

Determination of the critical cyclic fracture toughness for the mode II in mixed fracture of structural steels

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ABSTRACT

The developed method of processing experimental data from tests performed according to the four-point asymmetric bending scheme made it possible to establish the coefficient of proportionality between the modes of failure I and II, which for structural steels is in the range of 2,5÷3. The established longevity before the appearance of the critical speed according to the developed models is within the limits of the natural dispersion inherent in fatigue failure, which indicates the effectiveness of the developed algorithm and the correctness of the determined indicators of resistance to failure. The problem of the appearance of an oblique crack during tests on four-point asymmetric bending has been solved. It can be assumed that about 90% of the growth of an oblique crack is caused by the contribution of the mode of failure II.

1. Introduction

In recent decades the scheme of materials testing with four-point asymmetric bending (4PAB) has become widespread. It is used to determine resistance to shear deformations. It is the most effective for elastic-brittle materials, for which failure occurs along a direct fracture in the planned location (crossing under force P , Fig. 1). Non-metallic construction, biological, and composite materials are tested according to the four-point asymmetric bending scheme [1–4].

Crack and failure under cyclic loading occur along an oblique fracture (line $x-a$, Fig. 1) [5] for structural steels under test conditions according to the 4PAB scheme. Thus, the conditions of mixed fracture for modes I + II are implemented. At the same time, quite often specialists are interested in the characteristics of cyclic fracture specifically for the mode II. For example, the "pure modes" method was developed to predict the risk of combined loading [6,7], for which a test method according to the 4PAB scheme was proposed [8]. But under such conditions only the threshold characteristics of the fracture in the mode II can be obtained. Since further failure occurs for the mixed form of the mode I+II, the critical indicators cannot be correctly determined. The mixed nature of the failure is evidenced by the change in the trajectory of the crack from straight to oblique (Fig. 1), while previously published

works do not provide a clear mathematical apparatus for the numerical analysis of this process occurrence.

Therefore, the task of actual research was the development of an algorithm for evaluating the critical characteristics of the fatigue failure kinetic diagram of the mode II during tests of structural steels according to the 4PAB scheme.

2. Materials and methods

Analysis of the previously developed algorithm for estimating durability in mixed failure is based on survivability curves, which represent the dependence of the crack growth period from the current stress. Samples for tests on rectangular cut are made of 9 HS steel (ultimate strength $\sigma_b = 803$ MPa, yield point $\sigma_y = 658$ MPa). Sample length $l = 120$ mm, thickness $b = 5$ mm, height $h = 20$ mm, a 5 mm deep U-shaped incision was made in the middle to initiate the crack.

The valid stresses for the mode I are the normal stresses $N_{gI}(\Delta\sigma)$, for modes II and III – the tangential stresses $N_{gII(III)}(\Delta\tau)$. The survivability curves are obtained by integrating the Paris equation, for which the following form can be taken for the mode I (II):

Abbreviations: δK^*_{II} , cyclic fracture toughness, (MPa \sqrt{m}); NI, indicator of appropriate mode's degree; a_c , fatigue crack length (mm); ε , relative crack length; Ng, number of cycles; FCG, fatigue crack growth; gI/II, coefficient of proportionality between fracture modes I and II.

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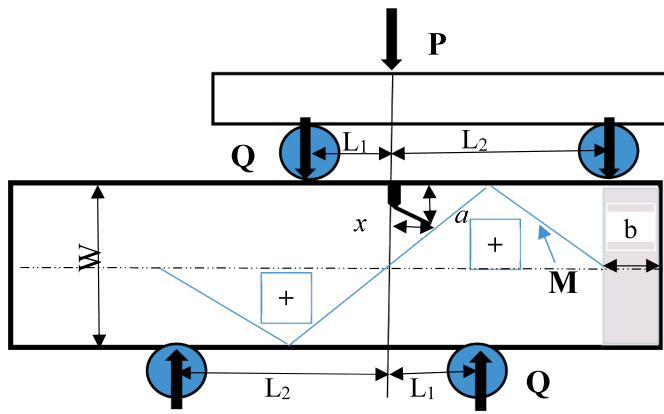


Fig. 1. Test scheme of the sample with the cross-sectional dimensions $b \times W$ on a four-point asymmetric bend [9] and the diagram of bending moments M .

$$V = 10^{-7} \left(\frac{\Delta K_{I(II)}}{\Delta K_{I(II)}^*} \right)^{n_{I(II)}}, \quad (1)$$

where V – fatigue crack growth (FCG) in m/cycle; $\Delta K_{I(II)}$ – range (twice amplitude) of the active SIF; $\Delta K_{I(II)}^*$ – range of the SIF which equals $V = 10^{-7}$ m/cycle fatigue failure diagrams; I (II) – mode of fracture; $n_{I(II)}$ – degree indicator for the corresponding mode.

The proposed algorithm for determining the survivability period assumes knowledge of the parameters of the cyclic fracture's kinetic diagram, which are obtained for the pure conditions of the corresponding mode. In research papers such conditions for the mode I were modelled for 3-point bending (3 PB) [5].

Therefore, a calculation method for determining the parameters of the mode II of cyclic failure based on the results of tests with four-point asymmetric bending (4PAB) has been developed.

It is based on a reliable assessment of the parameters – cyclic viscosity of stress intensity ($\Delta K_{I(II)}^*$) and the degree of the corresponding mode (n_i). The number of survival cycles (growth kinetics) of the sample in mixed mode $N_{g(I+II)}$ and parameters $\Delta K_{I(II)}^*$, $\Delta K_{I(II)}^*$, $a_{c(I+II)}$ are known from the tests [8]. They also correspond to mixed fracture, but obtained according to equations (6–7) in the research paper [8], as in the case of pure modes. Taking into account the dependence arising from the rule of combining safety indexes, we can write [7]:

$$N_{g(I+II)} = \left(N_{gI}^{-1} + N_{gII}^{-1} \right)^{-1}, \quad (2)$$

where $N_{gI(II)}$ – survivability in the conditions of the pure mode I or mode II.

If the values $\Delta K_{I(II)}^*$ and n_i are known, survivability N_{gI} for $a_0 = 5$ mm can be obtained. Meanwhile the same final crack size is assumed $a_{cI} = a_{c(I+II)} = a_{cII}$, which performs the critical role. Then for pure mode II we get:

$$N_{gII} = \frac{N_{g(I+II)}}{1 - \frac{N_{g(I+II)}}{N_{gI}}}. \quad (3)$$

Knowing this period of survivability, the range of the SIF at the crack growth rate of 10^{-7} m/cycle for the mode II is found [8]:

$$\Delta K_{II}^* = \frac{3.3 \cdot \Delta \tau}{\sqrt{W}} \left(\frac{5 \cdot 10^{-6} \cdot N_{gII}}{\frac{1}{(a_0 - 0.0005)^2} - \frac{1}{(a_c - 0.0005)^2}} \right)^{\frac{1}{3}}. \quad (4)$$

3. Results and discussion

When using the algorithm specified in Section 2, average values for pure mode II $\Delta K_{II}^* = 21$ MPa \sqrt{m} were obtained.

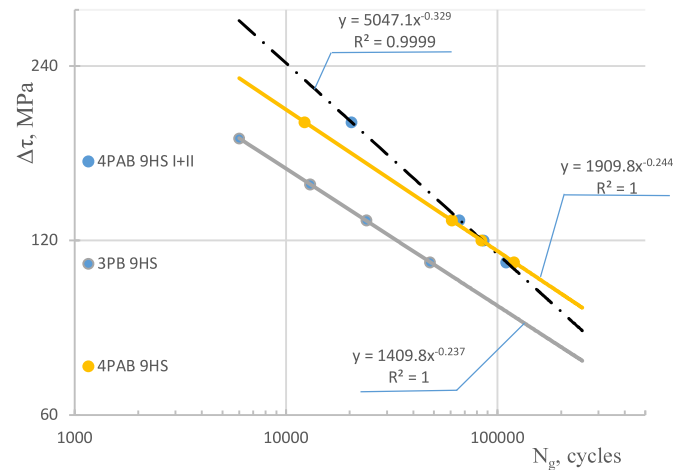


Fig. 2. Model survivability curve and their equations for mode I (straight cracks, solid line) and for modes I+II (oblique cracks, dotted line).

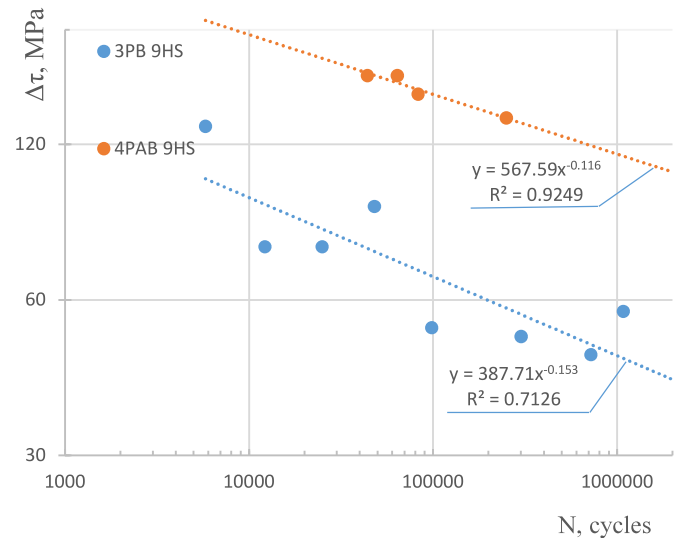


Fig. 3. Results of experimental fatigue tests before fracture (points) of 9HS steel samples by three-point and four-point bending (direct fracture, 4PAB), and survivability curves' equations.

That is 2,6...2,9 times less than $\Delta K_{I(II)}^*$ value for pure mode I. I.e. ratio of $\Delta K_{IC} / \Delta K_{IIc}$ indicators is lower than ration $g_{I/II} = \Delta K_{I(II)}^* / \Delta K_{II}^*$. Thus, it can be recommended to a priori estimate the ratio value $g_{I/II}$ for structural steels $g_{I/II} = 2,5 \dots 3$.

The found indicators together with the previously determined indicators $\Delta K_{I(II)}^* = 61$ MPa \sqrt{m} , $\Delta K_{II}^* = 66$ MPa \sqrt{m} , $n_I = 4$, $n_{II} = 3$, $a_0 = 1$ mm (unnotched samples) and $a_0 = 5$ mm (notched samples) served as initial data for determining model curves of fatigue crack growth. The algorithm for this was as follows. For the current length of the crack a_{ci} (or ε_{ci}), according to equations (6)–(7) defined in the research paper [8], the current separate periods of survival of $N_{g(I+II)i}$ are determined. After that, according to (2), the current survival $N_{g(I+II)i}$ is found. The full period of survivability was taken as the final size of the crack, when the fatigue crack growth rate reached $v = 10^{-6}$ m/cycle.

Equations for determining survivability are valid when stresses are constant [9]. Based on equation (6) in [8], it can be concluded that the normal stresses $\Delta \sigma$ depend on the length of the crack. To overcome this contradiction, it was considered that $\Delta \sigma = \text{const}$ on the segment $\Delta a_{ci} = a_{ci} - a_{c(i-1)} = 1$ mm. Therefore, the survival period on this segment ΔN_{gIIi} was determined. And then the current survival N_{gIIi} was found as the sum

of the periods ΔN_{gII} .

Despite the differences in the forms of the model (Fig. 2) and experimental (Fig. 3) crack growth graphs, the longevity obtained for them until the appearance of the critical speed are within the limits of the natural dispersion inherent in fatigue failure, which are given in [8]. This testifies to the effectiveness of the developed algorithm and the correctness of the determined indicators of resistance to fracture.

With mixed modes, the slope of the survivability curves changes due to the fact that survivability $N_{g(I+II)}$ is lower than survivability in pure modes: $N_{g(I+II)} < N_{gI}$, $N_{g(I+II)} < N_{gII}$. In these researches the average is $N_{g(I+II)} = 0,9 N_{gII}$. That is, it can be assumed that about 90% of the growth of an oblique crack is caused by the contribution of the mode II. Therefore, the slope of the survivability curve in the mode II coincides with the slope in the mixed mode.

4. Conclusions

Despite the impossibility of obtaining a pure mode II fracture when testing selected steels under the conditions of the 4PAB-scheme, the obtained values of ΔK^*_{II} in mixed fracture from an oblique crack can serve as initial data for determining "pure" ΔK^*_{II} , bypassing the algorithm developed for this purpose.

The obtained results of the original research indicate that during testing structural steels under four-point asymmetric bending, on average, 90% of the contribution to the stable stage of crack development is given by the mode II, and immediately after the failure of the sample, mode I starts to dominate.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

Data availability

Data will be made available on request.

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