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A SEMI-EMPIRICAL MODEL FOR PREDICTING OVERLOAD-AFFECTED FATIGUE CRACK GROWTH IN STEELS

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The ability of semi-empirical crack closure models to predict the effect of overloads on fatigue crack growth in low-alloy steels has been investigated. The CORPUS model developed for aircraft materials and loading spectra has been checked first by comparison between the simulated and observed results. The CORPUS predictions of crack growth under several types of simple load histories containing overloads appeared generally non-conservative which prompted the authors to formulate a new model, more suitable for steels. With the latter approach, the assumed evolution of the crack opening stress during the delayed retardation stage has been based on the experimental results reported for steels. For all the load sequences considered, the predictions of the proposed model appear to be far more accurate than those from CORPUS. Based on the analysis results, the capability of semi-empirical prediction concepts to cover experimentally observed trends reported for sequences with overloads is discussed. Finally, possibilities of improving the model performance are considered.

Key words: crack growth, variable amplitude fatigue, prediction models

Symbols

K – stress intensity factor
ΔK – stress intensity factor range

N – number of cycles

N_{BL}, N_{OL} – numbers of baseline load cycles and overload cycles, respectively

R_{OL} – overload ratio

R – stress ratio

S – stress

S_u – ultimate stress

S_y – yield stress

a – crack length

d – size of the overload-affected zone

d_{min} – size of the increasing opening stress zone

da/dN – fatigue crack growth rate

$r_{p\sigma}$ – plane stress plastic zone size

t – specimen thickness

α – constraint factor.

1. Introduction

The ability to predict quantitatively fatigue crack growth is important in damage tolerant design and residual life assessment. For many fatigue-critical structural components, service conditions generally involve variable amplitude, rather than constant amplitude loading. The phenomenon of load interaction that is associated with variable amplitude fatigue has received intensive investigation for many years. The most often studied and best documented load interaction effects are those observed for load histories containing tensile overloads. The schematic of the so called delayed retardation of crack growth which typically follows the application of a single overload among constant amplitude cycles is shown in Fig.1.

Since Elber's (1970) discovery of plasticity-induced crack closure, its contributing to load interaction effects has been widely recognized. In fact, most of them and specifically the delayed retardation phenomenon can be rationalized in terms of plasticity-induced crack closure if it is assumed that the fatigue crack growth rate da/dN, is controlled by a current level of the effective stress intensity factor range ΔK_{eff}. Thus

$$\frac{da}{dN} = f(\Delta K_{eff}) \qquad \Delta K_{eff} = K_{max} - K_{op} \quad \text{or} \quad \Delta K_{eff} = U\Delta K \tag{1.1}$$

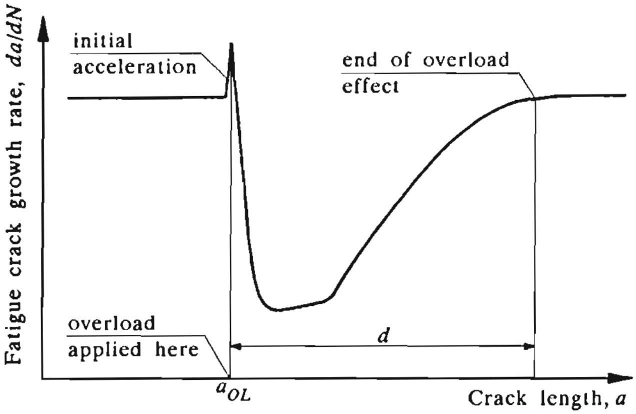

Fig. 1. Scheme of delayed retardation of crack growth after single overload

where K_{op} is the stress intensity level at which a crack is fully open and U is an emiprical function usually related to the stress ratio R. According to the plasticity-induced crack closure concepts, K_{op} in a current cycle depends on the previous loading history.

Research into the overload-affected fatigue crack growth has been mainly focussed on aircraft alloys, while the corresponding knowledge for other materials is far more meagre. Also, theoretical models put forward to predict crack growth in aircraft metals under flight-simulation loadings have not been validated for other metals and loading spectra.

The present paper aims at predicting the effect of overloads in several types of simple load histories on fatigue crack growth in low-alloy steels using semi-empirical, crack closure based concepts. For this purpose, the CORPUS model (Koning (1981)) which has been ranked as the most accurate tool among semi-empirical concepts for crack growth simulations under aircraft loading spectra (Padmadinata (1990)), is checked first by comparisons between predicted and observed crack growth in steel. Then, based on a detailed analysis of reported experimental results on post-overload transients in crack growth, a new model, more adequate for steels is proposed.

2. CORPUS model

In agreement with plasticity-induced crack closure concepts, rules for the material memory of previous loadings adopted in the CORPUS model follow directly from considering plastic deformations in the crack wake. It is assumed that fatigue crack surfaces are covered with ridges of plastically deformed material associated with crack tip plastic zones generated by previous maximum stresses, see Fig.2. A ridge created during an upward load excursion is then flattened during subsequent downward excursions. The crack opening load in a current cycle is identified as a level at which the last pair of ridges loses contact (pair k in Fig.2). Consequently

$$S_{op} = g(S_{max,k}, S_{min,k}) \tag{2.1}$$

where $S_{max,k}$ is the maximum stress associated with ridge k, $S_{min,k}$ is the lowest minimum stress between $S_{max,k}$ and the current cycle. The empirical function g is the same as for the constant amplitude loading.

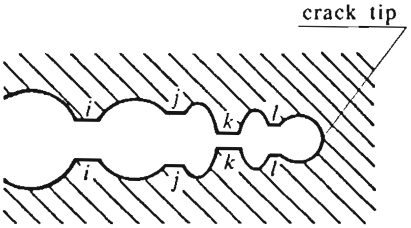

Fig. 2. Idealization of plastic wake of fatigue crack according to CORPUS

The "historical" $S_{max,k}$ and $S_{min,k}$ affect the current S_{op} value as long as the monotonic plastic zone produced in the current cycle is embedded within the dominating plastic zone generated by $S_{max,k}$. To account for the three-dimensional nature of plasticity-induced crack closure, the dominating plastic zone size is calculated depending on the ratio between the plastic zone size for plane stress conditions at the crack tip and the plate thickness.

An ideally plastic material is considered and, if interaction between overloads and overlapping plastic zones (which is part of the CORPUS model) is neglected, no other material related parameters than S_y, $U(R)$ and the ΔK_{eff} versus da/dN data from constant amplitude tests are required. The fatigue crack growth is calculated cycle-by-cycle assuming that the same ΔK_{eff} under constant amplitude loading and variable amplitude loading, respectively, will produce the same crack growth increment.

3. Predictions of fatigue crack growth in steels using CORPUS

To check the CORPUS performance for steels, the model has been used to simulate fatigue crack growth in the tests of Iwasaki et al. (1982) on 10 mm thick, central crack tension specimens in a low alloy steel ($S_y = 367\,\text{MPa}$, $S_u = 526\,\text{MPa}$). Table 1 shows the data characterizing the variable amplitude load histories from Iwasaki et al. (1982) selected for the present analysis. The terms in Table 1 are defined in Fig.3. The simple load histories include tests with a single overload, tests with a periodic repeating of single overloads, and tests with periodic blocks of overload cycles, respectively.

Table 1. Loading parameters of the variable amplitude fatigue tests used for the prediction models

Sequence	Symbol	R_{OL}	N_{OL}	N_{BL}
constant amplitude	A	1.0	0	–
single overload	B	1.5	1	–
	C	1.7	1	–
	D	2.0	1	–
periodic overloads	E	1.5	1	10
	F	1.5	1	5000
	G	1.5	1	10000
	H	1.5	1	50000
periodic blocks of overloads	I	1.5	50	10000
	J	1.5	100	10000
	K	1.5	1000	10000

The basic constant amplitude crack growth properties of the material have been reported by Iwasaki et al. (1982) in terms of da/dN versus ΔK data for a range of R ratios. We have transformed these results into the da/dN versus ΔK_{eff} data required for the CORPUS model by adopting the following empirical $U(R)$ relationship obtained by Kurihara et al. (1985) for the same steel

$$U = \begin{cases} 1/(1.5-R) & \text{for} \quad R \le 0.5 \\ 1.0 & \text{for} \quad R > 0.5 \end{cases} \tag{3.1}$$

For positive R ratios as used in the tests of Iwasaki et al. (1982), the crack growth rates were correlated reasonably well with the ΔK_{eff} parameter. The regression line equation was assumed in the form

$$\frac{da}{dN} = C\Delta K_{eff}^{m} \tag{3.2}$$

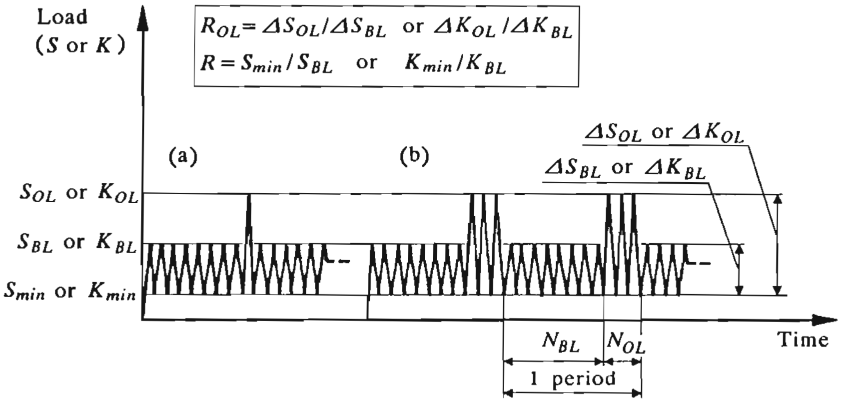

Fig. 3. Load sequences considered in analyses and definition of loading parameters ($S_{min} = 0$, $S_{BL} = 118\,\mathrm{MPa}$)

with $C = 1.49 \cdot 10^{-12}$, $m = 3.72$ and $da/dN\,[\mathrm{m/cycle}]$, $\Delta K_{eff}\,[\mathrm{MPa}\sqrt{\mathrm{m}}\,]$.

The CORPUS simulations of fatigue crack growth under the load histories listed in Table 1 are compared to the experimental results of Iwasaki et al. (1982) in Fig.4. Except for those corresponding to sequence C, the model predictions appear to be more or less non-conservative. The beneficial effect of a single overload is dramatically overestimated under sequence D and slightly underestimated in the case of sequence C, see Fig.4a. For the tests with periodic overloads, Fig.4b indicates a poor prediction accuracy for three (E, F, G) out of four load histories. In Fig.4c (tests with periodic blocks of overloads), a very good agreement between the prediction and the tests result is found for sequence J, whereas a much worse prediction quality is noted for the two other sequences. Any consistent tendency with regard to the prediction error can hardly be found in Fig.4. Poor, satisfactory and even good prediction accuracies, respectively, have been obtained for each of the three variable amplitude load histories.

4. Proposed prediction model

An excellent correlation between the measured and computed results for the constant amplitude loading (see three different curves for sequence A in Fig.4) proves the adequacy of Eq (3.2) for the considered steel. A primary reason for the unsatisfactory prediction accuracy for a single overload (Fig.4a)

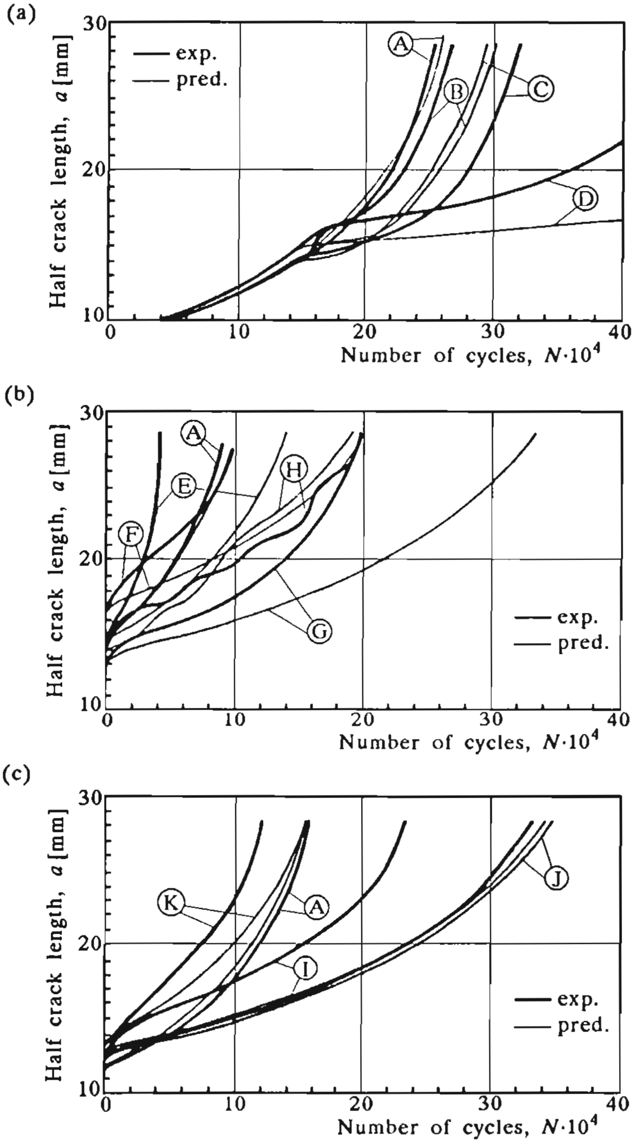

Fig. 4. Comparisons between the CORPUS predictions and test results of Iwasaki et al. (1982): (a) – single overload applied once, (b) – single periodic overload, (c) – multiple periodic overload

seems to be, therefore, the approximate description of post-overload transient S_{op} behaviour involved in the CORPUS model. The assumed in CORPUS evolution of S_{op} following an overload cycle is the block function shown as a dashed line in Fig.5. The thick full line in the same figure presents the "true" variations in S_{op} corresponding to the observed variations in crack growth rates, cf Fig.1. It is evident that the delayed retardation effect does not occur in the CORPUS model due to the assumption that the S_{op} level increases immediately on the overload application.

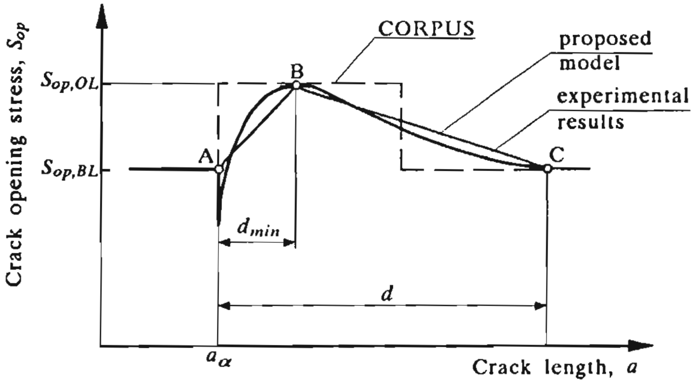

Fig. 5. Post-overload transient behavior of crack opening stress according to experiments and prediction models

To raise the prediction quality, an improved modeling of the post-overload transients in S_{op} behavior is needed. For this purpose, the triangular function ABC (the thin full line in Fig.5) is assumed as a simple approximation of the real S_{op} evolution after an overload. It is believed to be more realistic than in CORPUS because it reflects the delayed retardation phenomenon. The overload affected zone d has been related to the overload plastic zone size that would be induced under pure plane stress conditions at the crack tip $r_{p\sigma}$ by the equation

$$d = \frac{r_{p\sigma}}{\alpha^2} \tag{4.1}$$

where α is a kind of a constraint factor on local yielding and

$$r_{p\sigma} = \frac{1}{\pi}\left(\frac{K_{OL}}{S_y}\right)^2 \tag{4.2}$$

To evaluate the α factor, literature results on measured d values under sequences with a single overload are presented in Fig.6, where t denotes the plate thickness. The line plotted in Fig.6 is a hand drawn approximation of the experimental data. The results in Fig.6 correspond to a variety of loading parameters, namely $R_{OL} = 1.3 \div 3.1$, $\Delta K_{BL} = 10 \div 27\,\mathrm{MPa}\sqrt{\mathrm{m}}$ and $R = 0.05 \div 0.2$. The specimens were of compact tension, central crack tension and single edge notch types with thicknesses, $t = 3 \div 24\,\mathrm{mm}$. The steel yield stress ranged from 240 to 380 MPa.

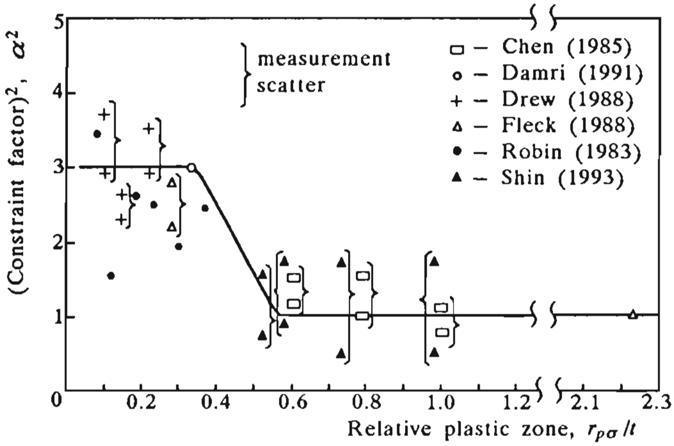

Fig. 6. Experimental results on the overload-affected zone size reported for steels *from K-controlled tests*

From Fig.6, the following values of $l\alpha$ should be adopted to estimate the delay distance d

$$
\begin{array}{ll}
\dfrac{r_{p\sigma}}{t} \leq 0.333 & \alpha^2 = 3 \\[2ex]
0.333 < \dfrac{r_{p\sigma}}{t} < 0.567 & \alpha^2 = 2 - \sinh^{-1}\Big(10\dfrac{r_{p\sigma}}{t} - 4.5\Big) \qquad (4.3) \\[2ex]
\dfrac{r_{p\sigma}}{t} \leq 0.567 & \alpha^2 = 1
\end{array}
$$

The d estimates resulting from Eqs (4.1) to (4.3) are compared with those according to the CORPUS model in Fig.7 for $S_{OL} = 177\,\mathrm{MPa}$ which, in terms of the Iwasaki et al. (1982) experiments, implies $R_{OL} = 1.5$. Fig.7 indicates that with the present model, the overload-affected zones are always larger and the transition region from plane stress to plane strain is less steep than in CORPUS.

Post-overload da/dN versus a evolutions reported in the literature from fatigue tests on steels are widely variable in shape depending on a particular combination of load, material and geometry parameters. Based on the analysis

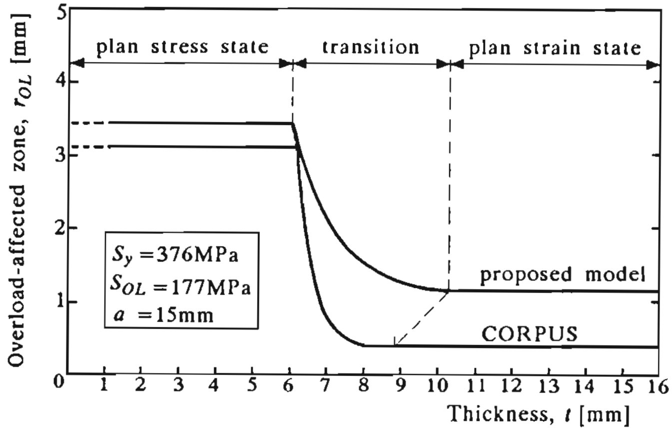

Fig. 7. Comparisons between sizes of overload-affected zone estimated according to CORPUS and proposed model, respectively

of the reported da/dN versus a data, the same maximum level in the S_{op} function (point B in Fig.5) as in the CORPUS model has been adopted, while the distance at which that maximum level is reached d_{min} has been assumed to be equal to $0.3d$.

The material memory rules accepted in the present model are illustrated in Fig.8. If the influence zones of two single overloads overlap, it has been assumed that the last overload erases the previous one from the material memory. In that case, application of the overload is always followed by the immediate S_{op} stress drop to the $S_{op,BL}$ level, as shown in Fig.8a. Similarly, for periodic blocks of overloads, applying overload block annihilates material memory of the previous block, see Fig.8b. To model crack growth acceleration observed in a number of tests during the low to high load transition, it has been assumed that the stress S_{op} gradually increases during an overload block from the baseline level towards the stationary value $S_{op,OL}$. Two situations illustrated in Fig.8b and Fig.8c may arise. If, see Fig.8b, $S_{op,OL}$ is attained within the overload block, S_{op} is kept constant at that level to the end of the block. Afterwards, S_{op} decreases towards the $S_{op,BL}$ value. If the $S_{op,BL}$ level is not reached within the overload block (Fig.8c), the S_{op} stress continues to increase during susbsequent baseline cycles to obtain the $S_{op,OL}$ value and decreases afterwards. Both within an overload block and baseline cycling the distance d_{min} is always kept the same as for the basic function shown in Fig.5. However, the slope of the decreasing S_{op} path can be different because the influence zone d of the last overload in the block be defined by Eqs (4.3), as

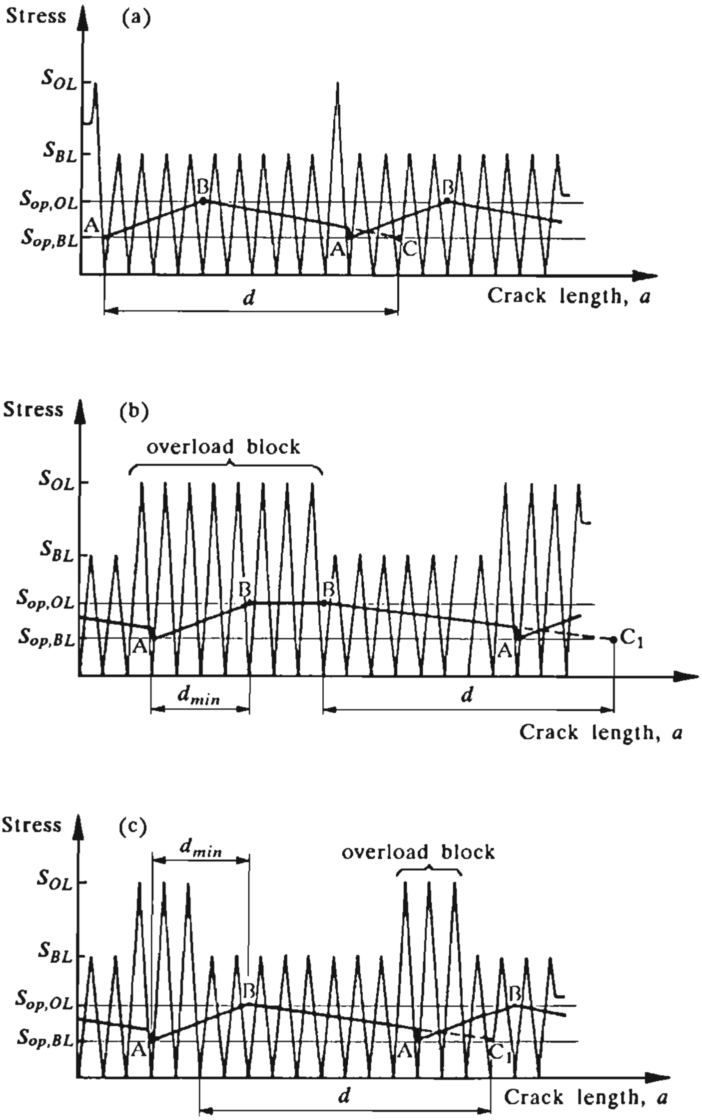

Fig. 8. Illustration of rules for crack opening stress evolution in the proposed model: (a) – overlapping influence zones for single periodic overload, (b) and *(c) – stationary value of crack opening stress reached and not reached, respectively,* within multiple overload block

in a single overload case. Consequently, the slope of line B-C_1 in Fig.8b and Fig.8c will generally differ from that of the path of the basic function (B-C in Fig.5).

5. Prediction results of the proposed model and discussion

In Fig.9, a comparison is made between predictions of the new model and test results. A very good agreement for a single overload (Fig.9a) proves adequacy of the basic S_{op} function adopted in the model.

The results in Fig.9 indicate that the model is capable of correlating quantitatively several empirical trends covered by the Iwasaki et al. (1982) tests. Similar trends were also observed in a number of other studies, as recently reviewed by Skorupa (1996). Fig.9a demonstrates that the model accurately predicts the R_{OL} parameter (overload ratio) effect on crack growth retardation after a single overload. Also the influence of periodic overload applications and the interaction between overloads is accurately estimated, as indicated in Fig.9b. For the periodic blocks of overload cycles, dependence of the load interaction effects upon the N_{OL} parameter (block size) is predicted with a somewhat declined accuracy, see Fig.9c. At the final crack length of 28 mm, the mean ratio between predicted using the proposed model and measured lives for all the variable amplitude load histories is 0.979 with the standard deviation of 0.22. The corresponding values for the CORPUS model are 1.609 and 0.759, respectively, which clearly demonstrates benefits of the new approach.

If during an overload block a faster increase in the S_{op} level had been assumed, the prediction quality for sequence J would be improved. Because direct measurement data on crack closure levels after a low-high load transition are lacking in the literature, the required information on S_{op} variations could only be deduced from observations on crack growth behavior. However, the related results reported in the literature are confusing. For example, basing on striation spacing measurements in an Al-alloy, Ling and Schijve (1992) noted acceleration in crack growth only during the first cycle of an overload block, whereas the crack growth rates during the subsequent overload cycles were the same as for the constant amplitude loading. On the contrary, in the tests of Ward-Close et al. (1989) on a Ti-alloy, the acceleration effect persisted for several thousand cycles of the overload block. A more accurate description of crack growth transients during an overload block would, therefore, require additional experiments establishing the corresponding parameters related to material and loading.

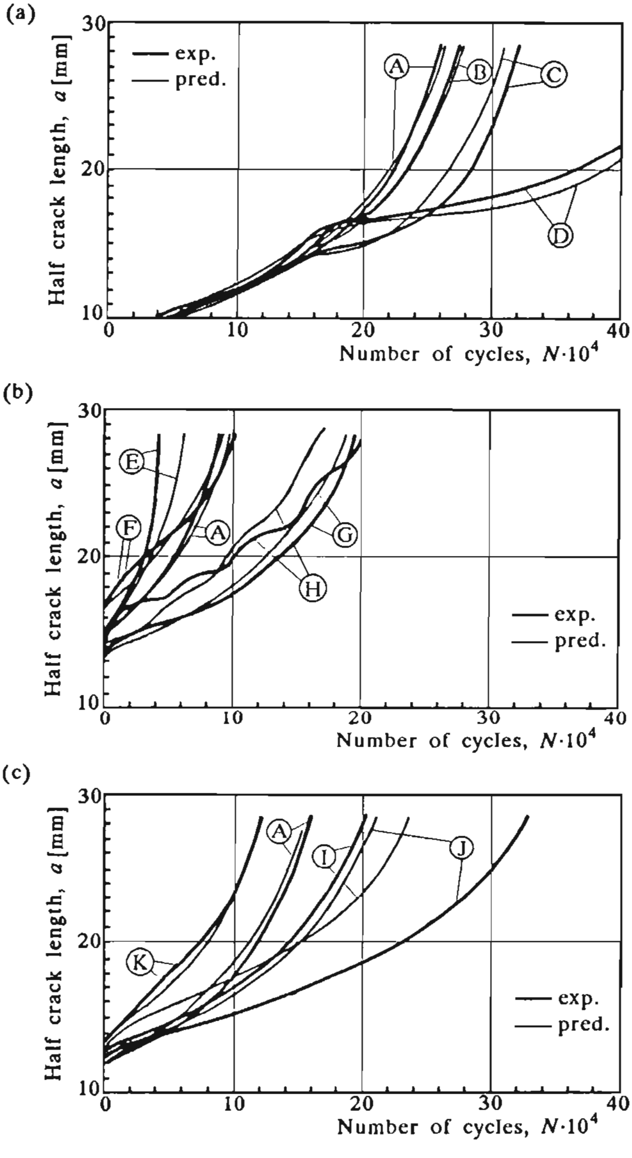

Fig. 9. Comparison between the proposed model predictions and experimental results of Iwasaki et al. (1982): (a) – single overload applied once, (b) – single periodic overload, (c) – multiple periodic overload

For sequences E, F and G, the periodic overloads are always applied within the increasing S_{op} zone (A-B, Fig.5) associated with the preceding overload. It can thus be concluded from a good correlation between predictions and experimental results (Fig.9b) that no interaction has occurred between the periodic overloads with overlapping influence zones for $R_{OL} = 1.5$. According to Ling and Schijve (1992), an interaction between blocks of overloads characterized by the same R_{OL}, as in the present study did occur in an Al-alloy. An enhanced retardation effect due to an overload that is applied within the influence zone of a previous overload seems to be in accordance with plasticity-induced crack closure arguments, particularly at larger R_{OL} values which involve significant plastic deformations. Evidently, the phenomenon of interaction between overloads in steels needs explanation through appropriate experimental research.

The effect of neither the stress ratio R nor the baseline stress intensity level ΔK_{BL}, on the retardation phenomenon are covered in the present paper. Test results for steels available in the literature show that retardation is weakened and becomes more immediate if the R ratio is elevated (cf Drew et al. (1982); Shin and Hsu (1993)). The influence of the ΔK_{BL} level remains a controversial issue. According to most observations (cf Petit et al. (1988); Ward-Close et al. (1989)), the retardation effect reaches a minimum at some intermediate ΔK_{BL} value and becomes enhanced both with increasing ΔK_{BL} towards instability and its decreasing towards threshold. An opposite trend, namely a maximum amount of retardation associated with some ΔK_{BL} level has been noted, however, for a stainless steel by Shin and Hsu (1993).

It has been suggested that at high R ratios a residual compressive stress ahead of the crack tip is a major cause of the overload-induced retardation (Shin and Hsu (1993)). With the ΔK_{BL} effect, roughness-induced crack closure and some phenomena associated with microstructural features, for example crack branching and kinking, are supposed to control the post-overload transients as the ΔK_{BL} level is decreased. It is not at all certain whether a plasticity-induced crack closure based prediction concept could adequately correlate the crack growth behavior over the range of R and ΔK_{BL} values where other than plasticity-induced crack closure mechanisms become operative.

To account in the proposed model for the effects which presently are either poorly predicted or not considered at all, the appropriate experimental data are needed. Based on these, additional empirical parameters and memory rules could be incorporated into the model in order to adjust the predictions to observed results. Typically, in fatigue tests to evaluate the influence of a given variable, other variables are kept constant. Such a strategy of experiments would not be useful for the purpose of the present model improvement since the combined effect of several loading variables on crack closure behaviour cannot be deduced by a simple superposition of the effects corresponding to any of these variables. Thus a carefully designed, extensive variable amplitude test program would be required for each new material. This would seriously detract from the attractiveness of semi-empirical approach which is mainly associated with its simplicity and low implementation costs.

An alternative and more advantageous option to improve the prediction quality seems to be a hybrid approach in which the semi-empirical model would be coupled with a more sophisticated concept, like the strip-yield model of Newman (1981). The latter could be activated only occasionally to analyse the effect of cycles considered to cause significant changes of crack closure levels. Work is presently going on to establish criteria for the strip-yield model initiation and to estimate plastic deformations in the crack wake required to start the strip-yield model analysis.

6. Conclusions

1. The CORPUS model yields generally unconservative estimates of crack growth in a structural steel under simple sequences with overloads and incorrectly predicts the related empirical trends.

2. A main reason of the CORPUS unsatisfactory prediction accuracy is an inadequate description of transient crack closure behavior following the application of a single overload.

3. A model is proposed in which the post-overload evolution of the crack opening stress is adopted based on the study of crack growth transients during the delayed retardation stage reported for a range of steels. The model accounts for the thickness effect. Simple rules for the material memory follow from the crack closure based interpretation of the observed experimental trends.

4. Except for one case, the model predictions of crack growth in steel are in a good or satisfactory agreement with the observed results for various types of sequences with overloads. The model adequately estimates the effect of several loading variables on crack growth.

5. Covering in the model all the empirical trends observed under various types of overload sequences requires an extensive test program to determine relevant material and/or load related parameters. This would seriously detract from the semi-empirical model attractiveness.

6. A hybrid approach in which the semi-empirical model is coupled with the strip-yield model seems to be an advantageous option to improve the prediction accuracy.

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Półempiryczny model do przewidywania wzrostu pęknięcia zmęczeniowego w stalach po przeciążeniach

Streszczenie

Przedmiotem zainteresowania autorów jest przewidywanie wpływu efektu przeciążeń na rozwój pęknięć zmęczeniowych w stalach niskostopowych przy użyciu modeli półempirycznych, rozważających zjawisko zamykania się pęknięcia. Najpierw sprawdzono model CORPUS opracowany dla materiałów i widm lotniczych poprzez porównanie symulacji z rezultatami doświadczalnymi. Przewidywania wzrostu pęknięcia przy wykorzystaniu modelu CORPUS dla kilku typów prostych sekwencji obciążeń zawierających przeciążenia okazały się generalnie niezachowawcze, co skłoniło autorów do sformułowania nowego modelu bardziej adekwatnego dla stali. W zaproponowanym podejściu przyjęto rozwój naprężenia otwarcia pęknięcia podczas stanu opóźnionego zwolnienia wzrostu pęknięcia oparty o wyniki badań przebiegu tego zjawiska w stalach. Dla wszystkich zastosowanych sekwencji obciążeń, przewidywania przy wykorzystaniu zaproponowanego modelu okazały się być daleko bardziej adekwatne niż przy użyciu modelu CORPUS. Opierając się na wynikach analizy, przedyskutowano przydatność modeli półempirycznych do opisu obserwowanych trendów doświadczalnych dla sekwencji z przeciążeniami. Na koniec rozważono możliwość udoskonalenia zaproponowanego modelu.

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