A TWO PARAMETER K_{max} AND ΔK MODEL FOR FATIGUE CRACK GROWTH

D. Kujawski & S. Stoychev
Department of Mechanical and Aeronautical Engineering
Western Michigan University, Kalamazoo, MI 49008, USA

ABSTRACT

In this paper, previously proposed two-parameter (K_{max} and ΔK) driving force model is adopted for fatigue crack growth analyses for both positive and negative load ratios. It is based on the premise that the damage at the crack-tip process zone is an interplay of two damage mechanisms, namely a monotonic damage due to K_{max} and a cyclic damage due to ΔK. Fatigue crack growth rate, for a constant amplitude loading, is represented by a new three dimensional crack propagation (CP) table in terms of K_{max} and ΔK in accordance with the two parameter model. It is shown that the CP table provides a general representation of crack growth data for constant amplitude loading. Experimental data taken from literature for 7055-T7511 aluminum alloy under various load ratios ranging from -1 to 0.7 were used to illustrate the two parameter approach.

1. INTRODUCTION

In general, load-bearing components/structures experience both an alternating load and a mean load during their service applications. Interactions between the alternating and mean loads on fatigue crack growth behavior are commonly introduced through a load ratio, R (= min. load / max. load), and an associated modification of the stress intensity factor range, ΔK. This is accomplished by considering different mechanisms that contribute to crack-tip shielding usually, crack closure (Elber, [1]) or residual stresses (Schijve [2], Klesnil and Lucas [3], Kujawski and Ellyin [4]). The vast majority of investigations assume that the crack growth is governed solely by the modified or 'effective' ΔK, where the effect of the maximum stress intensity factor, K_{max}, is only accounted indirectly through load ratio, R. However, it is well established that the K_{max} could significantly affect the crack driving force depending on the actual environment. Therefore, Vasudevan, Sadananda and coworkers [5-8] have reconsidered fatigue crack closure and its effects on fatigue crack growth behavior. They demonstrated that there is no significant contribution to crack closure due to residual plastic strain at the crack wake. Further, when asperity- or roughness-induced closure is present, the actual contribution is small, about one quarter of that computed from the experimental compliance measurements. They suggested that load ratio effects on fatigue crack growth behavior should be represented in terms of ΔK and K_{max}.

In this paper, previously proposed two-parameter (K_{max} and ΔK) driving force model (Kujawski [9,10], Dinda and Kujawski [11]) is adopted for constant amplitude fatigue crack growth analyses. It is based on the premise that the damage at the crack-tip process zone is caused by an interplay of two damage processes, namely a monotonic damage due to K_{max} and a cyclic damage due to ΔK. In this approach the mechanical driving force, ΔK^*, is related to the applied values of the stress intensities and is calculated as:

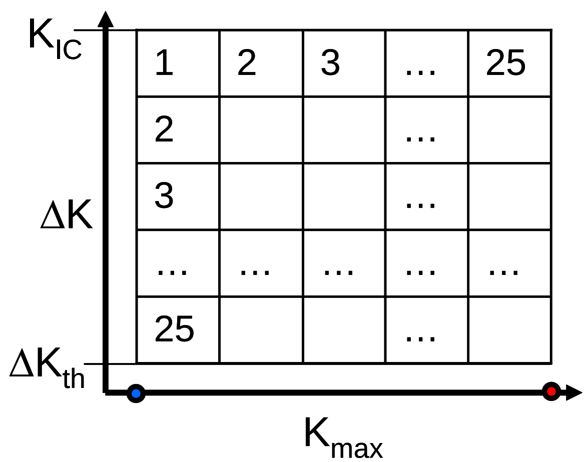
$$\Delta K^* = \left(\Delta K^+\right)^{\alpha} \left(K_{max}\right)^{1-\alpha} \quad (1)$$

, where ΔK^+ is the positive part of the applied stress intensity range and α is considered to be a material parameter. For positive load ratios the ΔK^* parameter depends on both ΔK^+ and K_{max}. However, for negative load ratios, since $K_{min} < 0$ will result in $\Delta K^+ = K_{max} = \Delta K^*$, which means that ΔK^* is insensitive to negative load ratios. In order to account for negative load ratios, the two-parameter driving force approach is modified by incorporating the total values of ΔK and K_{max} and using a new three dimensional crack propagation (CP) table relating da/dN to different combinations of the applied ΔK and K_{max} values.

The biggest advantage of using CP table comes from the fact that the 'α' parameter from Eq. (1) is no longer needed.

2. CRACK PROPAGATION TABLE

First, a combination of 25x25 values of ΔK and K_{max} parameters is constructed, according to Fig. 1.



$$(K_{\max})_i = \left(\left(\frac{K_{IC}}{K_{\max th}} \right)^{\frac{1}{24}} \right)^i \quad (\Delta K)_i = \left(\left(\frac{K_{IC}}{\Delta K_{th}} \right)^{\frac{1}{24}} \right)^i$$

, where i = 1, 2, 3 … 25

Fig.1 A table representation of ΔK and K_{max} parameters.

According to Fig.1, both parameters, ΔK and K_{max}, are equally spaced in log-log coordinate system between the threshold, K_{th}, and fracture toughness, K_{IC}, values. For a given combination of ΔK and K_{max}, for every element of this table is related to a corresponding da/dN. Thus, fatigue crack growth rate, da/dN, for constant amplitude loading is represented by a new three dimensional crack propagation (CP) table in terms of the K_{max} and ΔK, in accordance with the two parameter model. This CP table can be represented graphically as as a three dimensional surface. The values of the crack growth rates for any combination of ΔK and K_{max} are typically extrapolated from experimental data conducted at constant load ratios, R. For variable amplitude loading conditions, only the transient crack growth effects have to be modeled, using the two parameter approach.

3. COMPARISON WITH EXPERIMENTAL DATA

Fatigue crack growth data for 7055-T7511 aluminum alloy taken from Ref. [12] with load ratios, R, ranging from -1 to 0.7 were selected for analysis. The data have been plotted using three methods for crack growth rate representation. These methods are:

1. conventional log(da/dN) versus log(ΔK);
2. constant da/dN lines in log(ΔK) versus log(Kmax) coordinates;
3. three dimensional CP table.

The plots on Fig. 2 (a) and (b) depict the obtained correlation results corresponding to the methods 1 and 2, respectively.

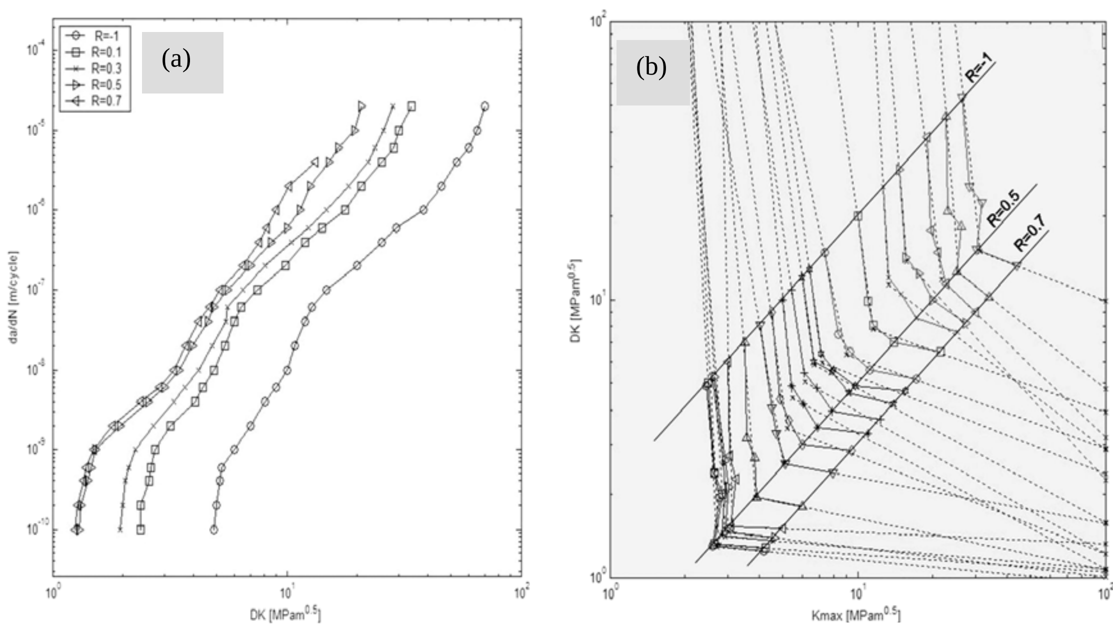


Fig. 2 Fatigue crack growth data [12] of 7055-T7511 aluminum alloy as a function of (a) ΔK and (b) ΔK and K_{max} for constant da/dn.

Fig. 2 (b) indicates that a linear dependence, with two different slopes, exists among log(ΔK), log(K_{max}) and any particular da/dN = constant. These two different slopes represent the ΔK and K_{max} dominated regimes for $R > 0.5$ and $R < 0.5$, respectively.

These two regimes are separated by a transition point, where the slope changes. Other possible relationships in terms of changes in the position of the transition point or in the log(ΔK) versus log(K_{max}) slopes are currently under investigation. The observations allow fatigue crack growth to be extrapolated beyond the experimental data to complete the CP table, as is shown in Fig.3. The grey area on Fig. 3 corresponds to the experimental data whereas the black one corresponds to the calculated values. Once a proper extrapolation is done, da/dN for any combinations of ΔK and K_{max} can be easily determined from the 3-D plot or by CP table lookup.

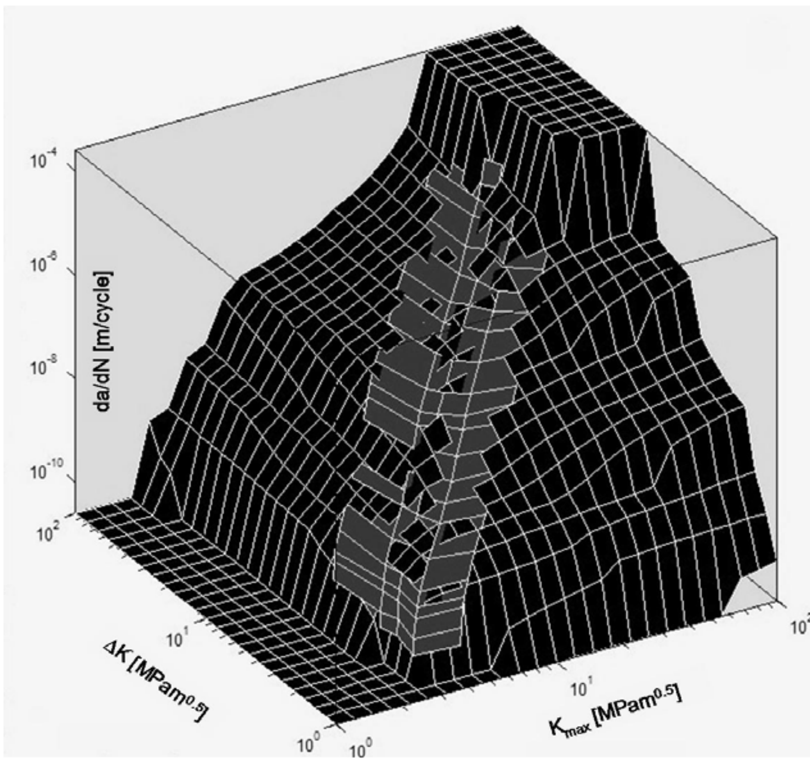


Fig. 3 Fatigue crack growth data [12] of 7055-T7511 aluminum alloy as a function of ΔK and K_{max}.

4. CONCLUSION

In this paper, previously proposed two-parameter (K_{max} and ΔK) driving force model is adopted for fatigue crack growth analyses for both positive and negative load ratios. Fatigue crack growth rate, da/dN, for a constant amplitude loading, is represented by a new three dimensional crack propagation (CP) table in terms of K_{max} and ΔK in accordance with the two parameter model. It is shown that the CP table provides a general representation of crack growth data for 7055-T7511 aluminum alloy under various load ratios ranging from -1 to 0.7. For variable amplitude loading conditions, only the transient crack growth effects have to be modeled, using the two parameter approach.

Acknowledgements
This investigation was supported by the Office of Naval Research under grant N00014-01-1-0952.

References

1. Elber W. The significance of fatigue crack closure. Damage Tolerance in Aircraft Structures, ASTM STP 486. American Society for Testing and Materials, Philadelphia, PA, pp. 130-242, 1971.
2. Schijve J. Fatigue crack propagation in light alloy sheet material and structures. In: Advances in Aeronautical Sciences, Vol. 62, Oxford, Pergamon Press, pp. 387-408, 1962.
3. Klesnil M, Lucas P. Effect of stress cycle asymmetry on fatigue crack growth. Materials Science and Engineering, Vol. 9, pp. 231-240, 1972.
4. Kujawski D, Ellyin F. A fatigue crack growth model with load ratio effects, Engineering Fracture Mechanics, Vol. 28, pp. 367-378, 1987.
5. Vesudevan AK, Sadananda K, Louat N. Reconsideration of fatigue crack closure. Scripta Mettallurgica et Materialia, Vol. 27, pp. 1673-1678, 1992.
6. Louat N, Sadananda K, Duesbury M, Vasudevan AK. Theoretical evaluation of crack closure. Metallurgical Transactions, Vol. 24A, pp. 2225-2232, 1993.
7. Vasudevan AK, Sadananda K, Louat N. Two critical stress intensities for threshold crack propagation. Scripta Mettallurgica et Materialia, Vol. 28, pp. 65-70, 1993.
8. Vasudevan AK, Sadananda K, Louat N. A review of crack closure, fatigue crack threshold and related phenomena. Materials Science and Engineering, Vol. 188A, pp. 1-22, 1994.
9. Kujawski D. A fatigue crack driving force parameter with load ratio effects. International Journal of Fatigue, Vol. 23, pp. S239-S246, 2001.
10. Kujawski D. A new $(\Delta K^{+}K_{max})^{0.5}$ driving force parameter for crack growth in aluminum alloys. International Journal of Fatigue, Vol. 23, pp. 733-740, 2001.
11. Dinda S, Kujawski D. Correlation and prediction of fatigue crack growth for different R-ratios using K_{max} and ΔK^{+} parameters. Engineering Fracture Mechanics, Vol. 71, pp. 1779-1790, 2004.
12. Paris P, Tada H, Donald JK. Service load fatigue damage – a historical perspective. International journal of fatigue, Vol. 21, pp. S35-S46, 1999.