Fatigue crack development experimental simulation in a railway structures steel under working load

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Abstract. The fatigue crack development regularities under working load simulation have been studied. The fatigue crack development pre-threshold region has been investigated. The level decrease method of irregular working load with similarity preservation has been applied. This is achieved with the test sample suppleness increase by a crack extension in it. Experimental dependences of the crack development rate on the number of working load blocks at its level decrease have been obtained.

1. Introduction

A significant number of works have been devoted to the study of fatigue cracks development regularities under working load [1,2]. The damage accumulation processes, especially at low pre-threshold load levels when the crack passes the local formation stages with the crack mechanisms change, are determined by many factors. The main ones are the stress and strain cyclic hysteresis processes in the crack apex, their interaction with residual stresses. At the same time, with a decrease in the fatigue crack development rate the environment impact on the crack process increases [3,4,5]. Given this, it is important to accumulate relevant experimental data for further theoretical generalizations. Of particular interest to the railway structure developers are the fatigue crack development regularities at low-level working stresses, taking into account the load processes irregularity.

2. Regularity determination of a crack development rate change with a decrease in the working load level without sacrificing its similarity

To study the load irregularity influence on the fatigue crack development, it is important to maintain the basic relations between the initial process cycles and their action sequence while reducing the load level. That means, to preserve the initial process similarity but at the same time to ensure a gradual decrease in its level. The results of initial experimental studies are presented in [6] in order to achieve this. Here are the studies results conducted in a more extended format. The work was carried out in the following sequence. A working load cycles block was applied to a standard type 3 sample (out-of-centre tension) [7] with an initial fatigue crack in it. At the same time, the signal from a double-console extensometer was recorded. The extensometer was installed according to the accepted scheme to measure the displacement on the sample end surface with the help of overhead knife-edge support [7]. Thus, the crack face displacement process (opening) was recorded when controlling the load channel. Then, a transfer to the obtained record simulation of test sample opening process (suppleness)
is made. At the first moment, when the crack has not yet shifted, such a suppleness process simulation program gives a completely identical load process to the original one when the opening was recorded. Further, as the crack extends — the stiffness of the sample decreases and its suppleness increases respectively. And in order to perfect the previously recorded opening process with the extensometer (namely, the test bench performance monitoring is based on it), it is necessary to apply less and less force as the crack extends. That is, as the crack extends — the load will gradually decrease, as shown by further analysis while maintaining similarity with the original working process. The calculation analysis of a stress intensity factor change (SIF) is carried out preliminary. This was done for a sample size of 125x120x10 mm and a fixed length of fatigue crack, at which the experiment was carried out in the future. The calculation results are shown in figure 1.

![Figure 1](image)

**Figure 1.** SIF change simulation at the load change (14.8-13.5 kN) and 10 mm crack length for the C(T) sample in the size of 125x120x10 mm. 1 - constant load, 2 - load varies from 14.8 to 13.5 kN, 3 - combined action of constant and variable load.

It follows from the calculation analysis that by controlling two opposite dependencies, in particular, the SIF growth with increasing crack length dependence 1 in figure 1 and a decrease in the same parameter from a decrease in the load level it will fall due to an increase in the sample compliance, dependence 2 in figure 1 different values of the SIF level decrease gradient can be obtained dependence 3 in figure 1. This allows the calculation to plan the desired experimental conditions. To these factors, the choice of sample size, initial crack length, and the extensometer installing method should be added.

3. Simulation of the working block load
To determine the working block load, the working stress extreme value distribution on the frame of the type 327 trolley of the refrigerator car was used [8]. Data obtained using a resistive strain gage and type KLA-2 classifier. Based on the obtained distribution of stress repeatability in the trolley frame, a sequence of extreme values of the cyclic load is formed using a random number sensor. It involves 11 stress levels from 7.2 to 45.6 MPa. Figure 1 (a) shows a block of the load cyclic sequence obtained according to the working distribution of their repeatability. This block was used in the digitalised form as an initial, predetermined process for simulating the working process of loading samples on a SHIMADZU electro-hydraulic stand (controller 4830) with a maximum force of 50 kN. figure 2 (a) shows a record of the simulated loading block.

4. Sample type selection
Sample type C(T) is selected – compact sample for eccentric tension [7] of standard size 125x120x10
mm. Samples were cut out from the truck bolster [9]. To track the crack developing during cyclic loading, the sample surface was polished and marker risks were applied, allowing the crack length to be fixed without stopping the tests. Analysis of the chemical composition of the steel samples showed the following results: C 0.2104%; Mn 1.085%; Si 0.292%; P<0.0030%; S 0.020%; Cr 0.108%; Ni 0.130%; Cu 0.215%; V<0.0030%; Fe 97.91%.

5. Test procedure
The initial crack velocity, under load control (the process in Fig. 2a, soft loading) was $V = 5.495 \cdot 10^{-7}$ m/block. Herewith, a signal was recorded from an extensometer figure 2 (b), which was used for opening control (loading). The initial crack length was $L_0 = 36.1$ mm from the load application line. From this crack size, its further growth $\Delta L$ (mm) was monitored using a digital microscope. With the crack extension increased, the load decreased. This decrease was determined by the $\Delta P$ (kN) value, is measured from the initial value $P_{max} = 14.742$ kN. It is the maximum value in the first block after the transition to loading.

![Figure 2. The sample experimental working load block: (a) - under load channel monitoring, (b) - the recorded extensometer signal](image)

The processing speed is selected, with an average value of about three cycles per second. This is determined by the accuracy of testing the initial loading process on the sample.

![Figure 3. The loading block registration graphs: load (kN) – time (sec) – (top graph); load (kN) - crack faces displacement (mm) at the points of the extensometer installation (bottom graph).](image)
During the tests, the dynamometer readings and the corresponding displacements of the extensometer installation points were constantly recorded. The sample rate was 5000 points per minute on each recording channel. At the same time, the displacement of the point determining the maximum load of each block was monitored point 1 in the graphs, figure 3. So the load reduction value $\Delta P$ at the crack extension to the value $\Delta L$ was determined. Figure 4 (a) shows 1 – the regularity of the maximum load changes point 1 in figure 2 in the block to $\Delta P$ value and a corresponding increase in the crack length to $\Delta L$ – 2 value from the loading block N number. Figure 4 (b) shows the distribution of extreme values of loading processes: 1 – the first block immediately after the control mode changing and 2 – a similar distribution of the changed loading process from an increase in the crack.

Figure 4. (a) - the maximum load reduction (point 1 in figure 2) in the block by $\Delta P$ with a corresponding increase in the crack length $\Delta L$- (2) from the loading block N number; (b) - the extreme value distribution of loading processes: 1- at the beginning of the control mode changing and 2 - the distribution displacement with the crack development.

Figure 5 (a) shows the velocity change $V$ (m/block) of the crack development, both from the loading block N number and from the decrease in the maximum load in each block figure 5 (b).

Figure 5. (a) - the dependence of the crack extension rate on the number of loading blocks N; (b) - from a decrease in the level of loading $\Delta P$; (1 - experiment, 2 - regressional dependences with extrapolation. To the value $V = 0$.

Regressional dependences (2) were determined from the experimental points and their extrapolation to the zero velocity was carried out. Figure 5 (b) shows that to stop the crack, that is, at $V = 0$, the maximum load in the block should be reduced by $\Delta P = 4$ kN, with a proportional decrease in its entire level. Taking into account the nature of such an unstable crack extension process, the values obtained by extrapolation should be considered as an approximation to the real threshold.

The variation analysis of the loading process with the crack development testified that the ratios, both for the maximum and minimum values of the cycles, remain proportionally dependent, and the amplitude in this case, accordingly, decreases.
6. Conclusions
The method has been developed to determine the law of fatigue crack development under reducing the level of working load. The controlling factor to reduce the level of working load is the natural increase in the sample suppleness under the crack extension.

The method allows simulating the required decrease gradient of the stress intensity factor. At the same time, an irregular similarity of the initial working load process is maintained.

The experimental approval of the method was carried out. Herewith, a record of working load in railway transport was used. The tests were carried out on samples of low alloy steel type 20L.

The loading process under crack extension, with a corresponding decrease in its level, according to the ratio of the maximum and minimum values of the corresponding cycles, remains constant and depends on the decrease level. That means, the process remains similar, with a similarity coefficient corresponding to each reduction level.

According to the dependences \( V(N) \) and \( V(\Delta P) \) obtained in the experiment, the value of the load reduction \( \Delta P \) was extrapolated to achieve zero value of the fatigue crack velocity.

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