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FATIGUE DAMAGE PREDICTION OF HSS BRIDGE

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Abstract: *In the construction of steel structures and especially bridges, the use of high-strength steel (HSS) has been increasing in recent decades. The use of steel with a higher yield strength allows the design of slimmer as well as more aesthetic constructions. Design often leads to cost and material savings. In cases where the ultimate limit state of the structure is not a decisive factor of the design (but on the contrary the serviceability limit state, dynamic behavior of the structure, stability or fatigue of the material), the advantage of HSS becomes questionable. In such cases, the resulting resistance of the HSS structure is affected mainly by fatigue resistance. The article is focused on the initial study of fatigue damage prediction of HSS structures using linear fracture mechanics and probabilistic approach.*

Keywords: Fatigue, Steel, HSS, Bridge, Failure.

1. Introduction

In the construction of steel structures and especially bridges, the use of high-strength steel (HSS - steel with a yield strength of 460 MPa or higher) has been increasing in recent decades, (Skoglund et al., 2020). The use of steel with a higher yield strength allows the design of slimmer as well as more aesthetic constructions. Design often leads to cost and material savings. In such cases, the resulting resistance of the HSS structure is affected mainly by fatigue resistance, because reducing the cross-section of the structure leads to a higher concentration of stress in the details prone to fatigue damage. For this reason, it is a very current topic for research, which is addressed by many authors. Ho et al. (2018) describes a detailed experimental investigation into structural behaviour of S690 steel materials under cyclic loading conditions to examine hysteretic behaviour. Ahola and Bjork (2020) analyzed fatigue strength of cruciform joints made of ultra-high-strength steel S1100 using experimental fatigue tests and FEM modeling. The issues associated with the use of HSS have to be given due attention.

The assessment of safety and choice of safety factors used with the resistance functions are based on the statistical evaluation of relevant experimental data carried out within the framework of the probabilistic reliability theory. EN 1990 allows the calculation of the design load carrying capacity using the FORM method as 0.1 percentile based on the stochastic analysis of resistance, which is generally a random variable and can be examined using Monte Carlo numerical simulation methods, (Sanches et al., 2015; Lehner et al., 2019), and computational models of structural mechanics. Failure primarily occurs due to the initiation of cracks through stress cracking followed by fatigue crack growth requiring a certain stress range and a sufficiently large number of cycles until final failure ensued through sudden and unstable fracture after fatigue growth to a critical crack size appears. Numerous methods have been proposed for the evaluation of the remaining fatigue life of load carrying steel structures and steel bridges, some of them are based on probabilistic approaches. Fatigue degradation of high strength steel is likely to be different than that of low/medium steel and not sufficiently explained yet and needs further investigation.

Propagation of the fatigue cracks and possible prediction of such propagation in time since the start of variable loading effects is the case when probabilistic methods must be used because too many uncertainties

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influence the determination of the input values. Stochastic approach is a powerful computing tool, which brings with it some difficulties associated mainly with insufficiently relevant input data and also often with computational complexity. Probabilistic analysis of structural durability usually leads to estimate the lifetime of the analyzed load-bearing elements. For this reason, new probabilistic approaches are still evolving. One of them is also the DOProC method (Krejsa et al., 2017), which is an important method for this type of calculation. This approach is characterized by the high precision of computing of the failure probability p_f, as well as considerable efficiency of the calculation in a number of probability tasks. The following analysis is focused on the initial study of fatigue damage prediction of HSS structures using DOProC method and linear fracture mechanics, (Anderson, 2005).

2. Probabilistic fatigue damage prediction

When studying the propagation, the fatigue crack that deteriorates a certain area of the structure components is described with one dimension only – fatigue crack length a. In order to describe the propagation of the crack, the linear elastic fracture mechanics is typically used. This approach uses Paris-Erdogan's law and defines relation between propagation rate of the crack size a, and range of the stress rate coefficient, ΔK, in the face of the crack:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C \cdot \Delta K^m \;, \tag{1}$$

where C, m are material constants, that are determined experimentally, N is the number of loading cycles and ΔK is range of the stress intensity factor in front of the crack tip and it is defined as follow:

$$\Delta K = \Delta\sigma \cdot \sqrt{\pi \cdot a} \cdot F\left(\frac{a}{h}\right) \;, \tag{2}$$

where $\Delta\sigma$ is constant stress range (the value of $\Delta\sigma$ corresponding to each way of loading), h is the height of the rectangular cross-section of the component and $F(a/h)$ is the calibration function which represents the course of propagation of the crack (e.g., at the edge or on the surface of the component) and various boundary conditions.

Three sizes are important for the characteristics of the propagation of fatigue cracks. The fatigue crack will propagate in a stable way only if the initial crack a_0 exists in the place where the stress is concentrated. Existence of the initiation cracks during the propagation should be revealed, along the detectable length of the crack a_d, e.g., during inspections. The crack propagates in a stable way until it reaches the third important size - acceptable length of the crack a_{ac}, which is a limit for the required reliability.

The main assumption is that the primary design should take into account the effects of the extreme loading and the fatigue resistance should be assessed then. The probabilistic methods should be used for the investigation into the propagation rate of the fatigue crack until the acceptable size is reached because the input variables include uncertainties and reliability should be taken into account. The resistance of the structure can be regarded using Eqs. (1) and (2) as:

$$R(a_{ac}) = \int_{a_0}^{a_{ac}} \frac{\mathrm{d}a}{\left(\sqrt{\pi \cdot a} \cdot F(\frac{a}{h})\right)^m} \mathrm{d}a \;. \tag{3}$$

Similarly, it is possible to define the cumulated effect of loads that equals to:

$$E(N) = \int_{N_0}^{N} C \cdot \Delta\sigma^m \mathrm{d}N = C \cdot \Delta\sigma^m \cdot (N - N_0) \;, \tag{4}$$

where N is the total number of oscillations $\Delta\sigma$ for the change of the length from a_0 to a_{ac}, and N_0 is the number of oscillations in the time of initialization of the fatigue crack (typically, the number of oscillations is zero).

The probability of failure P_f equals to:

$$P_f = P\left(G_{fail}(\mathbf{X}) < 0\right) = P\left(R(a_{ac}) - E(N) < 0\right) \;, \tag{5}$$

Tab. 1: Overview of variable input quantities expressed in a histogram with parametric distribution of probabilities.

Quantity	Type	Mean value	Standard deviation
Oscillation of stress peaks $\Delta\sigma$ [MPa]	Normal	30	3
Total number of oscillation of stress peaks per year N [-]	Normal	10^6	10^5
Nominal stress in the flange plate σ [MPa]	Normal	200	20
Yield stress f_y of SSS [MPa]	Lognormal	280	28
Yield stress f_y of HSS [MPa]	Lognormal	460	46
Initial size of the crack a_0 [mm]	Lognormal	0.2	0.05
Smallest detectable size of the crack a_d [mm]	Normal	10	0.6

Tab. 2: Overview of deterministic input quantities.

Quantity	Value
Material constant m	3
Material constant C	$2.2 \cdot 10^{13}$
Width of the flange plate b_f [mm]	400
Thickness of the flange plate t_f [mm]	25
Nominal probability of failure p_d (eq. to $\beta_d = 2$)	0.02277

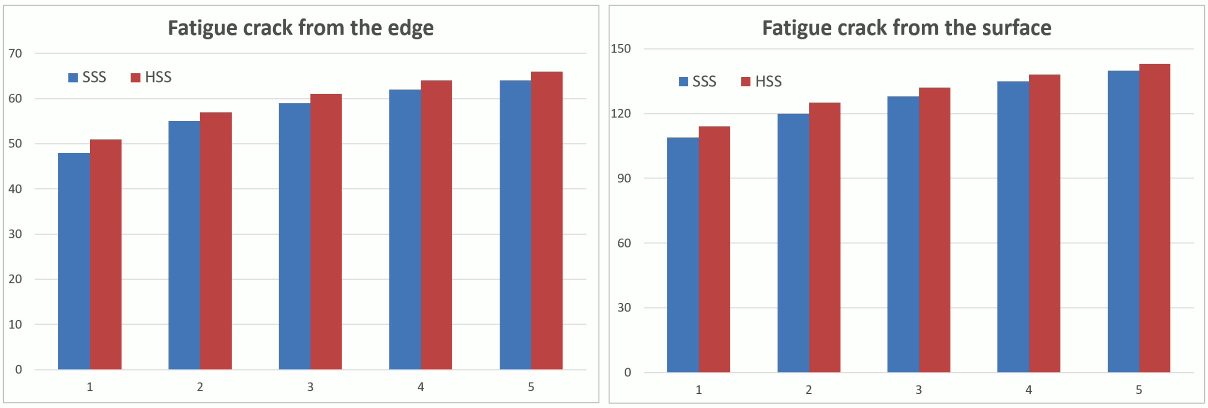

Fig. 1: Calculated times for the first 5 inspections of the analyzed structural element: Fatigue crack from the edge (left), fatigue crack from the surface (right).

where **X** is a vector of random physical properties such as mechanical properties, geometry of the structure, load effects and dimensions of the fatigue crack.

When the probability of failure P_f according Eq. (5) exceeds the specified designed probability, P_d, the inspection should be performed. On the basis of the results of the first inspection, a system of following inspections can be established using conditional probability. The reference probabilistic calculation included the probabilistic assessment of a steel/reinforced concrete bridge from (Krejsa et al., 2017) (see input quantities in Tabs. 1 and 2). A longitudinal steel beam connects to a steel transversal beam, which tends to suffer from fatigue damage. In this study, the probability calculation for two variants of used steels (standard structural steel - SSS and HSS) was proved.

Tab. 3: Calculated times for the first 5 inspections of the analyzed structural element.

Inspection	Time of inspection [years]			
	Fatigue crack from the edge		Fatigue crack from the surface	
No.	SSS	HSS	SSS	HSS
#1	48	51	109	114
#2	55	57	120	125
#3	59	61	128	132
#4	62	64	135	138
#5	64	66	140	143

Two conclusions can be drawn from the results obtained in the table 3 and Fig. 1:

- The fatigue crack from the edge propagates about 2 times faster than the fatigue crack from the surface.
- The use of HSS, compared to SSS, slightly slows down the propagation of both types of fatigue cracks.

3. Conclusions

This paper describes probabilistic prediction of fatigue damage dealing with propagation of fatigue cracks from the edge/surface in steel structures and bridges made from SSS and HSS. A comparison of the fatigue resistance of a detail of a steel-concrete bridge made from SSS and HSS was performed. So far, the exact determination of fatigue parameters C and m, which will be experimentally determined for HSS specimens in the following period, was not taken into account.

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