Influence of Multiple Overload on Fatigue Crack Retardation in High Strength Low Alloy Structural Steel

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ABSTRACT

The influence of multiple overloads at various stress intensity levels (ΔK) in the linear regime of Paris plot was studied in high strength low alloy structural steel SANH-55. It was observed that crack retardation increases by increasing the overlaod ratio and the number of overloads. Saturation effect was observed for overload peak ratio lower than 1.8 and crack arrest for overload peak ratio greater than 2.3. The endurance limit has been found to have increased by 14% under multiple overload condition.

KEYWORDS

Multiple overload; crack retardation; overload peak ratio.

INTRODUCTION

High strength low alloy structural steel SANH-55 is being used in the fabrication of various air and vacuum brake actuation system components. These system components in actual service suffer a random load history and the fatigue crack propagation depends on the loading sequence. This was observed earlier by Elber[1] and this has prompted much research into load sequence effects associated with variable amplitude loading. It is well documented that the application of an overload can cause a significant decrease in the fatigue crack propagation rate and in some cases can even lead to complete crack arrest [2, 3, 4]. Crack closure has met with some success in accounting for these load interaction effects by correlating crack growth with that part of the stress intensity range for which the crack is open.

The growth of fatigue crack was predicted by Paris and Erdogen [5] is inadequate because of residual stresses which may hold the crack closed until sufficient external load is applied to overcome them. The crack retardation is explained by crack closure concept. Elber [6] proposed a modified fatigue crack growth equation as, $da/dn = C' (U \Delta K)$ ---------(1) in which 'U' is termed the effective stress range factor and is defined by;

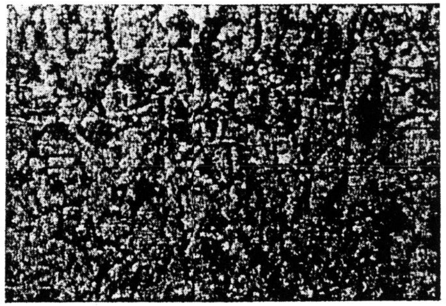


Fig. 1. Microstructure of a typical high strength low alloy structural steel.

an equation as,

$$U = (\sigma_{max} - \sigma_{op})/(\sigma_{max} - \sigma_{min}) \text{ --------------- } (2)$$

σ_{max} and σ_{min} being respectively the maximum and minimum values of stress in the specific cycle of interest, and σ_{op} being the stress at which the crack starts to open along its length.

Elber [1] introduced the hypothesis that crack propagation can occur only during that portion of the loading cycle in which crack is fully open at the crack tip. Elber defined the effective stress intensity range, $\Delta K_{eff} = K_{max} - K_{op}$, where K_{max} and K_{op} are the maximum and crack opening intensity respectively. The crack growth behavior after overload applicaton in hgih strength low alloy steel was similar to the experiemental results of Vancon [7], which indicated that a saturation effect appears and Dahl [8], noticed the possibility of crack arrest for high overload ratio greater that 2.0. In the present work test results on retardation behavior for various ΔK levels in the linear regime of Paris plot and the influence of number of overload peaks, at different overload peak ratio (Rp) and K_{max} values are presented. The beneficial effect of multiple overloads in increasing the life time of components from the point of view of fail safe damage tolerant design is also discussed.

MATERIAL AND MECHANICAL PROPERTIES

Experiments were carried out on a high strength low alloy structural steel SANH-55. The chemical and mechanical properties are given in Table-1 The microstructure of the steel tested is shown in figure (1).

CHEMICAL COMPOSITION (WEIGHT %)

C	Mn	Si	Ni	S	P	Al	Cr	Cu	Mo
0.15	1.2	0.3	0.4	0.02	0.02	0.04	0.10	0.15	0.08

MECHANICAL PROPERTIES

Y.S MPa	UTS MPa	EL. TO RUPTURE (%)	REDN. IN AREA (%)	Y.R
420	590	29	58	0.71

Table-1 CHEMICAL COMPOSITION (WEIGHT %) and MECHANICAL PROPERTIES

EXPERIMENTAL CONDITIONS AND RESULTS:

The tests were carried out on compact tension specimens of 70 mm width and thickness B = 8.0 mm [9]. Tests were performed in load control conditions in a 100 kN servo-hydraulic testing machine. Test frequency was typically 25 Hz in air. The specimen surface was polished up to 1u to facilitate crack length measurement with an optical microscope (x 100) on one side of the specimen with an accuracy of 0.02 mm.

Precracking of C(T) specimen was carried out in such a way to produce a final crack growth. In figure (2) are reported the data from four specimens tested under laboratory conditions. The first one was conducted with increasing ΔK and other threee with decreasing ΔK to low ΔK values. This curve corresponds to an exponent in Paris equation $((da/dN) = C(\Delta K)^m$ of 3.57. When the applied ΔK is decreased below 8.5 MPa m. the value of the slope 'm' becomes very large defining a ΔK threshold between 5.5 and 6.0 MPa $\sqrt{m}$ for fatigue crack growth rate equal to 10^{-8} mm/cycle. This threshold behavior was observed with three specimens within a noticeable accuracy.

The retardation behavior tests under multiple overload were carried out in the linear range of Paris plot corresponding to various ΔK levels so as to have little influence of load ratio, environment and microstructure. The crack opening load was determined by compliance method. Tests were performed with four values of the maximum stress intensity factor K_{max} = 9.5, 19, 24, 28, MPa $\sqrt{m}$ and with a load ratio R = 0.1 and an overload ratio defined as the ratio of peak load range to the initiated cycle load range were 1.8, 2.0, 2.3.

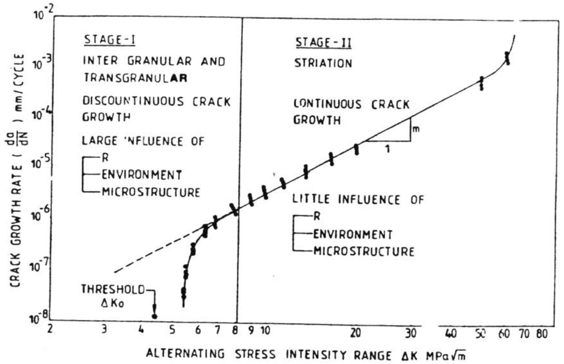
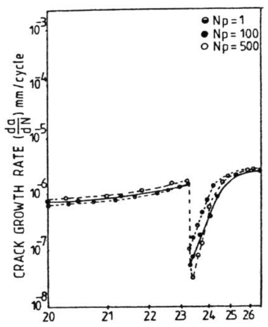


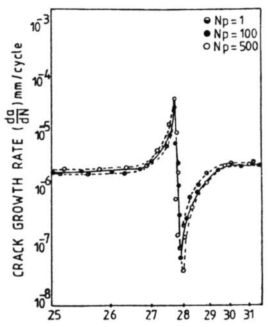
FIG.2 VARIATION OF FATIGUE CRACK PROPAGATION IN AIR FOR HIGH STRENGTH LOW ALLOY STEEL AT R = 0.1

After the application of overload, the initial stress intensity factor was resumed and kept constant with in 2% of Kmax. After the test specimen surface were examined under interferencial contrast to analyze the development of the plastic ones and the behavior of the crack in the overload affected region.

Figure(3) shows the evolution of crack growth rate at various stress intensity ranges. In fig(3a) the application of number of overloads (Np) causes very slight crack advance, after which the crack remains blocked before reaccelerating to reach its preload growth rate. The number of cycles during which the crack is blocked is 2.7×10^5 for Np = 10 and 3.6×10^5 for Np = 500. The number of cycles during which the crack is blocked can be associated to the time necessary to induce new fatigue damage at the crack tip. After this a stable regime is reached for a crack to propagate at 10^{-6} mm/cycle. In fig(3b) and (3c) the crack growth rate following the overload is at first accelerated and then decelerated to reach (da/dn) min. The minimum delay observed in this case corresponds to the fact that crack is not blocked at all after deceleration period. The reacceleration process after this point is sudden and crack growth rate reaches its preoverload value immediately. This behavior is characteristic of development of plane stress conditions with a large overload plastic zone affecting several grains and corresponding to several deformation levels at the crack tip. In this case, it has been shown that the observed delay can be explained by residual stress effect [10,11]. In fig(3d) the overload is characterized by by transient acceleration and then gradual reacceleration of the crack growth. This kind of behavior is known as delay retardation [2,11]. Experimental results showing the acceleration and deceleration behavior in figure (3a), (3b), (3c) and (3d) can also be explained using the crack closure model [12, 13].



CRACK LENGTH (a) mm
3a. RETARDATION BEHAVIOR FOR ΔK =9.5MPa√m



CRACK LENGTH (a) mm
3b. RETARDATION BEHAVIOR FOR ΔK = 1[illegible] MPa√m

The major effect of increasing the number of overload peaks Np is to increase crack retardation. This point is shown in fig(4a) and (4b) where N_d represents the number of cycles of delay. It is observed that with increase in the ΔK level the number of overload required to arrest the crack also increases. In fig (4a) and (4b) for different R peak ratios the following different behaviors were noticed. For peak ratio greater than 2, crack arrest occur after several overload peaks; for peak ratio lower than 1.8 the crack retardation reaches a constant value.

A comparative study was carried out between the cyclic overload plastic zone 'r_p' and crack length after delay 'a_d'. The plastic zone r_p is given as,

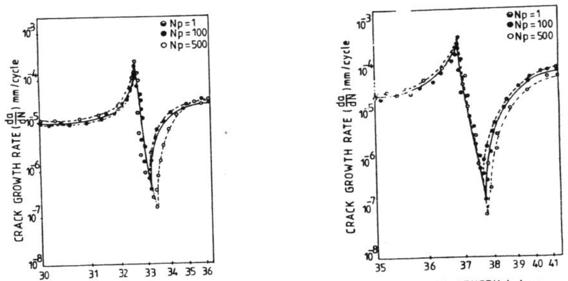
$$r_p = 1/4 \times ((Kpeak - Kmin)^2/\sigma_y{}^c) \quad (3)$$

where $\sigma_y{}^c$ is yeild strength on cyclic stress strain curve. In fig(5) 'a_d' is equivalent to the overload plastic zone but not constant.

The influence of Kmax for several overload peaks is similar to that of a single overload peak. With smaller Kmax there is a possibility of crack arrest. Four values of Kmax (9.5, 19, 24 and 28 MPa $\sqrt{m}$) were examined and results are presented as a "delay ratio" N_d/N_c, where Nc is the number of cycles needed to propagate over a distance 'a_d' (distance affected by overload)as shown in fig(3).

The maximum stress intensity factor range influences the cyclic overload 'a_d' and plastic overload zone 'r_p'. This behavior is shown in fig(5).

Variationof U ratio is similar to crack growth rate variation; U increases when crack growth rate begins to increase as shown in fig(6).



3c. RETARDATION BEHAVIOR FOR ΔK = 24MPa√m

3d. RETARDATION BEHAVIOR FOR ΔK = 30 MPa√m

FIG.3 EVALUATION OF CRACK GROWTH RATE

It is now well established that single tensile overloads can cause crack retardation or even crack arrest, in long crack growth rate, which accordingly increases the life time. Although overloads can be considered to promote "damage" thereby reducing S/N life, their occupance in the presence of "long" Mode - 1 crack additionally promotes crack deflection and crack closure and thus increases the life time as shown in fig(7). In the figure fatigue propagation life was estimated from a crack closure analysis.

DISCUSSION

The main objective of this work is to consider the effect of overload ratio (Rp) on crack retardation behavior when the number of overload peaks is increased. For a large number of overload peaks, the way to obtain crack arrest is to increase the overload peak ratio. For 480 overloads, a value of overload ratio greater than 2.3 is necessary to arrest the crack.

The possibility of crack arrest can also be explained with a residual stress model [10,14]. The R peak value for which crack arrest can be obtained produces an overload cyclic plastic zone which is equivalent or larger than the base line monotonic plastic zone. In this situation, the compressive residual stresses should be more prominent so that they can annihilate the tensile applied stress and stop crack more easily.

The prediction of crack propagation under multiple overloading are extremely important from the point of view of fail safe damage tolerant design. The significance of delay and acceleration effects depends on the load spectrum, type of material, including thickness and environment.

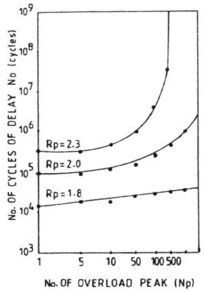


FIG.4a EFFECT OF R PEAK RATIO ON THE DELAY WHEN THE NUMBER OF OVERLOAD PEAK IS INCREASING FOR ΔK = 9.5 MPa√m

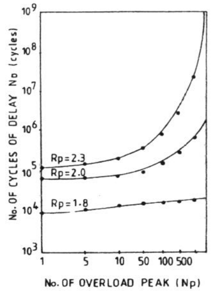


FIG. 4b EFFECT OF R PEAK RATIO ON THE DELAY WHEN THE NUMBER OF OVERLOAD PEAK IS INCREASING FOR ΔK = 19 MPa√m

CONCLUSION

The influence of **Δ**K in retardation behavior the number of overload peaks associated with the evolution of cyclic properties has been studied in a high strength low alloy steel SANH-55 and the parameters Kmax, Rp and Np have been examined. The following conclusions are presented:

1. At **Δ**K = 9.5 MPa √m a high delay is observed. The number of cycles during which the crack is blocked is 2.7 x 10^5 for Np = 10 and 3.7 x 10^5 for Np = 500. At **ΔK**=9.5 MPa√m crack arrest is observed which is dependent on the microstructure and it can vary from one grain to another depending on the orientation.

2. At **Δ**K = 19 MPa √m and 24 MPa √m a mimimum delay corresponding to a predeformed fatigue zone affecting several grains is observed. The minimum delay corresponds to the fact that crack is not blocked at all after deceleration.

3. At **Δ**K = 28 MPa √m a more pronounced delay associated with the plane stress condition developed at the crack tip is observed.

4. The retardation behavior increases with increase in the number of of overload. A low crack growth is reached during retardation.

5. The crack length after overload at (da/dn)min and the distance affected by retardation are not constant, but slightly increases with number of overload peaks.

6. Saturation effect was observed for overload ratio lower than 1.8, crack arrest for overload ratio greater than 2.3.

7. The endurance limit has been found to have increased by 14% under multiple overload condition.

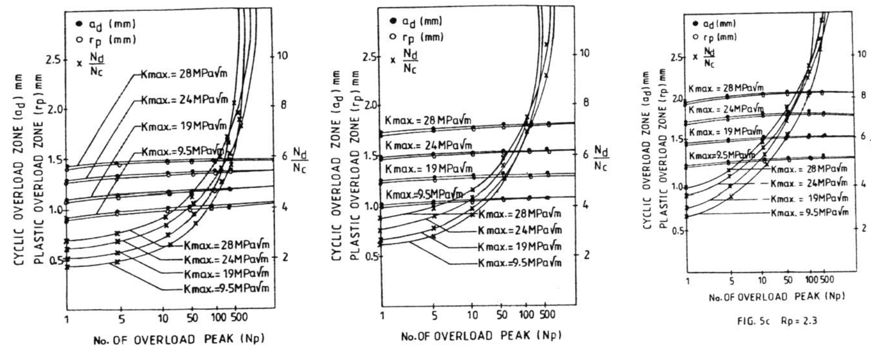


FIG. 5a Rp = 1.8

FIG. 5b Rp = 2.0

FIG. 5c Rp = 2.3

FIG. 5 EFFECT OF Kmax. ON THE CYCLIC OVERLOAD ZONE (a_d) Nd/Nc RATIO AND PLASTIC OVERLOAD ZONE (r_p) WHEN THE NUMBER OF OVERLOAD PEAK IS INCREASING

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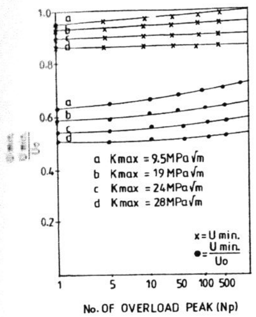

FIG. 6 EFFECT OF Kmax. ON U min. AND $\frac{U min.}{Uo}$ WHEN THE NUMBER OF OVERLOAD PEAK IS INCREASING

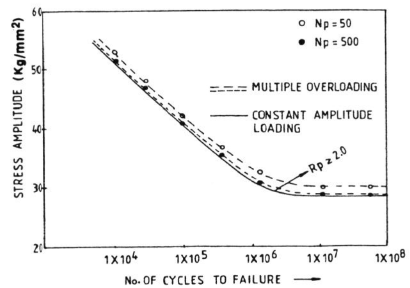

FIG. 7 EFFECT OF MULTIPLE OVERLOAD ON FATIGUE CRACK PROPAGATION LIFE

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