AN EXPERIMENTAL AND ANALYTICAL STUDY OF CRACK GROWTH RETARDATION IN A STRUCTURAL STEEL

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Abstract

The purpose of the present work is to test the validity of the Wheeler model in predicting fatigue crack growth retardation in welded steel joints. The fatigue data were obtained under constant amplitude loading cycles and crack retardation was effectively induced by applying a single overload at a given crack length. This made it possible to determine the crack growth retardation factor γ, which was then related to both the current and overload plastic zone sizes. The results have indicated that the delay period predicted by the model is in fair agreement with that experimentally observed. The exponent involved in the power function, as proposed by Wheeler for the factor γ, was calculated using the experimental data and was found to vary along the crack growth delay period. One may thus conclude that the Wheeler formulation could lead to imprecise predictions of the retardation in crack growth due to overloading.

Introduction

It has been known for more than four decades that overload cycles of sufficient magnitude can result in a transient retardation in the rate of fatigue crack growth at the baseline level [1]. It is also well established that this retardation is closely related to the residual compressive stress field induced in the vicinity of the crack tip [2]. Following an overload cycle, the fatigue crack starts to advance into the overload (OL) plastic zone and the residual compressive stresses in an element just behind the crack tip are relaxed. This contributes to the level of crack closure in the wake of the crack tip, thus retarding fatigue crack propagation. As the crack exits the OL plastic zone, the propagation rate is generally back again at the baseline level corresponding to the constant amplitude (CA) loading.

The model proposed by Wheeler [3] represents an approach to explain crack growth delays caused by high loads. The model recognizes that new plastic zones are created inside the large monotonic plastic zone of an overload. A crack growth retardation factor γ, which is related to the sizes of both the cyclic and monotonic plastic zones, was then introduced by Wheeler, making it possible for one to predict crack growth rate within the delay period, $(da/dN)_{VA}$, from the expression:

$$(da/dN)_{VA} = \gamma\,(da/dN)_{CA} \qquad (1)$$

The present study was initiated to evaluate the applicability of the Wheeler model to predicting fatigue crack growth retardation brought about by a single overload cycle applied at a given crack length during CA loading of an R3 grade structural steel. As this grade steel is largely used for fabricating offshore mooring chains, the study was extended to include flash welded chain links both in the as-welded and welded and heat treated conditions.

Experimental

The steel used for this investigation was received in the form of hot rolled round bars of circular cross section with a nominal diameter of 85 mm. The steel contains, in weight percent, 0.26% C, 1.2% Cr, 1.75% Mn, 0.35% Ni with the balance being Fe and traces of impurity elements. The circular bars were bent in conformity with the typical stud link geometry before they were butt flash welded [4]. Following the welding process, a number of links were austenitized at $900\,^0$C for 90 minutes, water quenched and then tempered at $620\,^0$C for 90 minutes.

Compact tension (CT) specimens were machined along the L–T orientation, in accordance with the ASTM E647-99 recommendation [5]. The CT specimens were cut off from the welded joint as well as from the opposite side of the links in both as-welded and welded and heat treated conditions. The study, therefore, was carried out contemplating four different microstructural conditions: as-welded joint (AW), welded and heat treated joint (WH), as-received base metal (BM) and heat treated base metal (BH).

The specimen width, W, and specimen thickness, B, were taken as 32 and 8 mm, respectively and a starter notch was machined to a depth of 7 mm. The specimen surfaces were polished and fine lines were drawn parallel to the specimen axis in order to facilitate monitoring crack growth during cyclic loading. Finally, the CT specimens were precracked up to a crack length of 2 mm, i.e., to a total crack length-to-specimen width ratio, a/W, of 0.28. The AW and WH specimens were precraked in a way such that the crack plane always coincided with the weld plane.

CA cyclic loading was applied to the precracked specimens so as to obtain the typical da/dN versus ΔK curves for the four microstructural conditions in question. The tests were performed at room temperature using a servo-hydraulic machine, operated at a frequency of 20 Hz. All of the CT specimens were submitted to a tension-tension mode I loading with a maximum load of 9 kN and a load ratio R ($R = K_{min} / K_{max}$) of 0.33 and fatigue crack length was monitored using a traveling microscope.

Overload cycles were applied manually at a/W = 0.33 under load control by increasing the load to the designated level, going down to the minimum value of 3 kN and then returning to the CA loading scheme. The overload ratio R_{OL}, defined by K_{OL} / K_{max} [6], was taken as 1.5 and 1.8, which corresponds to single overload levels of 13.5 and 16.2 kN, respectively, where the parameters K_{OL} and K_{max} are the overload stress intensity factor and the CA maximum stress intensity factor, respectively.

Results and Discussion

Examples of the variation of the fatigue crack growth rate da/dN with ΔK under CA and variable amplitude (VA) loading are presented in Figs 1-4. These figures exemplify the crack growth retardation caused by the application of a single overload. As expected the maximum crack propagation rate is reached only after a small crack length increment [7]. After passing this minimum, da/dN starts to increase and eventually returns, over some substantial further crack extension, to the normal CA crack growth rate of the CA baseline cycles. The ratio between the minimum growth rate and the corresponding baseline rate, γ_{min}, is presented in Table 1, for the four microstructural conditions and the two overloads considered in this work. The fatigue crack length, Δa_d, over which the delay effect was detected, is also presented in the same table, together with the corresponding overload plastic zone size, $(r_p)_{OL}$. This was calculated using the following expression:

$$(r_p)_{OL} = \frac{1}{\pi}\left(\frac{K_{OL}}{\sigma_Y}\right)^2 \qquad (2)$$

where K_{OL} is the OL stress intensity factor calculated according to reference [5] and σ_Y is the yield stress, determined as 465, 500, 530 and 545MPa for the AW, WH, BM and BH conditions, respectively.

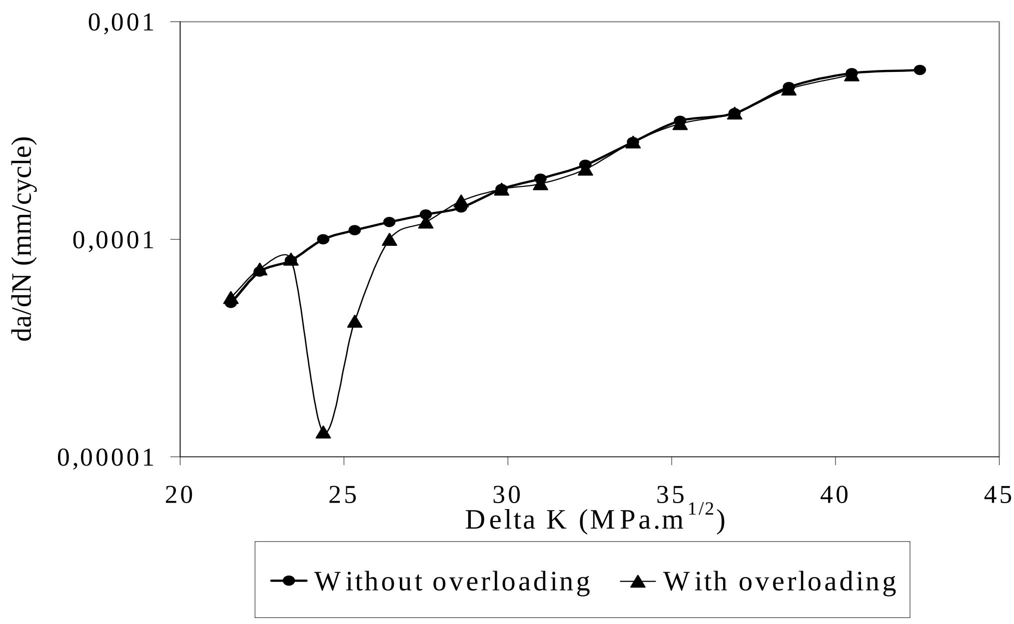

FIGURE 1. Variation of da/dN with ΔK for AW microstructural condition after an overload of 16,2 kN.

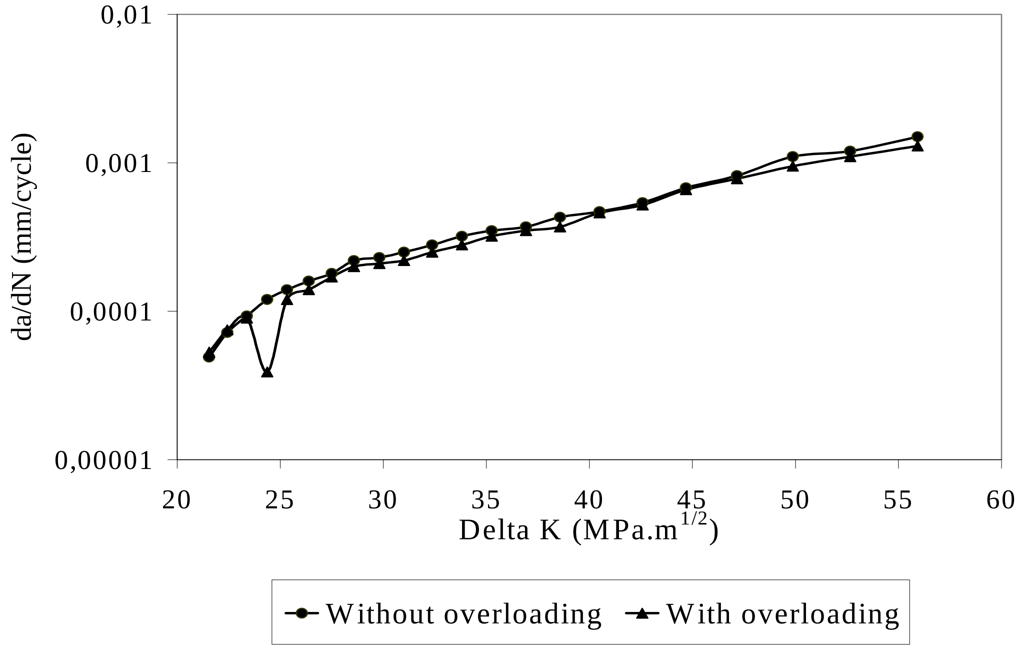

FIGURE 2. Variation of da/dN with ΔK for WH microstructural condition after an overload of 13,5 kN.

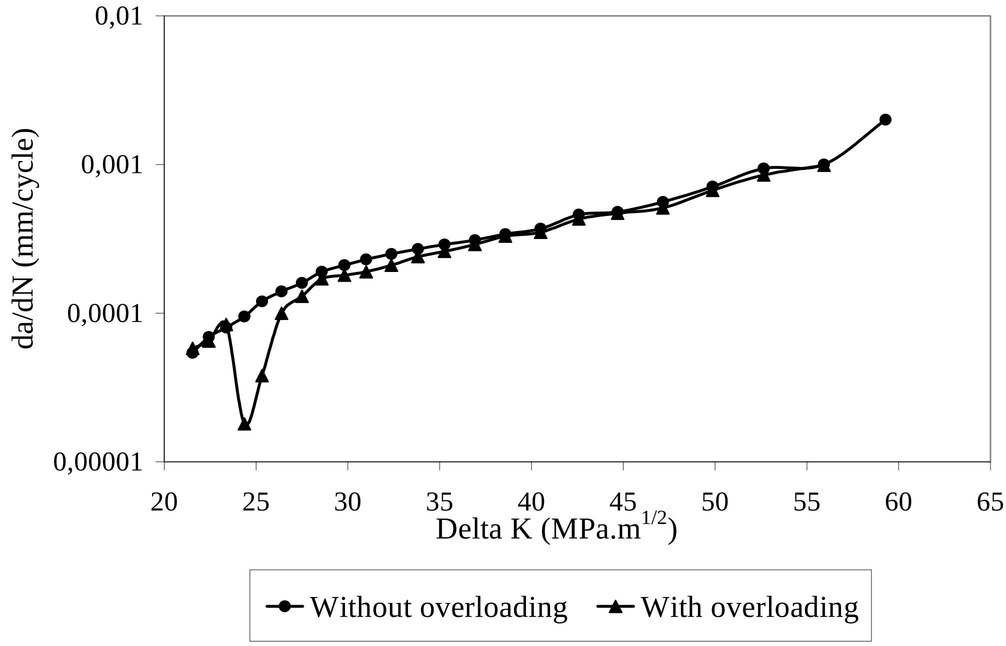

FIGURE 3. Variation of da/dN with ΔK for BM microstructural condition after an overload of 16,2 kN.

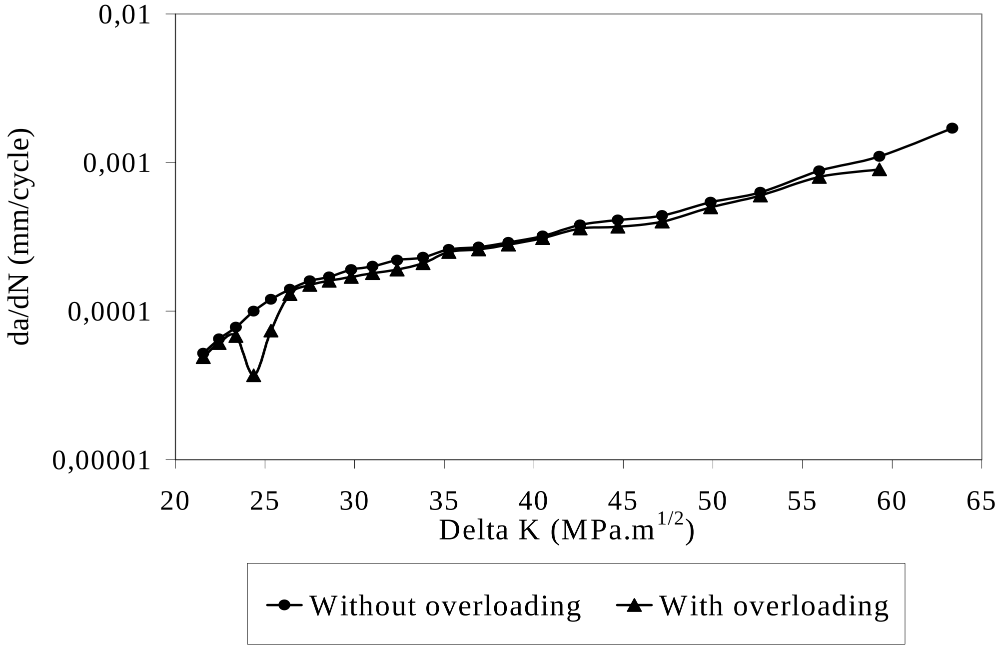

FIGURE 4. Variation of da/dN with ΔK for BH microstructural condition after an overload of 13,5 kN.

TABLE 1. Values of $\gamma_{\min}$, Δa_d and $(r_p)_{OL}$ according to the microstructural conditions.

Specimen code	R_{OL} = 1.5			R_{OL} = 1.8		
	$\gamma_{\min}$	Δa_d / mm	$(r_p)_{OL}$ / mm	$\gamma_{\min}$	Δa_d / mm	$(r_p)_{OL}$ / mm
AW	0.40	2.0	4.65	0.14	3.0	6.70
WH	0.42	1.3	4.02	0.14	2.5	5.80
BM	0.39	1.5	3.60	0.20	2.0	5.16
BH	0.52	1.3	3.39	0.21	2.0	4.88

The results presented in Table 1 indicate that an increase in the overload ratio R_{OL} from 1.5 to 1.8 is more effective in retarding crack growth in the welded joints than in the base metal. This is clearly evidenced by comparing the values of $\gamma_{\min}$ associated with the applied overloads for each of the microstructural conditions in question. The behavior of $\gamma_{\min}$ described above is seen to be consistent with what was reported, in a previous work [8], on extending the residual fatigue life in these microstructures. The delay cycles number N^* was found to increase by a factor of about 7 for both AW and WH joints as R_{OL} was increased from 1.5 to 1.8. For the base metal, on the other hand, this factor amounted to only about 1.5. This drastic difference in behavior between the base metal and the welded joints has been attributed to the fact that fatigue crack propagation in the joints occurs along a natural path represented by the weld plane [8]. Further, the marked improvement in the fatigue behavior of the welded joints, upon increasing the intensity of overloading, has been associated with crack growth retardation mechanisms, which become increasingly operative at higher overloads. Mechanisms such as crack blunting [9], strain hardening of the material within the OL plastic zone [10] and crack surface asperity [11] seem to have their efficiency improved by increasing the intensity of overloading, particularly for the welded joints.

According to the Wheeler model [3], the retardation factor γ is assumed to be a power function of the ratio $r_{p,i} / \lambda_i$, where $r_{p,i}$ is the current plastic zone size corresponding to a given crack length a_i and λ_i the distance between the crack tip and the edge of the OL plastic zone. Thus γ is expressed as:

$$\gamma = (r_{p,i} / \lambda_i)^m \tag{3}$$

where the exponent m is an empirical constant dependent on the type of the VA load history.

The current plastic zone size $r_{p,i}$ can be calculated from the expression below:

$$r_{p,i} = \frac{1}{\pi}\left(\frac{K_{\max}}{\sigma_Y}\right)^2 \tag{4}$$

where $K_{\max}$ is the maximum stress intensity factor corresponding to the CA loading for a crack length a_i. For this crack length, λ_i is given by the expression:

$$\lambda_i = a_0 + (r_p)_{OL} - a_i \tag{5}$$

where a_0 is the crack length at which the overload was applied.

As the crack propagates through the delay zone, $r_{p,i}$ becomes larger whereas λ_i gets smaller. As a result, γ will increase gradually from its minimum value $\gamma_{\min}$ to a maximum value of unity as the far edge of the current plastic zone starts to exit the OL plastic zone and the delay effect would thus be gone. With this in mind, one can estimate Δa_d from:

$$\Delta a_d^* = a_0 + (r_p)_{OL} - (a_i^* + r_{p,i}^*) \tag{6}$$

where a_i^* is the crack length necessary for the current plastic zone to reach the far edge of the OL plastic zone.

The Δa_d^* values estimated from the above relation are listed in Table 2 in comparison with the values determined from the experimental data. One can conclude from this comparison that the delay period measured experimentally agrees fairly well with the corresponding Δa_d^* value estimated from equation (6) for each of the microstructural conditions considered in this study.

TABLE 2. Values of Δa_d , Δa_d^* and *m* according to the microstructural conditions.

Specimen code	R_{OL} = 1.5			R_{OL} = 1.8		
	Δa_d / mm	Δa_d^* / mm	*m*	Δa_d / mm	Δa_d^* / mm	*m*
AW	2.0	1.8	1.5 ± 0.2	3.0	3.0	1.5 ± 0.4
WH	1.3	1.5	1.5	2.5	2.7	1.6 ± 0.3
BM	1.5	1.5	1.3 ± 0.3	2.0	2.5	1.4 ± 0.2
BH	1.3	1.5	1.2	2.0	2.7	1.5 ± 0.1

An experimental value of γ, corresponding to a given crack length a_i within the delay zone, Δa_d, can be used to estimate the exponent *m* by substituting in equation (3) the appropriate $r_{p,i}$ and λ_i values calculated, respectively, from equations (4) and (5). The value of *m* thus obtained was found to vary with the crack length a_i, giving rise to a considerable degree of scatter as can be verified from Table 2. The use of the average *m* values listed in this table may lead initially to overestimating the retardation factor γ, and as crack propagation proceeds, the value of γ would tend to be underestimated. These observations appear, as pointed out by Schijve [7], to corroborate the limitations of the Wheeler model in predicting the crack growth behavior under VA loading.

Conclusions

From what is presented above, the following conclusions can be drawn:

- The extent of the fatigue crack growth retardation period predicted by the Wheeler model agrees fairly well with the experimental observations made on flash welded steel joints as well as on the base metal.

- An increase in the intensity of overloading results in a more effective crack growth retardation as evidenced by an observed decrease in the minimum propagation rate, with the effect being more pronounced for the welded joints than for the base material.

- The form of the power function proposed by Wheeler for the retardation factor implies in different values of the exponent m as calculated from the experimental data. A single value of that exponent would therefore lead to imprecise estimates of the crack propagation rate along the delay period.

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