INFLUENCE OF MULTIPLE OVERLOADS ON FATIGUE CRACK GROWTH

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ABSTRACT

The influence of multiple overloads has been studied in a structural steel E36. It is shown that crack retardation increases with increasing the overload ratio and the number of overloads. These results point out the importance of residual stress evolution induced by multiple overloads.

KEYWORDS

Fatigue, mechanisms, overloads, crack growth retardation, crack closure.

INTRODUCTION

In structures, materials suffer a random load history and the fatigue crack propagation depends on the loading sequence. Though the effect of a single peak overload associated with a constant amplitude load history is now well understood (Robin, 1982,1983), the influence of the number of peaks has received very few attention. Vancon (1978) on aluminium alloys, Taïra (1979) and Dahl (1980) have considered this problem.

Schematically, the following points have been observed in our experiments (Fig. 1).

- The lowest crack growth rate $(da/dN)_{min}$ reached during retardation is a decreasing function of the number of overloads (Np).
- The crack length at which the minimum crack growth rate is reached is practically invariant.
- The distance affected by the retardation is constant (a_d^*).
- The number of cycles of delay (Nd) increases with the number of overloads.

It is important to notice that two possibilities of crack growth behaviour are observed after overload application. Experimental results of Vancon (1978) indicated that a saturation effect appears and Dahl (1980) noticed the possibilities of crack arrest for high overload ratio (R peak > 2).

In order to determine precisely the influence of the number of overload peaks, tests were performed on a structural steel at different R peak ratios (R_p) and Kmax values.

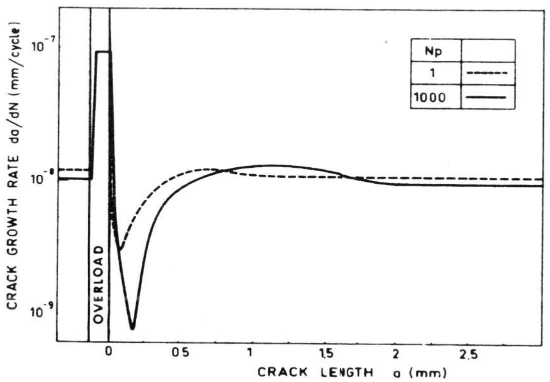


Fig. 1 : Evolution of the crack growth rate

MATERIAL AND EXPERIMENTAL CONDITIONS

Experiments were carried out on a structural steel E36 (AFNOR standard). The chemical and the mechanical properties are listed in Table 1.

TABLE 1 - Chemical composition (weight %) and Mechanical Properties

Chemical Composition (weight %)

C	Mn	Si	Ni	S	P	Aℓ	Ti	Cr	Cu	Mo
0,14	1,4	0,29	0,42	0,003	0,007	0,02	0,005	0,07	0,07	0,035

Mechanical Properties

σ_y (N/mm^2)	UTS (N/mm^2)	Elongation to rupture (%)	Reduction in area (%)
380	520	30	64

The tests were run on compact tension specimens of 80 mm width and thickness B = 15 mm or B = 19 mm. The crack growth rate was measured with an optical microscope (x 50) on one side of the specimen. The crack opening load was determined by a compliance method. Tests were performed with two values of the maximum stress intensity factor Kmax = 18 MPa $\sqrt{m}$ and Kmax = 30 MPa $\sqrt{m}$ with a load ratio R = 0,1 and an overload ratio 1,6 $\leq$ R peak $\leq$ 2. After the application of overloads, the initial stress intensity factor was resumed and kept constant within 2% of Kmax by manual load shedding. High-low tests were also done and were considered to be equivalent to an infinite number of applied overload peaks.

RESULTS

The major effect of increasing the number of overload peaks Np is to increase retardation. This point is shown in Table 2 where N_d represents the number of cycles of delay ; ΔK_o is equal to (Kmax - Kmin).

TABLE 2 - Crack growth retardation (ΔKo = 16,2 MPa $\sqrt{m}$)

	Np	1	10	35	50	1000	8000
N_d	Rp = 1,6	70×10^3	115×10^3	--	130×10^3	190×10^3	--
	Rp = 2,2	490×10^3	535×10^3	$1,1 \times 10^6$	crack arrest	--	crack arrest

Crack arrest = no propagation during 2×10^6 cycles

The two rows of Table 2 are for two different R peak ratios and we noticed two different behaviours. For high R peak ratio, crack arrest occurs after several overload peaks ; for low R peak ratio, the retardation reaches a constant value.

According to several models which assume that retardation can be explained by crack closure concept, we have studied the changes in the U ratio during experiments ($U = \frac{Kmax - Kop}{Kmax - Kmin}$). A particular attention was given to the minimum value of this ratio Umin in order to see if it can be correlated with crack growth decrease and crack arrest. Results can be seen in Table 3.

TABLE 3 - Minimum values of U ratio (Δ Ko = 16,2 MPa $\sqrt{m}$)

	Np	1	10	35	50	100	500	8000
Umin	Rp = 1,6	0,74	0,69	--	0,72	0,85	0,61	--
	Rp = 2,2	0,74	0,61	0,58	crack arrest	--	--	crack arrest

The variation of the U ratio is not similar to the crack growth rate variation ; U is still decreasing when the crack growth rate begins to increase. In case of crack arrest, the U ratio remains high and different from zero.

In connection with crack growth retardation models, which postulate that the plastic zone (monotonic or cyclic) plays a major role in this phenomenon, we have compared the affected crack length a_d^* and the cyclic overload plastic zone. This plastic zone w_s^c is equal to :

$$w_s^c = \frac{1}{4\pi}\left(\frac{K\ peak - Kmin}{\sigma_y^c}\right)^2$$

where σ_y^c is the yield strength measured on cyclic stress-strain curve. In Table 4 we notice thad a_d^* is constant and equivalent to the overload plastic zone.

TABLE 4 - Comparison between the cyclic overload plastic zone and a_d^*

Np	1	10	35	1	10	50	100	500
a^*_d mm	1,1	1,1	1	1	0,83	0,8	0,8	1,03
w^c_s mm	0,92	0,92	0,92	0,68	0,68	0,68	0,68	0,68
	R peak = 2,2; ΔKo = 16,2 MPa $\sqrt{m}$			R peak = 1,9; ΔKo = 16,2 MPa $\sqrt{m}$				

The influence of the maximum base line stress intensity factor for several overload peaks is very similar to that of a single overload peak but with the possibility to obtain crack arrest more easily with smaller Kmax. Two values of Kmax (18 MPa $\sqrt{m}$ and 30 MPa $\sqrt{m}$) were examined and the results are presented as a "delay ratio" Nd/Nc where Nc is the number of cycles needed to propagate over a distance a^*_d (distance which is affected by overload) at constant stress intensity factor range without any overload. This ratio increases significantly for Np = 500 and Kmax = 18 MPa $\sqrt{m}$ (Table 5).

TABLE 5 - Influence of Kmax and Np on the delay ratio Nd/Nc (Rpeak = 1,9)

Np	1		10		50		500	
Kmax (MPa $\sqrt{m}$)	18	30	18	30	18	30	18	30
Nd	180×10^3	76×10^3	250×10^3	99×10^3	330×10^3	119×10^3	$2,16\times10^6$	185×10^6
$\frac{Nd}{Nc}$	2,16	2,69	3,61	4,89	4,95	5,63	25,17	10,17

Taking into account the fact that the initial U value before overload Uo is influenced by Kmax value (Mille 1979) (Kmax = 18 MPa $\sqrt{m}$; Uo = 0,77) (Kmax= 30 MPa $\sqrt{m}$; Uo = 0,91), the results are presented as a relative change of minimum U value Umin/Uo . This ratio decreases with Kmax and with the number of overload peaks (Table 6).

TABLE 6 - Influence of Kmax and Np for Rpeak = 1,9

Np	1		10		50		500	
Kmax (MPa $\sqrt{m}$)	18	30	18	30	18	30	18	30
Umin	0,74	0,66	0,69	0,61	0,72	0,58	0,61	0,48
$\frac{Umin}{Uo}$	-	0,73	0,9	0,67	0,94	0,64	0,79	0,53

The maximum stress intensity factor range evidently influences the cyclic overload plastic zone w^c_s and consequently a^*_d . This behaviour is shown in Table 7.

TABLE 7 - Influence of Kmax on the distance a^*_d (Rpeak = 1,9).

Np	1		10		50		500	
Kmax (MPa $\sqrt{m}$)	18	30	18	30	18	30	18	30
a^*_d (mm)	1	2,15	0,83	2,05	0,80	2,12	1,03	2,03
w^c_s (mm)	0,68	1,89	0,68	1,89	0,68	1,89	0,68	1,89

The main point is to consider the effect of the R peak ratio on retardation when the number of overload peaks is increased. For a large number of overloads, the way to obtain crack arrest is to increase R peak. For 1000 overloads, a value of R peak greater than 1,9 is necessary (Table 8). This phenomenon can be seen in Fig. 2 where two asymptotic behaviours are observed.

TABLE 8 - Influence of R peak on the crack growth retardation

Np	1			10			50			1000		
Rpeak	1,6	1,9	2,2	1,6	1,9	2,2	1,6	1,9	2,2	1,6	1,9	2,2
N_d	70×10^3	180×10^3	490×10^3	115×10^3	250×10^3	535×10^3	130×10^3	330×10^3	arrest	190×10^3	arrest	arrest

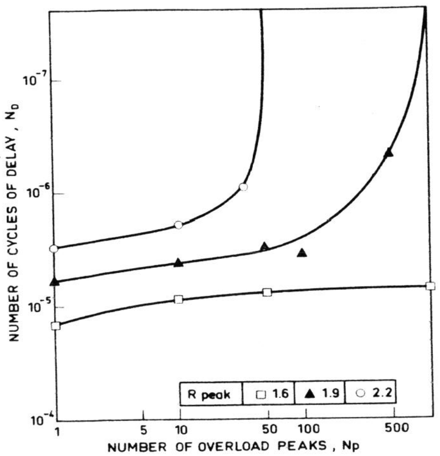
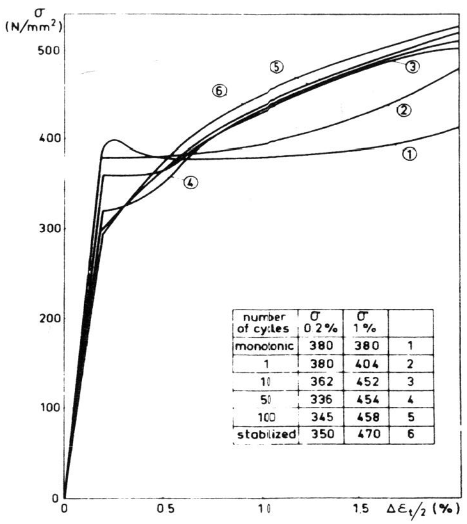


Fig. 2 : Effect of R peak ratio on the delay when the number of overload peaks is increasing.

DISCUSSION

The following assumptions are generally adopted to explain the influence of the number of overload peaks : the crack closure concept and the residual stresses.

- according to our results the crack closure concept cannot explain retardation since the evolutions of the crack growth rate and the U ratio are not similar. This situation is identical to that produced by a single overload (Robin, 1983).
- The models based on residual strains and stresses at the crack tip (the crack closure is produced by the residual strains and stresses located both in the plastic zone wake and ahead of the crack tip) are generally more reliable to explain the retardation (Robin, 1982). A modification of the residual state of stress and strain during the overload sequence could be attributed to the modification of the cyclic constitutive equation. A particular attention was given to the cyclic stress-strain curve in the period before getting stabilization of the cyclic properties. The E36 steel strain hardens in a complex manner so that the stabilized hysteresis loop is obtained after a number of cycles which depends on the strain range (Fig. 3). The yield strengthes defined conventionally at 0,2% and 1% of strain are listed in the same figure.



number of cycles	σ 0.2%	σ 1%	
monotonic	380	380	1
1	380	404	2
10	362	452	3
50	336	454	4
100	345	458	5
stabilized	350	470	6

Fig. 3 : Evolution of the stress-strain curve.

A rough idea of the actual situation can be obtained by considering the material rigid perfectly plastic with an evolutive plastic flow. A more sophisticated approach can be used as in reference (Glinka, 1984). The evolution of the overload plastic zone due to 8000 overload peaks is shown

in Fig. 4. The evolution is small and suggests that the modification of the stress and strain intensities should be more important than the modification of the plastic zone size.

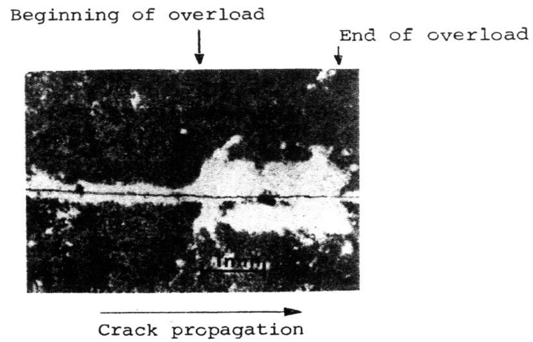


Fig. 4 : Overload plastic zone due to 8000 overload peaks. (Metallographic etch)

- The saturation at low R peak value (R peak ≦ 1,9) can be associated with the modification of the cyclic properties.
- The possibility of crack arrest can also be associated with a residual stress model. The R peak values for which we can get crack arrest, produce 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 important so that they can annihilate the tensile applied stress and stop the crack more easily (R peak= 1,9 for Np = 1000). For a single overload crack arrest is obtained at higher R peak ratio 2,8 < R peak < 3,1.

CONCLUSION

The influence of the number of overload peaks has been studied in a structural steel E36 and the parameters Kmax, Rpeak and Np have been examined. The following points are to be noticed :

- the larger the number of overloads is, the larger the delay is and the lower the minimum crack growth rate $(da/dN)_{min}$ reached during retardation is.
- the crack length after overload at which $(da/dN)_{min}$ is reached and the distance affected by retardation are both practically constant.
- two crack growth behaviours are observed after overload application depending on the Rpeak ratio for an increasing number of overloads : crack arrest possibility or saturation effect (the increase of overloads doesn't increase the delay).

The crack closure concept being not satisfactory to explain retardation, the influence of the number of overload peaks should be associated with the evolution of the cyclic properties before stabilization by using a residual stress model of crack growth retardation.

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REFERENCES

Dahl W. and Roth G. (1979). Quantitative determination of sequence effects for several steels. Deutscher Verband für Materialprüfung e.V, 5 Sitzung des Arbeitskreises Betriebfestigkeit, Stuttgart.

Glinka G. Robin C., Pluvinage G. and Chehimi C. (1984). A cumulative model of fatigue crack growth and crack closure effect. International Journal of Fatigue, 6, 37-45.

Mille P. (1979). Phénomène de fermeture à la pointe d'une fissure de fatigue dans le cas des aciers. Thèse de Docteur-Ingénieur. Université de Technologie de Compiègne, Mécanique Appliquée et Sciences des Matériaux, Compiègne, France.

Robin C., Chehimi C. and Pluvinage G. (1982) Proceedings ICSMA6, Melbourne, Australia, 2, p 919-926.

Robin C., Louah M. and Pluvinage G. (1983). Fatigue of Engineering Materials and structures, 6, 1-13.

Taîra S., and Tanaka K. (1979). Transactions ISIJ, 19, 441-418.

Vancon, M. and Bathias C. (1978). Engineering Fracture Mechanics, 10, 409-424