Crack Growth in D6ac Steel Structural Components

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Abstract Cracking in D6ac steel has played a key role in the development of the damage tolerant design philosophy. Until recently it had been thought that cracking in D6ac steel was well understood. However, Forth et. al. [1] have recently reported that crack growth data obtained by NASA for D6ac steel revealed that there was little R ratio dependence in the Paris Region and that there was thus little, if any, crack closure. In this paper we reveal how the NASA data conforms to the Generalised Frost-Dugdale crack growth law. We then show how the average block variant of the Generalised Frost-Dugdale law can be used to predict the growth of small cracks in a USAF study into crack growth in D6ac steel specimens representative of the critical region of F-111 wing pivot fitting.

1. INTRODUCTION

Cracking in D6ac steel has played a key role in the development of the damage tolerant design philosophy. Indeed, the USAF adoption of a damage tolerant design philosophy arose from an in-flight failure, on December 22 1969, of an F-111 aircraft which lost a wing while on a training flight. The failure was found to originate on the lower tension surface of the D6ac steel wing pivot fitting. A Scientific Advisory Board assembled for the F-111 investigation subsequently recommended that a damage-tolerant design methodology be used for all future aircraft. These new design concepts were subsequently incorporated into MIL-STD-1530, Aircraft Structural Integrity Program, Airplane Requirements.

Until recently it had been thought that cracking in high strength aerospace quality steels was well understood. However, Forth, James, Johnston, and Newman [1] reported that crack growth data obtained for 4340 steel using CT specimens was essentially R ratio independent. Similarly crack growth data obtained for D6ac steel using CT specimens, exhibited an apparently anomalous behaviour in that whilst there was essentially no R ratio dependence in the Paris Region, i.e. Region II, the da/dN v ΔK relationship was R ratio dependent in Region I. This study led Forth, James, Johnston, and Newman to state: "there is little closure in high strength steels" and "This data also does not follow the crack closure argument."

Forth, Johnston, and Seshadri [2] subsequently reported that in Region I D6ac steel crack growth data obtained using different ASTM standard specimen geometries tested under the ASTM constant R ratio load reducing method gave different da/dN v ΔK relationships. The implication of the latter finding was that, in Region I, similitude did not hold for ASTM constant R ratio load reducing tests. Indeed, Forth, Newman, and Forman [3] have shown that the ASTM constant R ratio load reducing test procedure generates Region I crack growth data that are inconsistent with the true material response.

At this stage it should be noted that Frost and Dugdale [4] reported that there was little R ratio dependency in mild steels, and that Jones, Pitt, and Peng [5] have show that there was little R ratio dependency in a 350 MPa Grade locomotive steel. Jones, Pitt, and Peng [5] also revealed that crack growth in this particular 350 MPa Grade locomotive steel conformed to the Generalised Frost-Dugdale law [6], i.e. Equ. (1):

$$da/dN = C^* a^{(1-\gamma/2)} (\Delta\kappa)^{\gamma} - (da/dN)_0 \quad (1)$$

where $\Delta\kappa$, is the crack driving force, C^*, and γ are constants and the term $(da/dN)_0$ reflects both the fatigue threshold and the nature of the notch (defect/discontinuity) from which cracking initiates. (The link between this law and the fractal concepts of Carpenteri [7] and Spagnoli [8] is outlined in [6].) Indeed, Jones, Chen, and Pitt [9] have shown that a large crossection of rail steels also conform to the Generalised Frost-Dugdale law. As a result the purpose of this paper is to evaluate whether cracking in D6ac steel, used in the NASA space shuttle [10], reported in [11] follows the Generalised Frost-Dugdale law. This investigation shows that there is a simple linear relationship between da/dN and $a^{(1-\gamma/2)} (\Delta\kappa)^{\gamma}$ that holds over five orders of magnitude, viz: 10^{-8} mm/cycle < da/dN < 10^{-3} mm/cycle.

2 CRACKING IN D6AC STEEL

Forth, James, Newman, and Everett [11] presented the results of an extensive study into crack growth in D6ac steel using compact tension test specimens. This paper focuses on cracking in the LT direction under both constant K_{max}, and constant R ratio load increasing tests. Details of the various tests are given in Table 1. Analysis of the test data revealed that crack growth conforms to the Generalised Frost-Dugdale crack growth law, i.e. Equ. (2):

$$da/dN = 8.12 \times 10^{-9} * a^{(1-\gamma/2)} (\Delta\kappa)^{\gamma} - 2.79 \quad 10^{-7} \quad (2)$$

with $\gamma = 2.6$, and where as per Walker [12] we have defined the crack driving force as per Equ. (3):

$$\Delta\kappa = K_{max}^{(1-p)}\,\Delta K^{p} \qquad (3)$$

where a value of p = 0.95 was found to best collapse the data. This low value of p shows that the increment in the crack length per cycle (da/dN) is essentially no R ratio independent. This finding is also seen in Figure 2, where we show the da/dN versus ($K_{max}^{0.05}\ \Delta K^{0.95}$) relationship. Indeed, Figure 1 shows that there is a simple linear relationship between da/dN and ($K_{max}^{0.05}\ \Delta K^{0.95}$)/ $a^{0.3}$ that holds over five orders of magnitude, viz: 10^{-8} mm/cycle < da/dN < 10^{-3} mm/cycle.

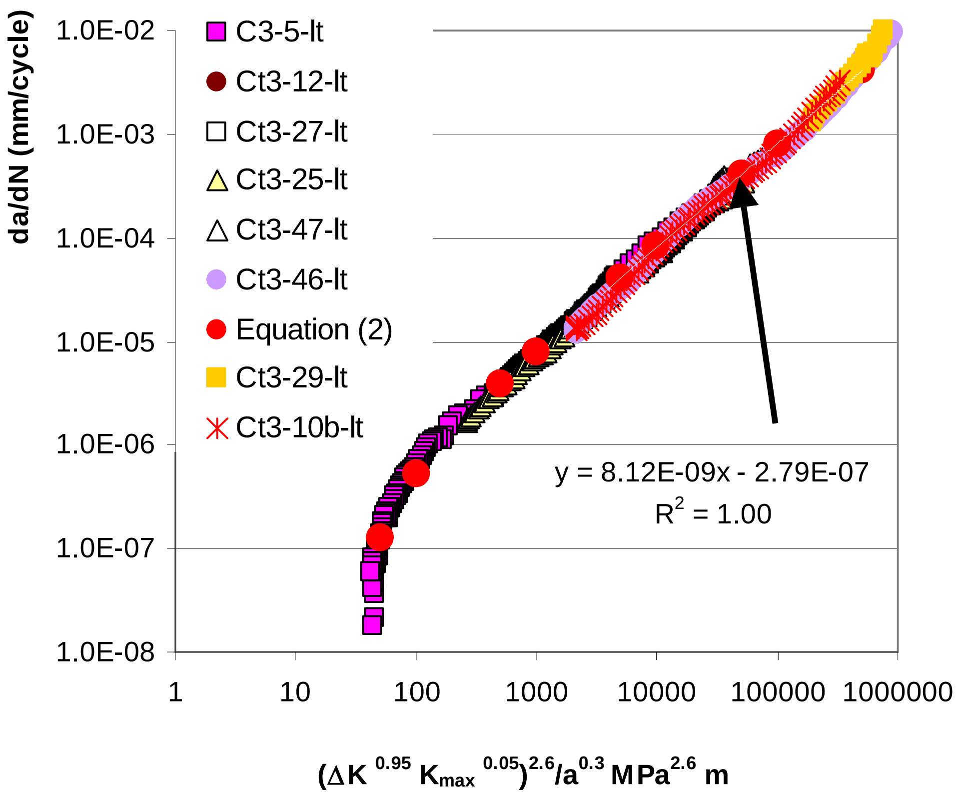

Figure 1 Generalised Frost-Dugdale representation of crack growth.

Table 1 Test matrix

		Test frequency Hz
Ct3-5-tl	Constant K_{max} (=15 MPa √m) test	18
Ct3-10b-lt	Constant R=0.3, Load increasing	20
Ct3-12-lt	Constant R=0.9, Load increasing	20
Ct3-25-lt	Constant R=0.7, Load increasing	20
Ct3-27-lt	Constant R=0.9, Load increasing	22
Ct3-29-lt	Constant R=0.3, Load increasing	10
Ct3-46-lt	Constant R=0.1, Load increasing	20
Ct3-47-lt	Constant R=0.8, Load increasing	10

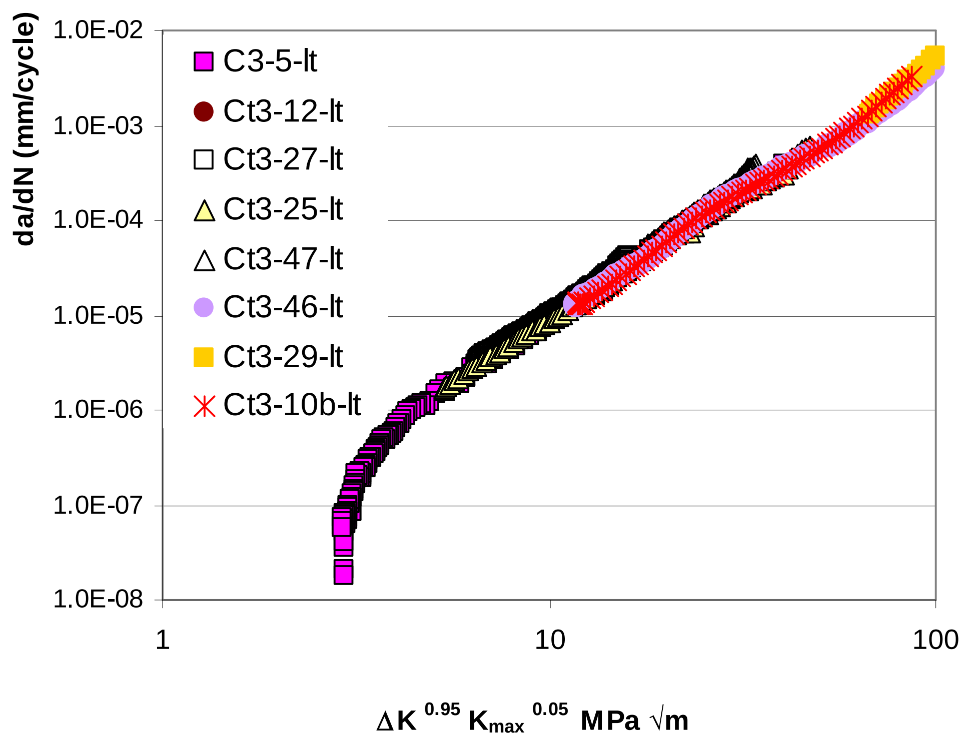

Figure 2 Crack growth in D6ac steel.

3. AN EQUIVALENT BLOCK METHOD FOR PREDICTING FATIGUE CRACK GROWTH

It is now known that the mechanisms underpinning crack growth under variable amplitude load may differ from those seen under constant amplitude loading [13]. We also know [1] that cracking in D6ac steel is not consistent with the crack closure hypothesis. The question thus arises how can we predict crack growth under complex variable amplitude loading if we can't use crack closure based models, or models such as modified Willenborg model that use changes in crack growth resulting from changes in the effective R ratio to model sequence effects ? (In the latter case since there is essentially no R ratio effect, see Figures 1 and 2, then approach this can't be used to account for sequence effects.)

At this stage it is worth noting that Schijve [14], Miedlar, Berens, Gunderson, and Gallagher [15], Barsom and Rolfe [16] and Miller, Luthra, and Goranson [17] have shown that repeated blocks of loads can, in certain circumstances, viz:

i) the slope of the *a* versus block curve has a minimal number of discontinuities,

ii) there are a large number of blocks before failure,

be treated as equivalent to load cycles. With these assumptions Jones, Molent and Krishnapillai [18] derived an “equivalent block” variant of the Generalised Frost-Dugdale crack growth law to account for the increment in the crack length per block, da/dB, i.e. Equ. (4):

$$da/dB = (\tilde{C}\, a^{1-\gamma/2}\, K_{max}^{\gamma} - da/dB_o)/(1.0 - K_{max}/K_c) \qquad (4)$$

Here *a* is the average crack length in the block, $\tilde{C}$ is a spectra dependent constant, K_{max} is the maximum value of the stress intensity factor in the block, and K_c is the apparent cyclic fracture toughness. Here, as described in [18], the term da/dB_o reflects the both nature of the discontinuity from which the crack initiates and the apparent fatigue threshold for this particular block loading spectra. However, it should be stressed that this variant of the Generalized Frost-Dugdale law is only applicable to crack growth data where the slope of the *a* versus Block curve has minimal discontinuities, and there are a large number of blocks to failure, see [18].

In the next section we present an example that illustrates how this approach, i.e. Equ. (4), can be used to accurately represent crack growth in D6ac steel specimens subjected to complex variable amplitude load spectra.

3.1 Comparison with USAF fatigue crack growth under variable amplitude loading

As part of the F-111 certification study the USAF [19] tested a number of surface flawed D6AC plate specimens under block loading, where one block represented 200 flight hours, representing the mission spectrum for the critical location in the F-111 wing pivot fitting. In this paper we focus on two specific specimens (P5I9 and P5I10) where both the initial and the final flaw shapes were very close to a semi-circular surface flaw. The spectrum used in specimen test P5I9 represented a tension-compression spectra whilst the spectrum used in specimen test P5I10 represented a tension-tension load spectra. The UASF specimens were 406.4 mm long, 96.52 mm wide and 7.62 mm thick and contained a 2.921 mm semi-circular surface flaw. The 7.62 mm thickness was representative of the critical location in the Wing Pivot Fitting location, see [19].

Crack growth was computed using Equ. (4), assuming that the aspect ratio was constant throughout the test. Here, as determined in Section 2, we used $\gamma = 2.6$ and in both cases we set da/dB_o to zero. For the tension compression tests we used $K_C = 90$ MPa $\sqrt{m}$, which is approximately 30% greater than the static fracture toughness measured in [19] for the material used in the tension-compression tests.

The value of the remaining constant $\tilde{C} = 2.12\ 10^{-10}$ was found by matching the time to grow from its initial size of 2.921 mm to approximately 3.099 mm in the tension-compression tests. For the tension-tension tests the value of K_c was increased by a factor of 1.10, which corresponds to the increase in the static fracture toughness observed in [19] for the material used in the tension-tension tests and the values of $\tilde{C}$, γ and da/dB_o were kept as given above. These values were then used to predict the entire crack length histories for both tests. A comparison of the predicted and measured crack length histories is shown in Figure 3. Here we see excellent agreement between the measured and computed crack length histories.

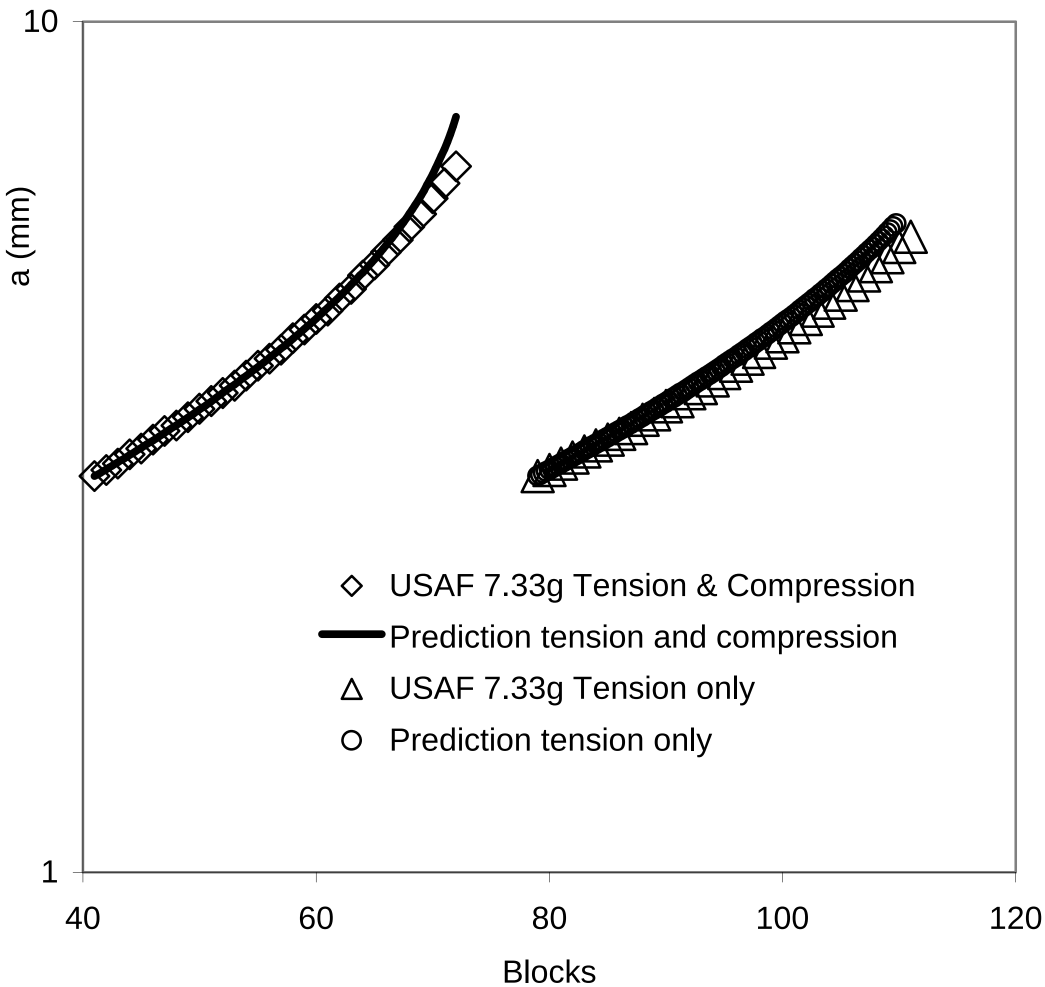

Figure 3 Comparison of measured and predicted crack length histories.

4. CONCLUSION

This paper has confirmed the prior NASA finding that crack growth in D6ac steel has little R ratio dependence and hence little, if any, crack closure. We also see that the NASA data conforms to the Generalised Frost-Dugdale crack growth law. We have then shown how the average block variant of the Generalised Frost-Dugdale law can be used to compute the growth of small cracks in a USAF study into crack growth in D6ac steel specimens under repeated block loading representative of the critical region of F-111 wing pivot fitting.

REFERENCES

1. S. C. Forth, M. A. James, W. M. Johnston, and J. C. Newman Jr., Anomolous Fatigue Crack Growth Phenomena In High-strength Steel, Proceedings Int. Congress on Fracture, Italy, 2007.
2. S. C. Forth, W. M. Johnston, and B. R. Seshadri, The effect of the laboratory specimen on fatigue crack growth rate, Proceedings 16th European Conference on Fracture, Alexandropoulos, Greece, July 2006.
3. S. C. Forth, J. C. Newman Jr, R. G. Forman, On generating fatigue crack growth thresholds, International Journal of Fatigue 25 (2003) 9–15.
4. N. E. Frost, D. S. Dugdale, The propagation of fatigue cracks in test specimens, Journal Mechanics and Physics of Solids, 1958, 6, pp 92-110.
5. R Jones, S. Pitt, and D. Peng The Generalised Frost–Dugdale approach to modeling fatigue crack growth, Engineering Failure Analysis, Engineering Failure Analysis, Volume 15, Issue 8, 2008, Pages 1130-1149.
6. R Jones, L. Molent and S. Pitt., Crack growth from small flaws, International Journal of Fatigue, Volume 29, (2007), pp 1658-1667.
7. Al. Carpinteri, Scaling laws and renormalization groups for strength and toughness of disordered materials. Int. J. Solids Struct. 31, (1994),2 91–302.
8. An. Spagnoli, Self-similarity and fractals in the Paris range of fatigue crack growth. Mechanics of Materials 37, (2005), 519–529
9. R Jones,, Chen B, Pitt S., "Similitude: cracking in steels", Theoretical and Applied Fracture Mechanics, Volume 48, Issue 2, 2007, Pages 161-168.
10. P. K. Liaw, M. G. Peck and G. E. Rudd, "Fatigue crack growth behavior of D6AC space shuttle steel," *Engineering Fracture Mechanics*, Vol. 43, pp. 370-400, 1992.
11. S. C. Forth, M. A. James, J. A. Newman., R. A. Everett, and W. M. Johnston, Mechanical Data for Use in Damage Tolerance Analyses, NASA/TM-2004-213503, December 2004.
12. E. K. Walker, The effect of stress ratio during crack 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, 1970, pp.1-14.

13. P. White P., S. A. Barter, and Molent L., Observations of crack path changes under simple variable amplitude loading in AA7050-T7451, Int. Journal of Fatigue, 30 (2008) 1267–1278.
14. J. Schijve, Fatigue crack growth under variable-amplitude loading, Engineering Fracture Mechanics, Engineering Fracture Mechanics, 1979, pp 207-221.
15. P. C. Miedlar, A. P. Berens, A. Gunderson, and J. P. Gallagher, Analysis and support initiative for structural technology (ASIST), AFRL-VA-WP-TR-2003-3002.
16. J. M. Barsom and S. T. Rolfe, Fracture and fatigue control in structures: Applications of Fracture Mechanics, Butterworth-Heinemann Press, November 1999.
17. M. Miller, V. K. Luthra, and U. G. Goranson, Fatigue crack growth characterization of jet transport structures, Proc. of 14th Symposium of the International Conference on Aeronautical Fatigue (ICAF), Ottawa, Canada, June 10-12, 1987.
18. R Jones, L. Molent, K. Krishnapillai, An equivalent block method for computing fatigue crack growth, International Journal of Fatigue 30 (2008) 1529–1542.
19. H. A. Wood, T. L. Haglage, *Crack propagation test results for variable amplitude spectrum loading in surface flawed D6AC stee*l 1971; FBR-TM-71-2.