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ACCEPTABLE FATIGUE CRACK SIZE - APPLICATION

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1. Introduction

This article is based directly on the introductory article which is focused on the theoretical background. The application part discusses particular details of steel structures and bridges and selecting the steel structures and bridges that have been investigated into. Because input data in theoretical relations suffer from uncertainties and a certain reliability is required throughout the designed service life, probabilistic methods have been used. Input data gained from experiments have been used for confronting specific methods. A particular attention has been paid to the selection of inspection intervals with the aim to monitor the growth of fatigue cracks.

2. Input data in probabilistic solutions with the focus on flanges

Mainly tension flanges have been chosen for applications of the theoretical solution suggested in the studies. Depending on the position of the initiation crack, it is possible to monitor the crack propagating from the edge or surface (Fig. 1). Regarding the frequency, weight and concentration of stresses, those locations rank among those with the major hazard of fatigue cracks appearing in the steel structures and bridges.

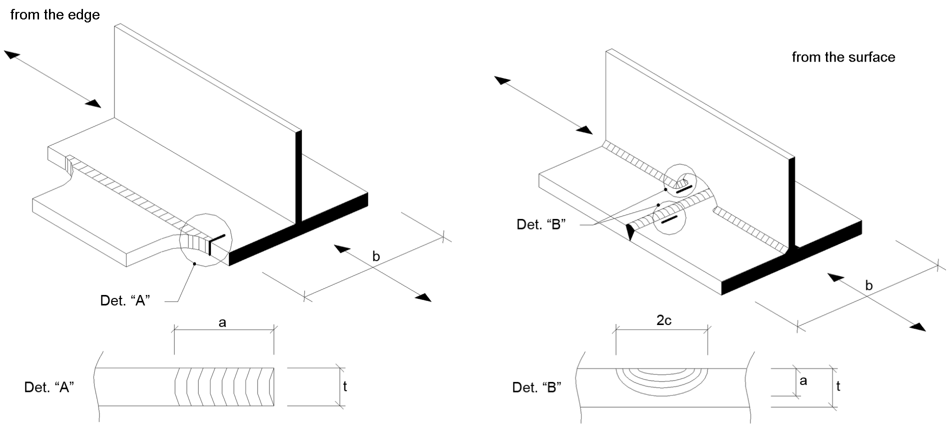

Fig. 1: Characteristic propagation of cracks: (a) from the edge, (b) from the surface

2.1. Propagation of cracks from the edge and surface

A flange without stress concentration is used for confronting the both cases depending on the location of the crack initiation. The events are different in calibration functions $F_{(a)}$, which are in many publications of their authors Newman and Raju, and cross section degradations that appear during the crack propagation.

The surface of the crack that deteriorates the flange with the t thickness is assumed to be $A_{tc} = a \,.\, t$. If the designed stress in the flange $\sigma_{\max}$ is increased by the deterioration of the original cross-section A_f, then:

$$\sigma_{\max} \cdot \frac{A_f}{A_f - A_{tc}} \leq f_y \tag{1}$$

where f_y is the yield stress. The acceptable crack size a_{ac} is possible to define from (1) (see [1]) . It is rather difficult to describe the surface propagation analytically, because a semi-elliptic crack changes its shape during the crack propagation. The derived formula:

$$\frac{1}{2}\pi .a\left(\frac{0{,}3027}{t}.a^2 + 1{,}0202.a + 0{,}00699.t\right) - b.t\left(1 - \frac{\sigma_{\max}}{f_y}\right) = 0 \tag{2}$$

was published in [5]. It is impossible to describe the crack size explicitly. Therefore, a numerical iteration is used to calculate the acceptable crack a_{ac} .

Based on the parametric probability study [5], the sensitivity of the crack propagation has been confronted for the same input conditions in the both methods. The most important result of the confronting study is that the deterioration of the same flange for the crack propagating from the edge grows approximately four times faster than the crack propagating from the surface. The propagation rate does not depend on dimensions of all flanges where the parameters were monitored.

2.2 Range stress intensity factor

Input values of the range in the stress rate coefficient ΔK are typically random. If the material constant m is not taken into account (the investigation into this constant is conducted within the metallurgical engine), the input quantities include the constant stress

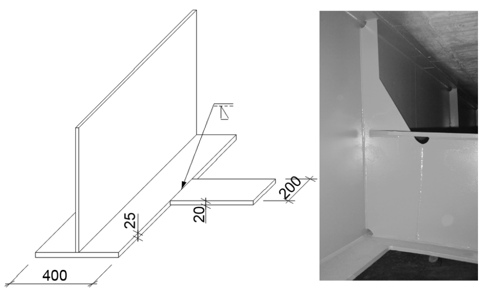

Fig. 2: Detail under measurement

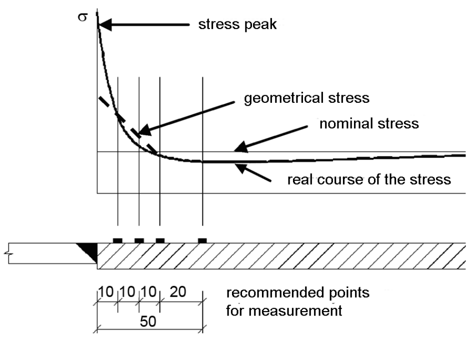

Fig. 3: Installation of sensors and courses of stress

range $\Delta\sigma$ in the point of creation and the propagation of the fatigue crack. The constant quantity is derived using Palmgrem – Miner hypothesis from a spectrum of effects of variable loads as an equivalent stress range. If the nominal stress in the place of the crack dislocated by non-linear course of the stress, then it is necessary to investigate into the stress range for various stress concentrations. The stress range is influenced then by the real course of the stress. This, however, does not mean that the initiation crack is located just in the hot spot stress. All those inputs are loaded with certain inaccuracies resulting from the exact calculation and random occurrence in reality. In order to create a realistic opinion on the data and processes that are investigated separately, measurements have been carried out in a new highway bridge (spectra of effects from traffic loads have been investigated into). The load carrying system consists in the continuous composite bridge with four steel beams. Detail on the lower flange inductive sharp stress concentration is on Fig.2.

2.3 Experimental measurements in the bridge

The gauges were located in line with recommendations [3] (see Fig. 3). The measurements were carried out in five time intervals during one working day. A Rain-flow counting method was used to analyze the strain gauge data. The gauge data need to be calculated until the stress peak. It is recommended to use two or three gauges [3] in distances shown in Fig.3. The linear extrapolation from two gauges gives a shape geometrical stress. Three gauges are either square or cubical extrapolation for the real course of the stress. Fig. 4 shows measurement records for one out of five series. There are the extrapolations both for compression and tension stresses. Because shapes of the measurement records are rather random, it was not possible to extrapolate the real course of the stress specifically for each case. To provide a kind of concept, the weighed average was calculated. The resulting courses are shown in Fig. 4.

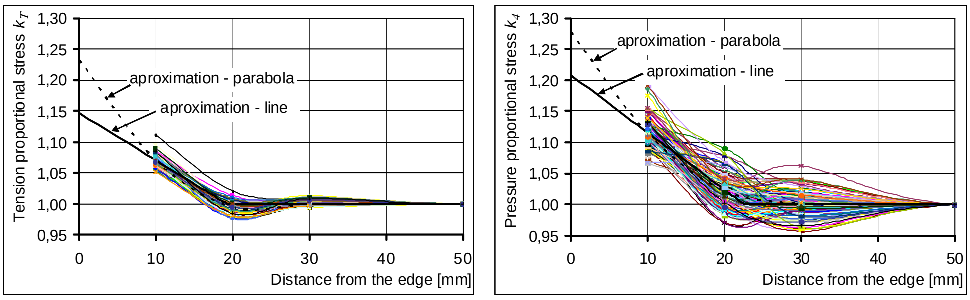

Fig. 4: Courses of negative stress

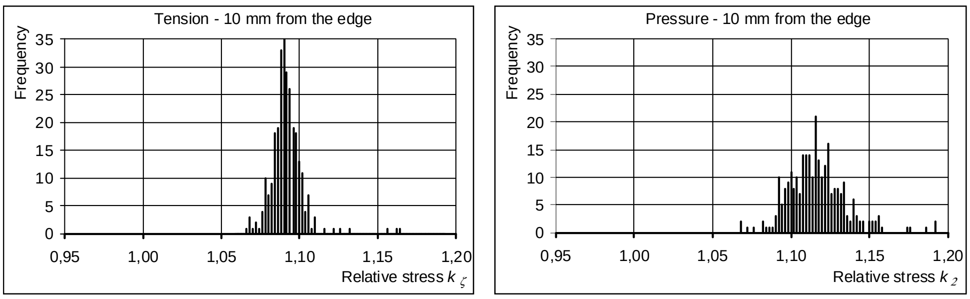

Fig. 5: Histograms of relative stress k_σ

For the sake of clarity, the stresses are related as follows $k_\sigma = \dfrac{\sigma}{\sigma_{ref}}$, where σ is the stress in the measuring point and σ_{ref} is the stress from control gauges that pick up the nominal stress. The histograms for the records near the stress peak (Fig. 5) have the normal distribution. They are different, and the distribution of compression shows a considerably higher variance. The vehicle selection of monitoring traffic which influences the fatigue crack difficulties. Heavy vehicles should be mentioned. In one series of the measurements, 2284 vehicles crossed the bridge, 282 vehicles were selected.

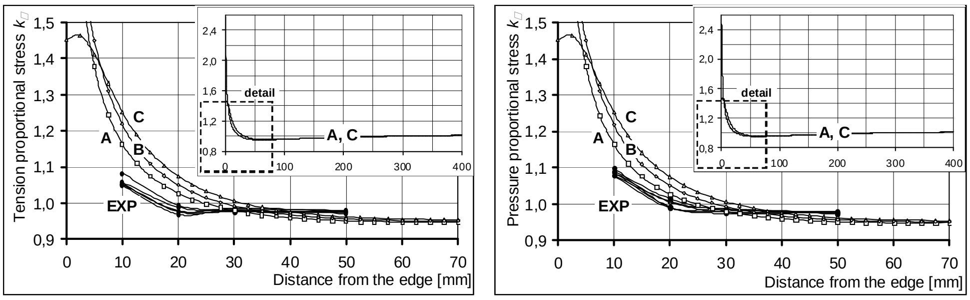

Fig. 6: Comparison of measured stress (selection) and FEM stress

2.4 Confrontation of calculation simplifications with experiment

The confronting of calculation simplifications and verification in real conditions has proved to be very useful. FEM was used to calculate the stress concentration in the detail. The relative course of the stress concentration is shown on Fig. 6. The course of the relative stress is same for both the compression and tension and depends only on the geometry of the detail. Fig. 6 shows three lines of the stress course. A is the course of the stress in the flange in the place where the transverse weldment is connected, while B and C are the courses of the stress in the flange in the distance of 5 and 10 mm, respectively, from the geometric joint of the two weldments. The stresses obtained during the measurements are transformed into the graphic description for six most significant heavy trucks (identified as an experimental origin EXP). The measurement results indicate in both cases that the real stress concentration is lower than that obtained by rather simple numerical calculations.

No general conclusions can be drawn from the only one measurement. This, however, proves that it is rather difficult to determine exactly the range of stresses contributing to the fatigue crack propagation.

3. Comparison example

The measurements and assessment can be used as a basis for the comparison during the inspections where the reliability should be proved. It should be pointed out that it was impossible to validate all inputs in practice within the relatively short measuring intervals.

Realistic are the geometric shape (and also the cross-sections), the yield strength of the material f_y with the mean value 280 MPa, the nominal design stress of extreme responses $\sigma_{\max}$ with the mean value 200 MPa, the material constant m=3 a C=2,2.10^{-13} (the mean values) and the constant stress range $\Delta\sigma$ resulting from the measured spectrum of load responses for the standard traffic. It is an equivalent to the effects of the heavy vehicles

(Lorries) $\Delta\sigma = \Delta\sigma_E \cong 30\text{MPa}$ [3]. Inaccurate inputs include the expected length of the measurable crack a_d=10 mm, the number of load cycles of the heavy vehicles per year N=1.10^6 and, in particular, the size and exact location of the initiation crack a_0. The selected mean value a_0 = 0.2 mm with the log-normal distribution represents a considerable asymmetry of the histogram where the variance is rather higher for a_0>0,2 mm [2]. Other input quantities have the normal division. The required reliability is expressed in the technical practice as a reliability index β=2 that corresponds to the failure rate of cca. P_f=0,0228.

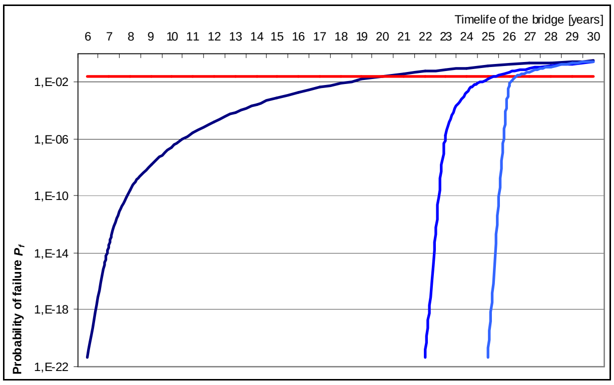

Fig. 7: Dependence of the failure probability P_f on operation years of the bridge and determination of inspection intervals for the designed failure probability P_d=2,277.10^{-2}.

The influence of short cracks in the spectrum a_0 is rather small in the context of other uncertainties [2]. What is more important is the estimated mean value and, in particular, the maximum size that is accepted during the fabrication and remains without any requirements.

In the parametric study based on Monte Carlo, the mean value a_0 was monitored from 0.2 to 0,5 mm. The maximum ranged from 2.0 to 3,0 mm. This was included into the calculation by bounding the log-normal distribution. The first inspection interval for those cases was chosen for 18 and 24 years. The shortest interval was chosen for the mean a_0=0.2 mm and $a_{0,\max}$=3.0 mm. The longest interval was chosen for the mean a_0=0.2 mm and $a_{0,\max}$=2,0 mm. The future inspection intervals were chosen based on the conditional probability for the measurable crack size a_d=10.0 without any cracks revealed. The intervals ranged from 6 to 7 years and repeated periodically, while the periods between the intervals shortened slightly.

The comparison of the results with those obtained by DDFPM for the first inspection times has proved a rather good agreement. Differences are evident in other inspections when the intervals are considerably shorter if the cracks are not found out. This is evidently for the first inspection after 20 years. Fig. 7 shows the results of this method. The difference is evident for the first interval (5 years) and the second interval that is shortened to 2 years. The other intervals were 1.50 and 1.0 year. The intervals for further inspections converged rapidly to zero.

In DDFPM it is possible to use better the conditional probability for the determination of future inspection times. It is possible to determine the time at which the expected probable size of the initiation crack was not determined correctly for a specific case (the crack size is small or there is not any crack).

4. Conclusion

The acceptable fatigue crack might be properly of the size, in cross-sections and elements of steel structures and steel bridges designed for the combined extreme loads, as a result of gradual degradation when the required reliability is reached at the end of the designed service life of the structure.

The probabilistic methods should be used for the investigation into the propagation of the fatigue crack until the acceptable size is reached because the input variables include uncertainties and reliability should be taken into account. The most important inputs are the initiation crack size and the acceptable crack size.

The new standard method is the damage tolerance method. Damage is caused there by an initial defect that has not been improvement by requirement procedures. The expected crack size or non-existence should be revealed during a special mode of inspections. Those inspections are considerably more important than standard inspections. This relates both to individual time and quality of inspections.

Acknowledgements

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Summary

This article continues discussing the acceptable fatigue crack size in steel structures and bridges. It is based on the theoretical part and deals with applications. A particular attention is paid to degradation of an element in an ultimate limit state. The article should explain the importance of the acceptable fatigue cracks in design guidelines mentioned in standards.