EFFECTS OF NOMINAL COMPRESSIVE LOAD ON VARIOUS STAGES OF CRACK GROWTH

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ABSTRACT

Based on data available for typical load spectra, effects of nominal compressive load on crack initiation, short and long crack growth are analysed. Experiments specially designed are conducted on various specimens to verify a pair of new and important ideas. The results of the present paper shows that the effects present themselves differently for different stages of crack growth and that the length of an effective wake plastic zone, l_0, is much responsible for the effects.

INTRODUCTION

Owing to the development of the studies of short crack growth, it is a usual measure to divide crack growth process into three stages, namely, crack initiation, short and long crack growth stages. Correspondently, the life of a structural member may be expressed as follows

$$N_f = N_i + N_s + N_l$$

where N_f, total life of the member.
N_i, crack initiation life of the member. Or, more definitely, the life from the first loading cycle to the cycle when the crack length reaches 0.01 mm, the minimum crack length that can usually be inspected in laboratories.
N_s, short crack growth life of the member.
N_l, long crack growth life of the member. The short and long crack are discriminated according to the rule presented in Ref. [1],

see the Appendix of the present paper.

During the long crack growth stage under constant amplitude loading, it has been proved[2,3] that only the tension part of the nominal load must be taken into account while the compression part can be neglected on account of its insignificant contributions to both the crack growth rate and the fatigue life of structural members, see Fig. 1. However, the measure described above will make the fatigue life an unsafe one in situations of crack initiation, short crack growth stage and of the retardative growth following an overload in long crack growth stage. A few authors have done some research works on the effects of the compressive load and several useful conclusions have been obtained[1-10]. Nevertheless, the problem does not seem have been completely settled and the analysis of the effects of the compressive load still is far away from being systematic and perfect, especially for the case of short crack growth. Models that can take the effects of the compressive load into consideration still remain to be reasonably established. The aim of this paper, therefore, is to provide some analysis and experiment results for the aforementioned problem and it is hoped that the additional information on the problem presented in this paper will prove to be useful in establishing models that can take the effects of the compressive load into consideration in a reasonable way.

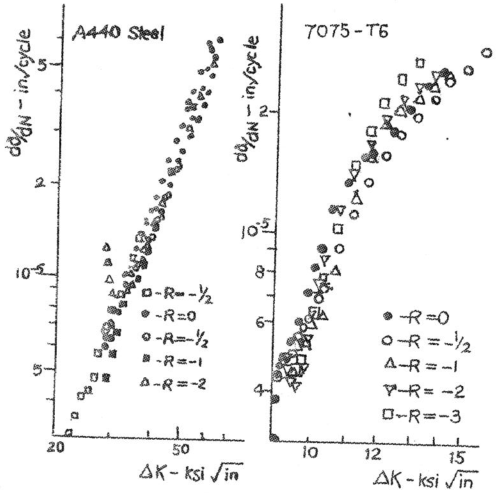


Fig. 1 The effect of negative load cycle ratios on long crack propagation rate (from Ref. [2])

EFFECTS OF NOMINAL COMPRESSIVE LOAD ON LONG CRACK GROWTH

It is generally accepted that the crack growth behavior is controlled by the length of reversal plastic zone around the crack tip. Now the following suggestion is made (and has been found) by the authors of this paper that the length l_0 of a certain wake plastic zone in the immediate neighborhood of a crack tip (see Fig. 2) may also has significant effects on crack growth behavior.

It is well-known that the wake plastic zone influences the closure of a propagating crack. And, as has been correctly pointed out by Elber, even when the nominal load is tensile, the crack can still be partly closed. However, it does not seem proper to neglect the tensile load, which is responsible in some degree for crack closure, in our consideration for crack propagation. On the other hand, in the situation of crack growth under constant amplitude loading, because the wake plastic zone of the crack is fully closed and the length of the wake plastic zone is sufficiently long, the compressive part of the nominal load produces slight effects on crack propagation and can be truncated (see Fig. 3(a)).

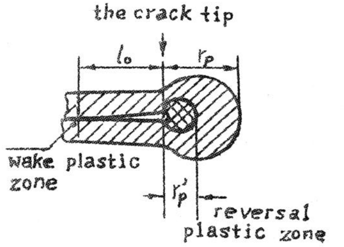


Fig. 2 The effective length of a wake plastic zone

Following a single tensile overload, especially a serious one with a high overload ratio, the crack appears remaining unclosed (see Fig. 3(b)) even when the tested specimen has been completely unloaded[7,8]. If a compressive load is applied subsequently on the specimen (a tensile-compressive overload), then the wake plastic zone is effective due to crack opening and the retardation cycles produced by the tensile overload can be diminished and finally cancelled[9] (see Fig. 4). Therefore, the overload shut-off ratio loses its constancy and will decrease as the overload cycle ratio R_1 decreases[6] (see Fig. 5). In this aspect of the matter, the sequence of overloads appears very important.

An interesting phenomenon is shown in Fig. 3(c). The multiple over-

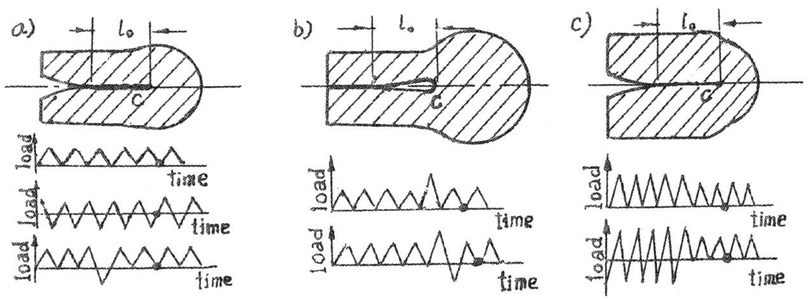
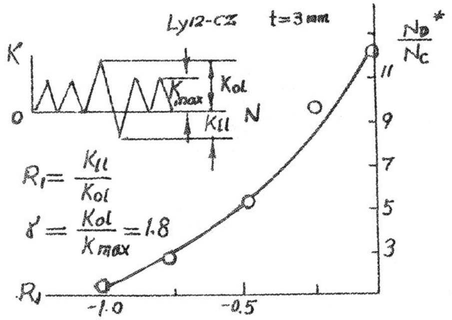


Fig. 3 The effective wake plastic zone under typical load spectra a) constant amplitude b) after a single overload c) after multiple over loads



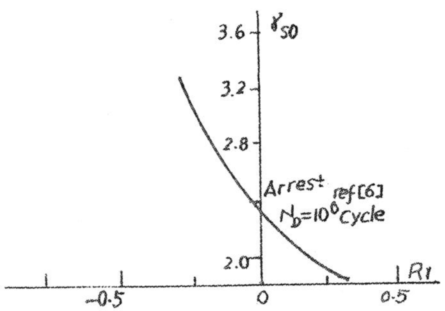


Fig. 4 N_D/N_C^* versus R_1 curves (From Ref. 9)

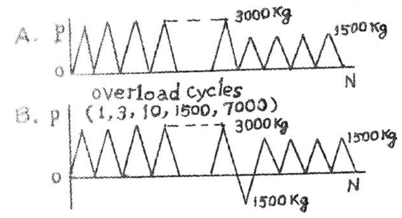
* — Shown in Fig.7

Fig. 5 The overload cut-off ratio γ_{SO} versus R_1 curves

loads can gradually make the compressive load ineffective so long as the length of the overload wake plastic zone is sufficiently long.

For the purpose of verifying the phenomenon just mentioned in the foregoing paragraph, crack growth tests under multiple overloads have been conducted on ten pieces of specimens. The material and geometry of the specimens and the measuring method are identical to those described in the Appendix of this paper. The loading spectra is shown in Fig. 6. N_D, the overload retardation cycle number, is defined in Fig. 7 and its values under various spectra are included in Table 1.

The N_D values in the table demonstrates that: (1) For both 0-tension and compression-tension overloads, due to the enlargement of the overload wake zone, the retardation cycle number increases with the increasing of overload cycles. (2) Once the length of the overload wake plastic zone reaches $l_0 \approx 2r_p$ (r_p is the length of the overload plastic zone around the crack tip), the nominal compressive load loses its effect on decreasing the retardation cycles.



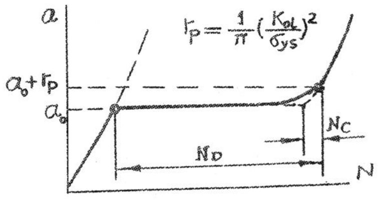


Fig.6 The spectra used in the tests

Fig.7 The definitions of N_D and N_C

Table 1. The testing result of N_D for various spectra

Overload cycles / groups	1	3	10	1500 ($\Delta a = 0.2mm$)	7000 ($\Delta a = 2r_p = 1.0mm$)
A	25,000	28,000	41,500	102,000	>260,000
B	12,000	17,000	26,000	61,000	>260,000

EFFECTS OF NOMINAL COMPRESSIVE LOAD ON SHORT CRACK GROWTH

If we regard the long crack as such a crack around its tip the steady wake plastic zone has been developed, then the short crack must be regarded as a crack with short length effective wake zone. A mechanical cut or an inherent flaw natually provides crack initiation, no crack closure occurs and they should be regarded as cracks with no wakes. It is well-known that the compressive load plays an important role in unclosed crack growth. So, it seems whether the compressive load has effects on crack propagation may be served as a criterion of judging if the crack is a short one.

To justify the above viewpoint, further crack propagation tests have been performed (see the Appendix). Three kinds of loading spectra with identical tensile but different compressive part are chosen for the tests.

It is shown in Fig.8 that the compressive load has no influence on the life of a long crack. On the other hand, for short cracks, it makes $\frac{da}{dN}$ higher than those under loads which have no compressive parts. Of course, for all the spectra, the lives in short crack growth stage are quite different (see Table 2).

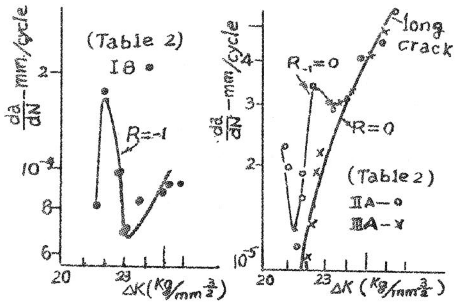
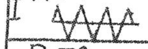


Fig.8 $\frac{da}{dN}$ versus ΔK curves for short cracks (compressive loads have been neglected)

Because no crack and wake are presented in crack initiation stage, the nominal compressive load can never be neglected during that period. For smooth specimens, the nominal compressive load effects the fatigue life through the nominal stress range while for notched specimens the effect is exerted through the local stress (or strain) range and the selfstresses produced in the first cycle. The fatigue cracking life can then be estimated by the use of local stress-strain method[10].

The N_D measured are shown in Table 2. The effects of compressive load on crack initiation, as can be seen, are rather evident.

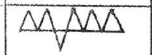
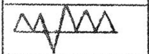
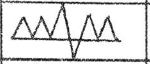
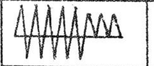
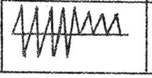
Table 2 The testing result for lives in various stages of crack growth

Spectra	Life of each stage / Groups of specimens	N_i, (Δa=0—0.01mm), Cycle		N_s, (Δa=0.01-0.12 mm), Cycle		N_l (Δa=0.12-3.0mm), Cycle	
		A	B	A	B	A	B
I R=-1 	A, ±1200 Kg B, ±1500 Kg	8,160 (1.0)*	650 (1.0)*	4,000 (1.0)*	1,350 (1,0)*	71,800 (1.0)*	50,800 (1.0)*
II R_{-1}=0  once	A. -1200; 0-1200 B. -1500; 0-1200	11,700 (1.43)*	3,000 (4.60)*	5,800 (1.45)*	——	65,500 (0.91)*	——
III R=0 	A. 0-1200 B. 0-1500	24,600 (3.01)*	5,500 (8.46)*	12,000 (3.0)*	3,900 (2.89)*	73700 (1.03)*	52,100 (1.025)*

( )* Ratio of lives: the life for Spectrum I, or II, or III/the life for Spectrum I at the same column.

SUMMARY AND CONCLUSIONS

1. In summary, the effects of neglecting the action of the nominal compressive load on the fatigue life in various stages can be qualitatively

Typical spectra	The lives of various stages	N_i	N_i	N_s	N_l
	The stages of the crack growth	Crack initiation (Smooth)	Crack initiation (notch)	Short crack	Long crack
Const.		XX[3]	XXX	→	○[1]
Single overload		○	XXX	→	○[9]
		○	○	○	○[9]
		○	XXX	XXX	XXX[9]
Multiple overload		XX	○[3]	○	○
		XX	XXX[3]	→	○

XXX — The effects as mentioned above are very serious.
XX — Serious
○ — light
— — transferable.

2. Based on Elber's crack closure concept, a new parameter— effective length of the wake plastic zone l_0 is introduced in this paper with which the different aspects of the effects of the nominal compressive load on crack growth can be reasonably explained.

3. The tests reported in the present paper show when the length of the multiple overload wake reaches $l_0 \approx 2r_p$, the compressive load following the overload has no influence on crack retardation.

4. The tests reported in the present paper again show that under the condition of constant ΔK, da/dN for short crack is higher than that for long crack, this phenomenon becomes more evident when the nominal load contains compressive component.

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It is shown in Fig.8 that the compressive load has no influence on the present paper.

APPENDIX TESTS OF GRACK CROWTH ORIGINALLY FROM A CUT

The material used in the tests was aluminum alloy Ly12-cz with yield strength $\sigma_{ys} = 35$ kg/mm² and ultimate strength $\sigma_u = 42$ kg/mm². The geometry of the tested sheets are shown in Fig. 9.

The tests were performed on a 10T fatigue testing machine with loading frequenoy of f ≈ 140 Hz. The crack lengths were measured by an automatic tracking instrument containing an eddy probe. The crack length loading cycle curve was drawn by an x-y plotter, see Fig. 9.

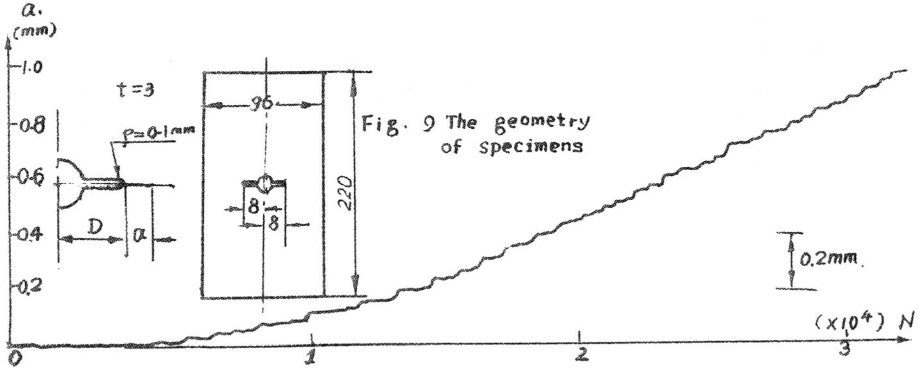

Fig. 9 Specimen configuration (a) and a-N curve (b) (reproduced from testing record)

Following Ref. [1], the depth of the notch field in uniaxially stressed plates can be approximated by

$$a_0 = 0.13\sqrt{D\rho}$$

and the stress intensity factor range can be expressed as

$$\Delta K = \Delta\sigma\sqrt{\pi a_e}$$

$$a_e = (1 + 7.69\sqrt{\frac{D}{\rho}})a \quad (0.01 < a < 0.13\sqrt{D\rho}, \text{ short crack})$$

$$a_e = D + a \qquad (a > 0.13\sqrt{D\rho}\ , \text{ long crack})$$

The corresponding results are included in Table 2 and Fig. 8.

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