FATIGUE CRACK PROPAGATION IN STRUCTURAL STEEL AFTER OVERLOADING CYCLES

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ABSTRACT

This work represents an approach to study the influence of overloading on the fatigue resistance of a structural steel with offshore applications. Constant amplitude loading was adopted for the fatigue tests making use of CT specimens. Two different single tensile overload cycles were applied in an effort to evaluate the influence of the intensity of overloading on the efficiency of crack retardation. After the overload cycles, residual stresses were measured in the region near crack tip by means of X-ray diffraction techniques. The results indicated that the extended fatigue life increases with the increase in the magnitude of overloading and in the presence of higher compressive residual stress fields. Further, 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 in the interval that separated the two overloads.

INTRODUCTION

Structural components when in service under cyclic loading may be subjected to either variable amplitude loading or occasional overloading cycles. Sometimes, the overloading cycles are purposely applied to produce some beneficial effects on the fatigue resistance of mechanical or structural components. Such overloads lead to the retardation of the fatigue crack growth that may sometimes culminate into temporary or permanent crack arrest [1]. Fatigue crack propagation prediction models are considered essential for the structural integrity assessment on the basis of damage tolerance criterion. However, load interaction phenomena complicate life prediction and, in order to achieve the maximum benefit from overloading cycles, it is imperative to understand the significance of post overloading crack retardation.

Although much effort has been given to the overloading effect since it was presented by Schijve and co-authors [2], in 1961, the phenomenon is still not fully understood. Plasticity induced closure, first proposed by Elber [3], is often cited as the mechanism responsible for delayed retardation [4-6]. Some authors [7,8] have proposed a “micro-roughness” model in which crack branching and asperity contact following an overload, reduce the crack driving force. Crack blunting [9] and strain hardening at the crack tip [10,11] following an overload may also contribute to a delay in the growth rate. The residual compressive stress field created ahead of the crack tip on application of the overload would tend to induce an immediate retardation [1,12-13]. It is clear from the literature that a state of confusion still exists over the primary mechanism controlling the crack retardation, if a single mechanism does in fact govern the process.

EXPERIMENTAL

Material and Test Specimens

The research 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. The material was received as an 85 mm diameter hot rolled circular bar and the typical microstructure consisted of tempered martensite. Concerning the mechanical properties, the material presented a yield and ultimate tensile strength of 600 and 690 MPa, respectively.

Compact tension (CT) specimens were machined from the mid-thickness of the bar in the L-T orientation, according to the ASTM E647-99 recommendation [14]. The dimensions of the specimens were B = 8 mm and W = 32 mm, where B and W represent the thickness and the width, respectively. A starter notch was machined to a depth of 7.0 mm. 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 2 h in a vacuum furnace to remove any residual machining stresses. Finally, the specimens were precracked up to a crack length of 1.5 mm, i.e. to a crack-length to specimen width ratio of a/W = 0.27.

Fatigue Crack Growth Testing

Fatigue crack propagation study was carried out to characterise the typical da/dN versus ΔK curve of the material under constant amplitude mode I loading, 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 under sinusoidal loading at a frequency of 20 Hz. All specimens were tested in a tension-tension mode with a load ratio R ($R = K_{min} / K_{max}$) equivalent to 0.3. The crack length was monitored using a travelling microscope.

Overload Histories

Overloading cycles were applied manually under load control by raising the load to the designated overload value, decreasing to the minimum value and returning to the same mean load as that prior to the overload, before re-fatiguing the specimens. Regarding the first overload series, the specimens were subjected to single overloading cycles applied at a total crack length, a, equivalent to 3.0 mm and corresponding to a/W = 0.31. The overload ratio (R_{OL}) was defined as $R_{OL} = K_{OL} / K_{max}$ where K_{OL} and K_{max} mean the overload stress intensity and the maximum value of the stress intensity 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, i. e. at a/W = 0.31 or at 0.25 mm of crack propagation (a/W = 0.32). The overload ratio was selected equal to 2. Table 1 summarizes the test parameters for single and consecutive peak overloads.

TABLE 1
TEST PARAMETERS FOR OVERLOADING CYCLES

a/W	R_{OL}	K_{min} (MPa.m$^{1/2}$)	K_{max} (MPa.m$^{1/2}$)	K_{OL} (MPa.m$^{1/2}$)
0.31	2	10.5	31.5	63.0
	3	10.5	31.5	94.5
0.32	2	10.7	32.1	64.2

Residual Stress Measurements

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. The evaluation was performed according to the multiple exposure $\sin^2\psi$-method [15]. A computer controlled ψ-diffractometer was adopted with a 0.5 mm diameter collimator to take into account steep stress gradients at the surface of the specimens. All experiments were carried out with an X-ray emission tube powered at 35 kV and 30 mA.

RESULTS AND DISCUSSION

The fatigue life of the material under constant amplitude (N_f) was determined as 91350 cycles. This failure cycles number 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), delay cycles ratio (D_r) and overload affected crack growth (a_d). The values of $2r_{OL}^m$, $2r_{OL}^c$, D_r and a_d were calculated using equations (1), (2), (3) and (4), respectively.

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

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

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

$$a_d = \alpha \left(\left(K_{OL} / \sigma_y \right)^2 - \left(K_{max} / \sigma_y \right)^2 \right) \quad (4)$$

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^{½})	$2r_{OL}^m$ (mm)	$2r_{OL}^c$ (mm)	N_d	D_r	a_d (mm)
2	63.0	3.51	0.62	15030	0.16	2.63
3	94.5	7.90	1.58	259220	2.84	7.01

The D_r ratio is considered to be a parameter which best describes the overload effect because it gives a lifetime benefit concerning the material's fatigue resistance. It is clearly evident in Table 2 that the D_r values are sensitive to the variation of R_{OL}.

It is well known that single or multiple peaks of tensile overload decreases the fatigue crack growth rate and different theories have been proposed to explain the retardation. The oldest one was postulated by Schijve [16], attributing the crack growth retardation to the generation of compressive residual stresses near crack tip region. Figure 1 is in agreement with Schijve's postulation. One can observe the presence of compressive residual stresses in front of the crack tip for both overloading ratios and, immediately after applying overload cycles, the crack propagation was retarded in both conditions. However, for the higher overloading ratio, larger area with compressive residual stresses is induced accompanied by higher stress levels. For this reason, the overloading ratio equal to 3 promotes a more effective crack retardation when compared with that one equal to 2. In this way, the residual life extension given in Table 2 is in accordance with the residual stress fields presented in Figure 1, considering that higher value of delay cycles ratio is related to the higher overloading ratio, i. e. higher compressive stress state.

Other important evidences of the overload effect are shown in Figure 1. Under baseline loading conditions before applying overloads, the crack flanks near the crack tip present compressive residual stresses. Always at crack tip, maximum compressive residual stresses are found. Concerning the region near crack tip, the stress changes to small tensile residual stresses after a steep gradient and then decreases to zero [17]. In both overloading conditions presented in Figure 1, 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.

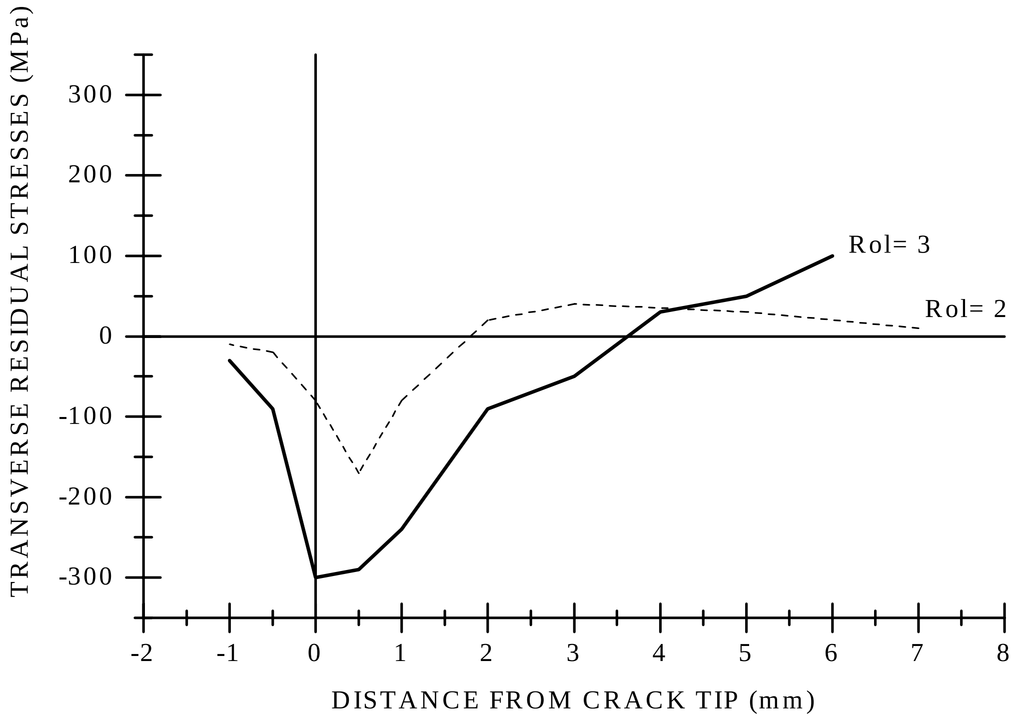

Figure 1: Residual stress distribution on the specimens' surfaces after single overload cycles.

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 at the crack tip. 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 equal to 2 and 3, respectively. The experimental results seem to be in a good agreement with these calculated values.

However, one finds some fundamental difficulties to explain extended fatigue life solely on the basis of compressive residual stresses in front of crack tip. The calculated values of the overload affected crack growth in Table 2 are larger than the measured and calculated sizes of the compressive residual stress fields. It means that retardation can persist even when the post-overload crack has traversed through the predicted zone of residual stresses. In fact, once the crack tip comes out of the compressive stress region, the fatigue crack growth rate relatively increases though still it does not return to the same da/dN rate before the overloading. The present authors believe that there is an interaction with other mechanisms and this interaction is responsible for the improvement in the fatigue resistance.

The increase in fatigue life of the material due to consecutive overloads is presented in Table 3. In this table d means the intervals of crack propagation between the consecutive overload cycles, while K_{OL2}, $2r_{OL2}^{m}$, $2r_{OL2}^{c}$, N_{d2}, D_{r2} and a_{d2} represent K, overload monotonic plastic zone, overload cyclic plastic zone, delay cycles number, delay cycles ratio and overload affected crack growth related to the second overload cycle, respectively.

TABLE 3

OVERLOAD PARAMETERS AND CRACK GROWTH RETARDATION DUE TO EQUAL (R_{OL} = 2) AND CONSECUTIVE OVERLOADING CYCLE

d (mm)	K_{OL2} (MPa.m$^{1/2}$)	$2r_{OL2}^{m}$ (mm)	$2r_{OL2}^{c}$ (mm)	N_{d2}	D_{r2}	a_{d2} (mm)
0.00	63.0	3.51	0.62	16090	0.18	2.63
0.25	64.7	3.73	0.66	92200	1.01	2.86

The simple observation of Table 3 reveals that the improvement of the delay cycles number is related to the interval that separates the two consecutive overloads. It seems that the second overloading applied immediately after the first one did not affect the fatigue resistance of the material significantly, when compared with that one applied after some crack growth. Figure 2 shows the residual stresses related to these consecutive overloading cycles. Although there is a large difference between both delay cycles ratios, their stress fields are quite identical concerning the region near crack tip. Hence, one may conclude that more interactive superposition of crack closure mechanism, higher strain hardening rate in the crack tip region, micro-roughness and crack meandering would lead to an increase in fatigue crack growth retardation due to consecutive overload cycles.

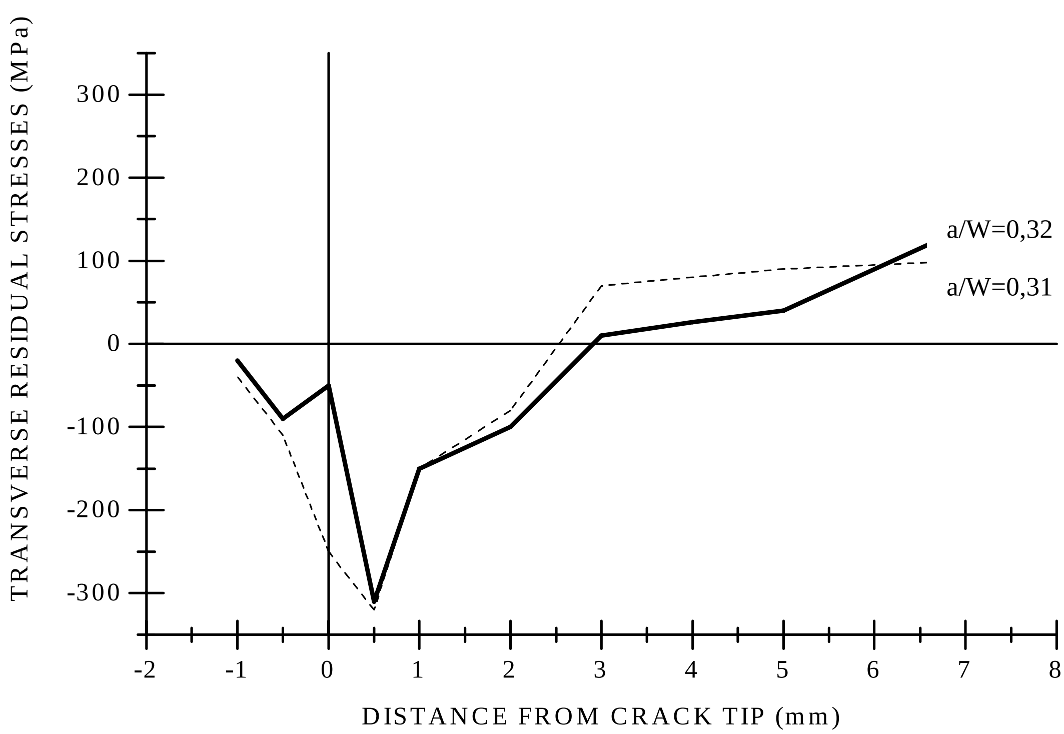

Figure 2: Residual stress distribution on the specimens' surfaces after consecutive overload cycles at different intervals of crack propagation. Both overloading ratios were equal to 2.

On the other, 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 affected crack growth relative to the first overloading as a result of a significant influence on the da/dN rate of the fatigue crack propagation. Simões [19-20], researching aluminium alloy for the aeronautic industry also presented similar results.

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. According to this assumption, the higher efficiency of the second overloading associated with a smaller crack growth interval may be attributed to a more effective interaction between the monotonic plastic zones resulting from the consecutive overloads. This more effective interaction, in turn, can signify higher compressive residual stress levels and more influential crack closure mechanism. This postulation is reinforced by Figure 3. In this figure, one can observe that a larger compressive residual stress field was created by the second overloading cycle applied at 0.25 mm of crack propagation.

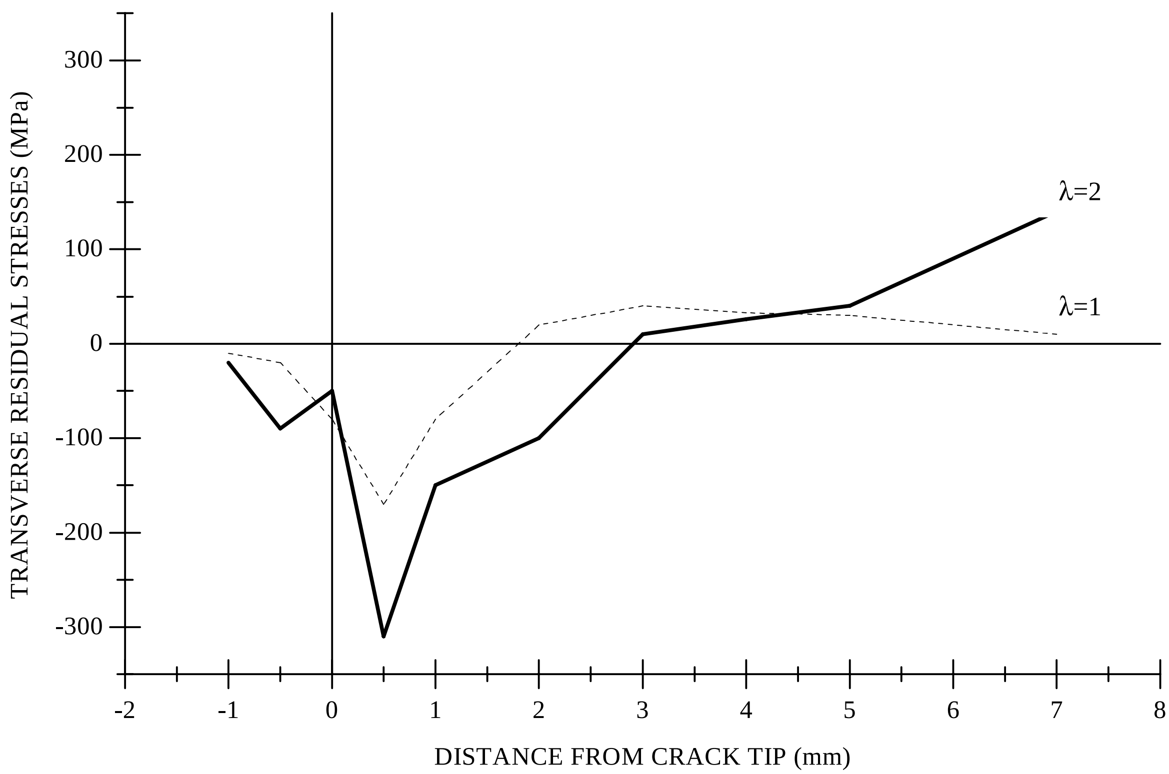

Figure 3: Residual stress distribution on the specimens' surfaces after single (λ=1) and consecutive (λ=2) overload cycles with the selected overloading ratios equivalent to 2.

CONCLUDING REMARKS

The first purpose of this research was to determine the influence of the overloading intensity on the fatigue crack growth retardation of a structural steel used in the offshore industry. 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 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 residual stress fields due to a second overloading after some crack propagation between the two consecutive overloads, the higher the fatigue crack growth retardation.

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