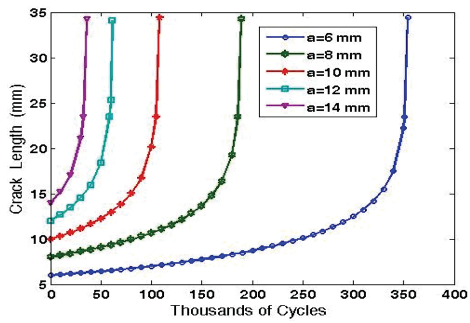

Figure 3: Effects of initial crack length on FCG for CT

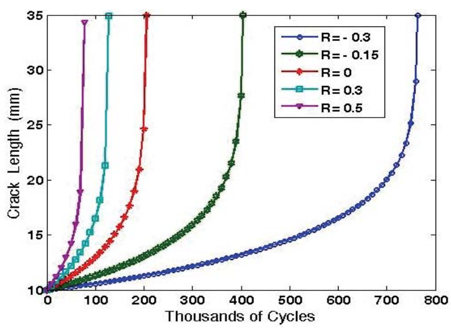

Figure 4: Effects of stress ratio on FCG for TPB

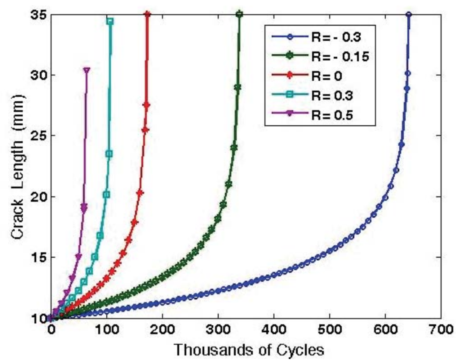

Figure 5: Effects of stress ratio on FCG for CT

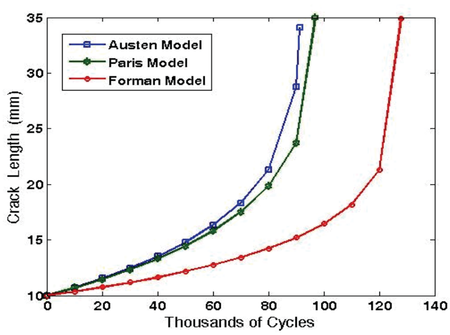

Figure 6: Effects of different FCG models for TPB

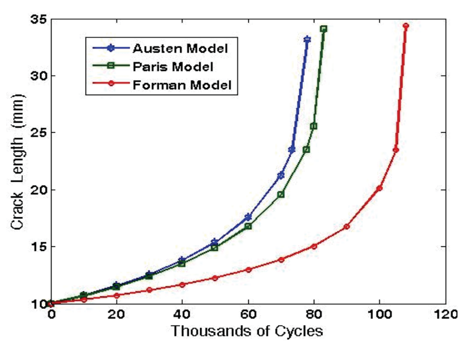

Figure 7: Effects of different FCG models for CT

shown in Figs. 4 and 5. Observation shows that specimen with higher stress ratio require less cycles for crack growth compared to that with lower stress ratio for the two specimens geometry. Although, the curves showed the same behavior, still the average difference of 16% for all values of R (from negative to positive values).

The results showed good agreement with that obtained by previous work (Maymon, 2007; Huang et al. 2008).

Due the number and complexity of the mechanisms involved in the fatigue crack growth problem, no universal model exists yet; there is no general agreement among researchers for any of the available models (Huang et al. 2008). Figs. 6 and 7 show the effect of using three different models namely, Austen, Paris and Forman for the TPB and CT geometries. The number of cycles calculated by Forman model is more than that calculated by Paris and Austen models by 23% and 28% respectively. While the differences for the two models (Paris and Austen) are very small (6%), due to the differences in main concept of the above models. The limitation of the Paris model is that, it is only capable of describing data in region II, while Austen model takes account of the threshold and short cracks, which leads to the minimum number of cycles. Forman is capable of describing region III of the fatigue rate curve and capable of representing stable intermediate growth (region II). The Forman equation is capable of representing data for various stress ratios, so Forman model is more preferable than the other two models.

Among the factors affecting the crack growth studied is the aspect ratio (α), which shown in Figs. 8 and 9. The two Figures showed that increasing the aspect ratio gives low number of cycles and verse vise. The difference in the number of cycles for the two specimens is about 20% in average, but still the number of cycles calculated for TPB higher than CT.

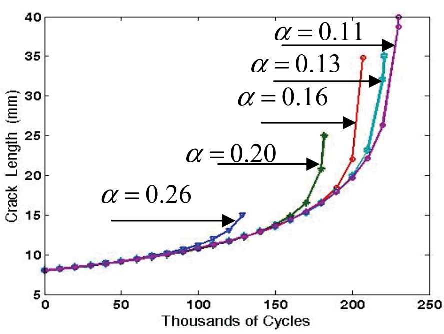

Figure 8: Effects of different aspect ratios on FCG for TPB

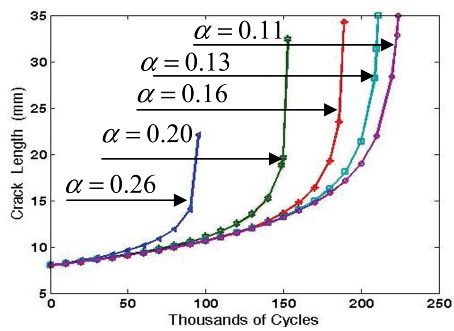

Figure 9: Effects of different aspect ratios on FCG for CT

The fatigue crack growth rate curves were generated for stress ratios (-0.3, to 0.5). The effects of stress ratio are shown in Figs. 10 and 11,which indicate that, for a given *dK*, *da/dN* increase*s* with increase in stress ratio. This effect is relatively more significant at lower *R*-values. This variation is mainly because of the crack closure effect, which gets reduced as stress ratio increases. It is also observed that *da/dN* versus *dK* behavior is nearly the same in TPB and CT specimens.

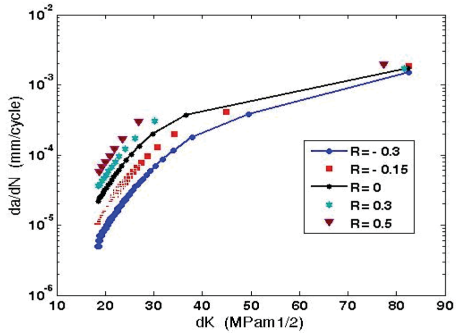

Figure 10: FCGR with dK for different stress

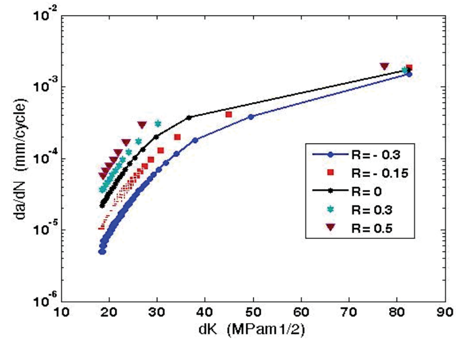

Figure 11: FCGR with dK for different stress ratios (CT)

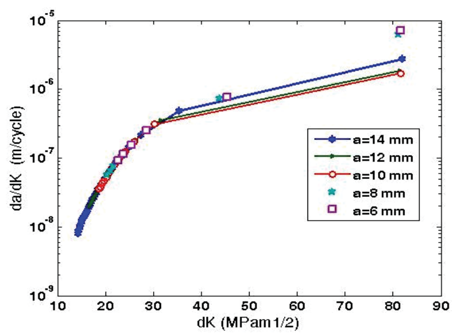

Figure 12: FCGR with dK for different initial crack Length (TPB)

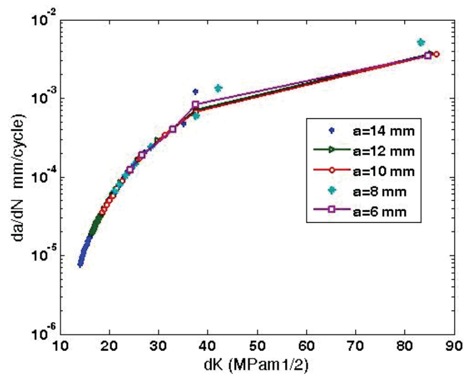

Figure 13: FCGR with dK for different initial crack Length (CT)

The effect of initial crack length ranging from 6 to 14 mm on FCGR was also studied and the results were presented in Figs. 12 and 13 for FCGR with *dK*. The results show that the value of initial crack length influences the fatigue crack growth rate, which is very fast for large value of initial crack length, while for small initial crack length still low for the two specimens.

Conclusion

Towards standardizing the fatigue crack studies on metallic materials under cyclic loading, tow types of specimens geometry (TPB and CT) were examined. This study mainly focuses on the evaluating of the fatigue crack growth with other factors studies. The results from TPB specimen geometry are compared with those obtained on CT geometry with application of the factors (initial crack length, stress ratio, aspect ratio and different fatigue crack models).

The number of cycles required for crack growth in structures have a long crack would be less in comparison to that with a small crack. Local stress range ahead of the crack tip will be higher for a deeper crack than for shallow crack. The observation shows that specimen with higher stress ratio require less cycles for crack growth compared to that with lower stress ratio for the two types. The number of cycles calculated by Forman model is more than that calculated by Paris and Austen models by 23% and 28% respectively. While for the two models (Paris and Austen) the difference is very small (6%).

For different aspect ratio the differences in the number of cycles for the two geometries is about 20% in average. The number of cycles calculated for TPB is higher than CT, i.e. increasing the aspect ratio gives less number of cycles. *da/dN* increases with increase in stress ratio for a given *dK*. FCGR was shown very fast for high initial crack length. It is also observed that *da/dN* versus *dK* behavior is nearly the same in CT and TPB specimens.

As a final conclude, there are a large number of factors affecting the FCG, so it is difficult to judge which one can be used as the standard one relating to such factors. For further study, need to take into account other factors such as; other type of geometries, FCG models as well as the aspect ratio, initial crack length and stress ratio.

References

1. **Paris, PC.; Erdogan, F.** (1963). A Critical Analysis of Crack Propagation Laws. *Journal of Basic Engineering*; Transaction, American Society of Mechanical Engineers, Series D;85: 528-534.

2. **Jeelani, S.; Natarajan, R.; Reddy, GR.** (1986). A subsize fatigue specimen. *International Journal of Fatigue*;8:159-164.

   Ellyn, F.; Li, H.P. (1984). Fatigue crack growth in large specimens with various stress ratios. *Journal of Pressure Vessel Technology*;106:255–260.

3. **Forman, RG.; Kearney, VE.; Engle, RM.** (1967). Numerical analysis of crack propagation in cyclic-loaded structures. *Journal of Basic Engineering*;89:459–464.

4. **Walker, EK.** (1970). The effect of stress ratio during cracks propagation and fatigue for 2024-T3 and 7076-T6 aluminum. In: Effect of environment and complex load history on fatigue life, ASTM STP 462. Philadelphia: *American Society for Testing and Materials*, pp:1–14.

5. **Newman, Jr JC.** (1981). A crack closure model for predicting fatigue crack growth under aircraft spectrum loading. ASTM/STP;748:53–84.

6. **Elber, W.** (1970). Fatigue crack closure under cyclic tension. *Engineering Fracture Mechanics*;2(1):37–44.

7. **Elber, W.** (1971). The significance of fatigue crack closure. In: Damage Tolerance in Aircraft Structures, ASTM-STP 486, ASTM PA; p. 230–242.Tesch, A., Pippan, R. and **Doker, H.** (2007). New testing procedure to determine da/dN–dK curves at different, constant R-values using one single specimen. International Journal of Fatigue; 29:1220–1228.

8. **Fujitiani, K.; Sakai, T.; Nakagawa, A.; Tanaka, K.** (1982). Effect of specimen thickness on fatigue crack propagation in high strength steels. Bulletin Japan Society of Mechanical Engineers;25:1195-1201.

9. **Heung-Bae, P.; Kyung-Mo, K.; Byong-Whi, L.** (1996). Plastic zone size in fatigue cracking. *International Journal of Pressure Vessel and Piping*;68:279-285.

10. **Sullivan, AM.; Crooker. TW.** (1977). The effects of specimen thickness and stress relief on fatigue crack growth rate in Ni-Cr-Mo-V steel. Journal of Testing and Evaluation;5:96-101.

11. **Putatunda, SK.; Rigsby, JM.** (1985). Effect of specimen size on fatigue crack growth rate in AISI 4340 steel. *Engineering Fracture Mechanics*;22:335-345.

12. **Rickerby DG.; Fenici P.** (1984). Fatigue crack growth in thin section type 316 stainless steel. *Engineering Fracture Mechanics*;19:585-599.

13. **Dover, WD.; Boutle, NF.** (1978). The influence of mean stress and thinness on fatigue behavior of the aluminum alloy 113 S 2L 71. Journal of Strain Analysis;13:129-139.

14. **Jack, AR.; Price, AT.** (1972). Effects of thickness on fatigue crack initiation and growth in notched mild steel specimens. Acta Met;20:857-866.

15. **Forman, RG.** (1972). Study of fatigue crack initiation from flaws using fracture mechanics theory. *Engineering Fracture Mechanics*;4(2):333–345.

16. nCode User guide manual. (2003). ICE-FLOW cracks growth. V2.0.

17. **Maymon, G.** (2005). A 'unified' and a $(\Delta K.K_{\max})^{1/2}$ crack growth models for aluminum 2024-T351. *International Journal of Fatigue*;27:629-638.

18. **Huang Xiaoping; Torgeir Moan; Cui Weicheng**. (2008). An Engineering model of fatigue crack growth under variable amplitude loading. *International Journal of Fatigue*;30:2-10.