SOME ASPECTS OF FATIGUE CRACK PROPAGATION AFTER OVERLOADING CYCLES

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ABSTRACT

This research was carried out to determine the influence of overload cycles on the fatigue crack growth resistance of a structural steel. Single tensile overload cycles were applied to evaluate the influence of the overloading ratio on the fatigue crack retardation and residual stresses were measured in the region near crack tip. The results indicated that the extended fatigue life increases with increasing the magnitude of overloading and in the presence of higher compressive residual stress fields. The effect of two equal and consecutive overloads, with the second one applied at different intervals of crack propagation from the first, was also considered. The residual life after overloading was found to increase after some crack propagation between the two overloads. Larger intervals of crack propagation lead to higher fatigue resistance.

KEYWORDS

Residual life, fatigue resistance, overloading, residual stresses, structural steel.

INTRODUCTION

Fatigue crack propagation prediction is considered essential for structural integrity assessment based on damage-tolerance considerations. The determination of the resistance of a mechanical or structural component to fatigue crack propagation and calculation of defect tolerance are two aspects intimately related to the dependence of crack growth rate on the variation of the stress intensity factor. Frequently, complex loading conditions exist with different amounts of static and dynamic loads or mixed loading modes, depending on the stress distribution near the crack. However, load interactions complicate life prediction and structural components when in service under cyclic loading may be subjected to either variable amplitude loading or occasional overloading cycles. It is well known that overloading cycles can cause some beneficial effects on the fatigue resistance and lead to crack retardation [1]. Although much effort has been given to the overloading effect since 1961, when presented by Schijve and co-authors [2], the phenomenon is still not fully understood. Plasticity induced closure [3-6], “micro-roughness” model [7-8], crack blunting [9], strain hardening at the crack tip [10,11] and residual compressive stress fields ahead of the crack tip [1,12-13] are often cited as the mechanism responsible for crack growth retardation.

EXPERIMENTAL

The work was carried out on a low carbon structural steel (0.26 C, 1.75 Mn, 0.20 Cr and 0.35 Ni) with offshore applications. Concerning the mechanical properties, the material presented a yield and ultimate tensile strength of 600 and 690 MPa, respectively. The typical microstructure consisted of tempered martensite. Compact tension specimens were machined in the L-T orientation, according to the ASTM E647-99 recommendation [14]. The specimen width (W) and specimen thickness (B) were adopted equivalent to 32mm and 8mm, respectively, and a starter notch was machined to a depth of 7.0mm. After machining, the surfaces of the specimens were polished and fine lines were drawn parallel to the specimen axis in order to facilitate monitoring the crack propagation. The specimens were stress relieved at 600°C for 2h in a vacuum furnace to remove any residual machining stresses. Finally, the specimens were precracked up to a crack length of 2.5 mm, i.e. to a crack-length to specimen width ratio, a/W, equal to 0.30.

Fatigue crack propagation study was carried out to characterize the typical da/dN versus ΔK curve of the material under constant amplitude as well as to determine the overloading effect on the material's fatigue resistance. The tests were performed at room temperature making use of a servo-hydraulic machine, which operated at a frequency of 20 Hz. All specimens were tested in a tension-tension mode I loading, with a load ratio R ($R = K_{min} / K_{max}$) equivalent to 0.3. The crack length was monitored using a travelling microscope.

Overloading cycles were applied manually under load control by increasing the load to the designated overload value, decreasing to the minimum value of 3kN and returning to loading scheme prior to overloading. Regarding the first overload series, the specimens were subjected to single overloading cycles applied at a/W = 0.34. The overload ratio (R_{OL}) was defined as $R_{OL} = K_{OL} / K_{max}$ where K_{OL} and K_{max} represent the overload stress intensity factor and the maximum value of the stress intensity factor prior to overloading, respectively. Two different values of R_{OL} equal to 2 and 3 were selected. During the second overload series, some specimens were subjected to two consecutive overloads, with the second overloading applied immediately after the first one or at different intervals of crack propagation. The overload ratio was selected equal to 2. Table 1 summarizes the test parameters for single and consecutive peak overloads.

Transverse residual stresses, acting in a direction perpendicular to the crack plane, have been measured near crack tip region by means of X-ray diffraction techniques, according to the multiple exposure $\sin^2\psi$-method [15].

TABLE 1
TEST PARAMETERS FOR OVERLOADING CYCLES

R_{OL}	K_{min} (MPa.m$^{1/2}$)	K_{max} (MPa.m$^{1/2}$)	K_{OL} (MPa.m$^{1/2}$)
2	10.5	31.5	63.0
3	10.5	31.5	94.5

RESULTS AND DISCUSSION

The fatigue life of the material under constant amplitude (N_f) concerning the first overloading series was determined as 91,350 cycles. This value was adopted to calculate normalized extended life in overload tests. The influence of single overloading cycles on the material's fatigue resistance is given in Table 2 where R_{OL} and K_{OL} are related to the overload monotonic plastic zone ($2r_{OL}^m$), overload cyclic plastic zone ($2r_{OL}^c$), delay cycles number (N_d) and delay cycles ratio (D_r). The values of $2r_{OL}^m$, $2r_{OL}^c$ and D_r were calculated using equations (1), (2) and (3) respectively.

$$2r_{OL}^{m} = \alpha \, (K_{OL} / \sigma_y)^2 \quad (1)$$

$$2r_{OL}^{c} = \alpha \, ((K_{OL} - K_{min}) / 2\sigma_y)^2 \quad (2)$$

$$D_r = N_d / N_f \quad (3)$$

where α and σ_y represent the Irwin's coefficient ($1/\pi$) and the yield strength, respectively.

TABLE 2
OVERLOAD PARAMETERS AND CRACK GROWTH RETARDATION DUE TO SINGLE OVERLOADING

R_{OL}	K_{OL} (MPa.m$^{1/2}$)	$2r_{OL}^{m}$ (mm)	$2r_{OL}^{c}$ (mm)	N_d	D_r
2	63.0	3.51	0.62	15,030	0.16
3	94.5	7.90	1.58	259,220	2.84

It is well known that single or multiple peaks of tensile overloading decreases the fatigue crack growth rate and different theories have been proposed to explain such retardation. The oldest one was postulated by Schijve [16], attributing the crack growth retardation to the generation of compressive residual stresses in the crack tip region. One can observe in Figure 1 the presence of compressive residual stresses in that region for both overloading ratios. As mentioned earlier, the residual stresses were measured by means of X-ray diffraction technique and therefore the stress distribution shown in Figure 1 refers to points on the surface of the specimen. At points removed from the surface, the residual stress levels are expected to be higher, consistent with the fact that the strain gradient ahead of the crack tip in the central region of the specimen (plane strain) is higher than that developed under essentially plane stress conditions on the specimen surface. This is borne out by the observation that residual stress levels calculated using a J integral approach were found to be consistently higher than those measured on the specimen surface [17]. After applying overloading cycles, the crack propagation was retarded in both conditions. However, for the higher overloading ratio, larger area with higher compressive stress levels is induced. For this reason, the overloading of 3 gives a better lifetime benefit concerning crack retardation when compared with that obtained with a ratio of 2.

Another important evidence of overload effect is shown in Figure 1, where maximum compressive residual stresses are found at the crack tip and changing over to tensile stresses at points removed from the tip. In both overloading conditions presented, the stress fields have their maximum values shifted in front of the crack tip and compressive residual stresses on the crack flanks are completely reduced.

One explanation for the influence of the overloading ratio on residual stress fields is that increasing R_{OL} causes an enhancement in K_{OL} and, consequently, an increase in the overload monotonic plastic zone size. In the post-overloading condition, the crack grows under the influence of a large compressive residual stress field created by the overload plastic zone. For this reason, the fatigue crack growth rate is significantly low during the overload affected crack growth.

In addition to the overload monotonic plastic zone, overload cyclic plastic zone is considered to be of significant importance. Matsuoka and Tanaka [18] demonstrated that the size of the compressive residual stress field at the crack tip is about 2.5 times the overload cyclic plastic zone and, therefore, postulated that the crack closure effect is most pronounced in this region. Considering the values of $2r_{OL}^{c}$ given in Table 2 and taking into account the correlation proposed by Matsuoka and Tanaka, one can calculate the size of the compressive residual stress fields presented in Figure 1. It should be about 1.6 and 4.0 mm for overloading ratios of 2 and 3, respectively. The experimental results seem to be in a good agreement with these calculated values.

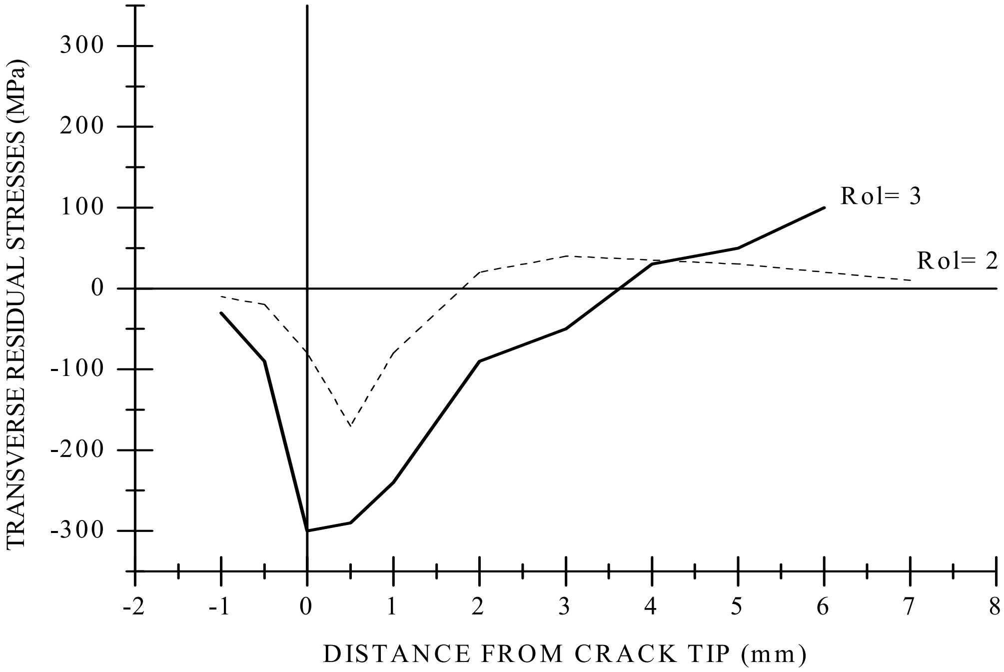

Figure 1: Residual stress distribution on the specimens' surfaces after single overload cycles.

The increase in fatigue life of the material due to consecutive overloads is presented in Figure 2. This figure reveals that the improvement of the delay cycles number is related to the interval that separates the two consecutive overloads. The larger the interval of crack propagation between the two consecutive overloads, the lower the fatigue crack growth rate, i.e. the higher the residual life of the material. Table 3 reinforces the affirmation that the second overloading affected the fatigue resistance of the material significantly. In this table d means the intervals of crack propagation between the consecutive overload cycles, while N_{d2} and D_{r2} represent the delay cycles number and delay cycles ratio, respectively. The fatigue life of the material under constant amplitude (N_f) concerning the second overloading series was determined as 61,950 cycles.

If one compares the delay cycles ratios related to R_{OL} (equal to 2 in Table 2) with those presented in Table 3, it is clearly observed that the second overloading cycle applied after crack propagation has improved the fatigue life of the material. The second overloading cycle increases the crack growth retardation brought about by the first overloading as a result of a significant influence on the rate of the fatigue crack propagation. Simões obtained similar results with an aluminium alloy for the aeronautic industry [19-20].

Regarding the effects of a second overloading applied after some crack growth, it is believed that the role played by such an overloading is largely influenced by the amount of crack growth as compared to the monotonic plastic zone size created by the first overloading [21-22]. According to this assumption, the higher efficiency of the second overloading associated with a larger crack growth interval may be attributed to a more effective interaction between the monotonic plastic zones resulting from the consecutive overloads. In this respect, one may mention that a larger amount of crack growth before applying the second overload means a larger extension of the compressive residual stress field under which the crack will propagate. Further, a higher K level and hence a larger monotonic plastic zone size are associated with the presence of a longer crack at the moment of applying the second overload. A more effective interaction between the monotonic plastic zones may also signify higher compressive residual stress levels, more influential crack closure and more effective strain hardening of the material ahead of the crack tip. No attempt, though, was made in this work to measure hardness levels or to map compressive residual stresses ahead of the crack tip in terms of the interval of crack propagation. However, in a previous work [21], it was observed that a larger compressive residual stress field was created by the second overloading cycle applied after some crack propagation from the first one.

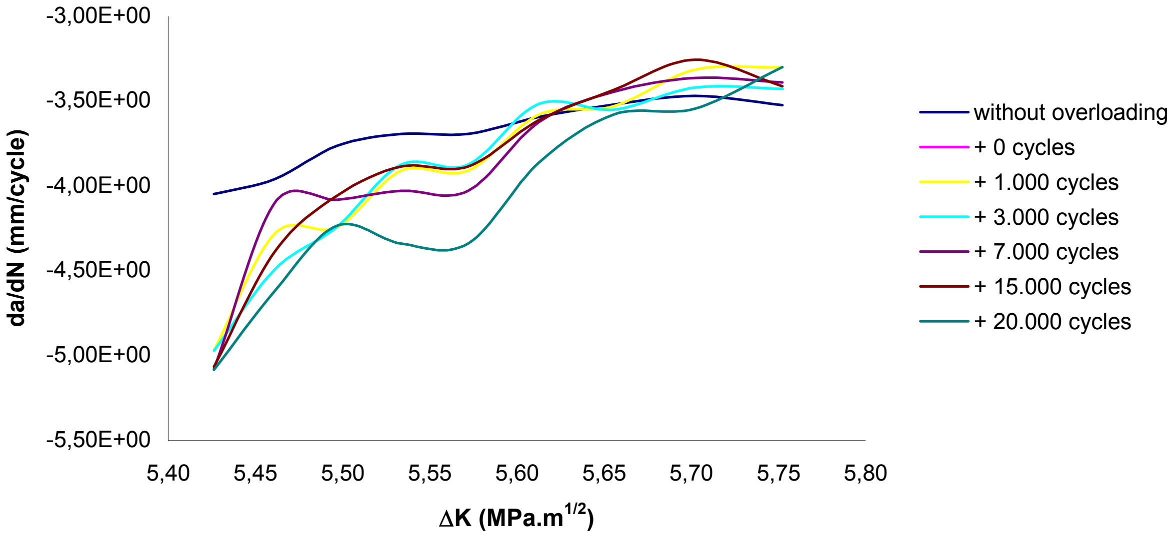

Figure 2: Crack growth rate (da/dN) versus the variation in the stress intensity factor (ΔK) for the material after the second overload series.

TABLE 3
OVERLOAD PARAMETERS AND CRACK GROWTH RETARDATION DUE TO CONSECUTIVE OVERLOADING CYCLES

D (cycles)	d (mm)	N_{d2}	D_{r2}
0	0.00	143,150	2.3
1000	0.01	162,190	2.6
3000	0,03	175,560	2.8
7000	0,06	184,340	3.0
15000	0,13	185,430	3.0
20000	0,17	235,200	3.8

CONCLUDING REMARKS

The purpose of this work was to determine the improvement in fatigue residual life of a structural steel due to overloading. Overload cycles resulted in an increase in the fatigue resistance of the material and the extended life is related to the presence of compressive residual stress fields acting in the region near the crack tip. The higher the overload ratio, the higher the delay cycles number. An increase in the overload ratio is more efficient for fatigue residual life in virtue of an increase in the mentioned stress fields.

Further, some tests were carried out aiming to study the influence of the overloading interaction on the fatigue crack growth. In this sense, the effect of two equal and consecutive overloads, with the second one applied at different intervals of crack propagation from the first, was also considered. The application of two overloads of the same magnitude increased in a more effective way the fatigue residual life of the material. The larger the interval of crack propagation between the two consecutive overloads, the higher the fatigue crack growth retardation.

REFERENCES

1. Lang, M. and Marci, G. (1999). *Fatigue Fract. Engng. Mater. Struct*. 22, 257.
2. Schijve, J., Broek, D. and Rijk, P. de (1961). NRL–TN M 2094.
3. Elber, M. (1971). *ASTM STP* 486, pp. 230-242.
4. Shin, C.S. and Fleck, N.A. (1987). *Fatigue Fract. Engng. Mater. Struct.* 9, 379.
5. Ward-Close, C.M., Blom, A.F. and Ritchie, R.O. (1989). *Engng. Fract. Mech.* 32, 613.
6. Damri, D. and Knott, J.F. (1991). *Fatigue Fract. Engng. Mater. Struct.* 14, 709.
7. Ritchie, R.O. and Suresh, S. (1982). *Met. Trans*. 13A, 937.
8. Suresh, S. (1983). *Engng. Fract. Mech.* 18, 577.
9. Hammouda, M.M.I., Ahmad, S.S.E., Sherbini, A.S. and Sallam, H.E.M. (1999). *Fatigue Fract. Engng. Mater. Struct*. 22, 145.
10. Jones, R.E. (1973). *Engng. Fract. Mech.* 5, 585.
11. Knott, J.F. and Pickard, A.C. (1977). *Metal Sci*. 11, 399.
12. Wheeler, O.E. (1972). *J. Basic Engng. Trans. ASME* 4, 181.
13. Matsuoka, S. and Tanaka, K. (1978). *J. Mater. Sci*. 13, 1335.
14. ASTM (1999). ASTM E647-99, U.S.A.
15. Pereira, M. (1993). PhD Thesis, Kassel University, Germany.
16. Schijve, J. (1960). NRL-MP 195.
17. Pereira, M.V., Wohlfahrt, H. and Darwish, F. (1997). In: Advances in Fracture Research, pp. 2087-2094, Karihaloo, B.L, Mai, Y.-W., Ripley, M.I. and Ritchie, R.O. (Eds). Pergamon, Amsterdam.
18. Matsuoka, S. and Tanaka, K. (1978). *Engng. Fract. Mech*. 10, 515.
19. Simões, A.F. (1997). MSc Thesis, PUC-Rio, Brazil.
20. Simões, A.F., Pereira, M. and Godefroid, L. (1999). In: *Fatigue'99*, pp. 1069-1074, Wu, X.R. and Wang, Z.R. (Eds). EMAS, West Midlands.
21. Ramos, M.S., Pereira, M. and Motta, S.H. (2000). In: Fracture Mechanics: Applications and Challenges (ECF-13), CD-Rom, Fuentes, M., Elices, M., Martín-Meizoso, A. and Martínez-Esnaola, J.M. Elsevier Science, Amsterdam.
22. Ramos, M.S. (2001). MSc Thesis, CEFET-RJ, Brazil.