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# DESIGN OF FATIGUE DAMAGE INSPECTIONS FOR HSS STRUCTURES

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**Abstract:** *Recently, the increasing use of High Strength Steel (HSS) can be observed in the field of civil engineering structures. The advantage of these materials is a particularly favorable strength/weight ratio. The behavior of these materials compared to standard structural steel is slightly different, and it also concerns fatigue resistance and susceptibility to corrosion, which are areas that are far from fully explored. The contribution is focused on the analysis of the fatigue resistance of bridge made from HSS, the prediction of damage of structural elements susceptible to the formation of a fatigue crack from the edge, and how these aspects are reflected in the design of a system of regular inspections of the structure during its operation.*

**Keywords: Fatigue, Steel Bridgers, HSS, Inspection, Probability.**

## 1. Introduction

Fatigue damage in steel structures is an important aspect affecting their reliability. Failure due to fatigue damage can lead to fracture, which can occur based on increasing load cycles cumulatively. The traditional theoretical approach for evaluating fatigue resistance is referred to as cumulative fatigue damage theory (Fatemi and Yang, 1998). More recent work develops a theory of fatigue crack propagation that is based on fracture mechanics and often uses a probabilistic approach. Currently, both theories are used to predict fatigue damage and assess the reliability of cyclically stressed steel structures (Cui, 2002).

High strength steel (HSS) with nominal yield stress in the range 460 MPa into 960 MPa has been used many times worldwide in the construction of modern building and bridge structures (Miki et al., 2002). The advantage of these materials is a particularly favorable strength/weight ratio. Research results show that the mechanical behavior of HSS is slightly different compared to standard structural steel. It also concerns fatigue resistance and susceptibility to corrosion, which are areas that are far from fully explored. These facts lead, among other things, to the need to update the current regulations and standards for designing HSS structures, e.g. (Shi et al., 2014), and bridges, and were also the motivation for the research described in this paper.

The contribution is focused on the analysis of the fatigue resistance of bridge made from HSS, the prediction of damage of structural element susceptible to the formation of a fatigue crack from the edge, and how these aspects are reflected in the design of a system of regular inspections of the structure during its operation for three types of HSS with a yield strength of 460 MPa, 690 MPa and 960 MPa. For probabilistic calculation of fatigue crack progression was used the original probabilistic methods - the Direct Optimized Probabilistic Calculation (”DOProC”), which is based on optimized numerical integration (Janas et al., 2017). The algorithm of the probabilistic fatigue damage prediction was applied in the FCProbCalc code (Krejsa, 2012), using which is possible to carry out the probabilistic modelling of propagation of fatigue cracks.

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## 2. Mathematical model

To describe the propagation of the crack, the linear elastic fracture mechanics based on Paris–Erdogan law was used. The purpose of the study was to compare the fatigue resistance of a load-bearing element of a steel/reinforced concrete bridge from the highway susceptible to fatigue damage (join of longitudinal and transversal steel beam) from three different types of HSS. Formulation of the load effect function $E$ and structural fatigue resistance $R$ for the analysed element has been published in (Krejsa et al., 2017), which contains calibration function $F(a)$ for the description of crack propagating from the edge in bearing element stressed in tension:

$$F(a) = 1.12 - 0.231 \cdot \frac{a}{b_f} + 10.55 \cdot \left(\frac{a}{b_f}\right)^2 - 21.72 \cdot \left(\frac{a}{b_f}\right)^3 + 30.39 \cdot \left(\frac{a}{b_f}\right)^4, \tag{1}$$

where $a$ is the length of the fatigue crack and $b_f$ is the width of the flange, and the acceptable crack size $a_{ac}$, which can be described by a formula resulting from the weakening of the cross-section area of the flange (with the limit $a_{ac} \leq 0.4 \cdot b_f$):

$$a_{ac} = b_f \cdot \left(1 - \frac{\sigma}{f_y}\right), \tag{2}$$

where $\sigma$ is nominal normal stress in the flange and $f_y$ is yield stress of the used steel.

The input quantities were determined deterministically or randomly using parametric probability distributions (see Tabs. 1 and 2).

*Tab. 1: Overview of deterministic input quantities*

| Quantity | Value |
|---|---|
| Material constant $m$ | 3 |
| Material constant $C$ | $2.2 \cdot 10^{-13}$ MPa$^m$m$^{(m/2)+1}$ |
| Width of the flange plate $b_f$ | 400 mm |
| Thickness of the flange plate $t_f$ | 25 mm |
| Target probability of failure $P_d$ | 0.02277 ($\beta_d = 2$) |

*Tab. 2: Overview of input random quantities expressed in a histograms with parametric distribution of probability*

| Quantity | Distribution | Mean | StDev |
|---|---|---|---|
| Total number of stress peaks per year $N$ | Normal | $10^6$ | $10^5$ |
| Nominal stress in the flange plate $\sigma$ [MPa] | Normal | 405 | 40.5 |
| Range of stress peaks $\Delta\sigma$ [MPa] | Normal | 32 | 3.2 |
| Yield stress $f_y$ of S460 [MPa]* | Lognormal | 490.82 | 3.18 |
| Yield stress $f_y$ of S690 [MPa]* | Lognormal | 817.10 | 6.15 |
| Yield stress $f_y$ of S960 [MPa]* | Lognormal | 1040.03 | 3.57 |
| 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 |

* Note: Calculated from measured data

## 3. Analysis of results

The calculation has been proceeded for all three types of HSS. Fig. 1 shows times for the first inspection and subsequent inspections resulting from the conditional probability for S690 steel. The curves describe dependence of the probability of failure, $P_f$, on time of operation of the bridge structure.

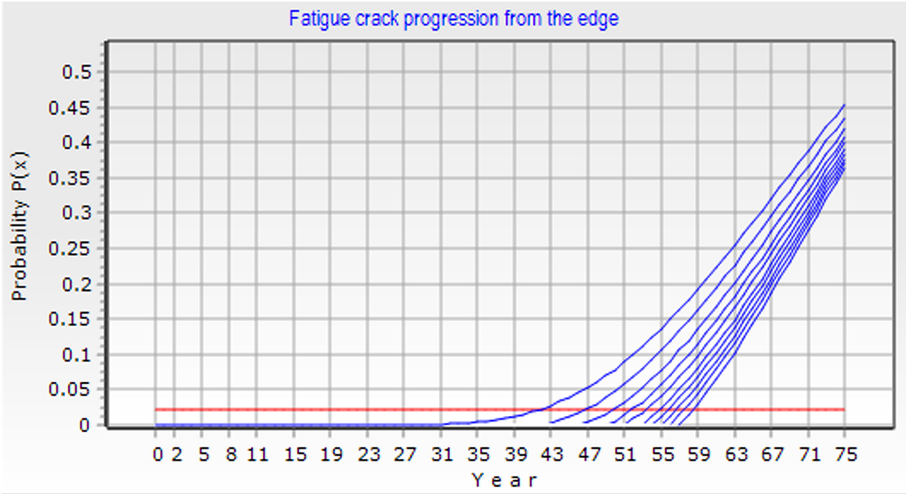


*Fig. 1: FCProbCalc desktop: Dependence of the failure probability $P_f$ on years of operation of the bridge structure (N=0 to 75 years) during the probabilistic calculation of propagation of fatigue cracks from the edge, steel S690.*

Fig. 2 includes the results for each type HSS under analysis. Results of S690 and S960 steels are very similar, which is due to the lower value of the nominal stress relative to the yield strength of these steels compared to the S460 steel with significantly different resulting values.

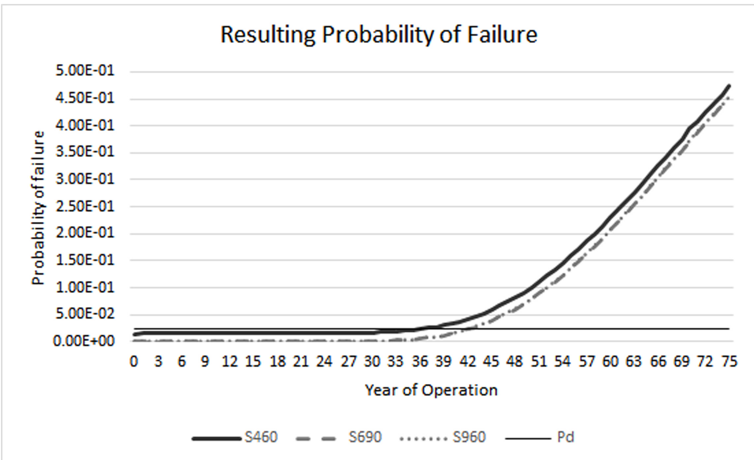


*Fig. 2: Comparison of results for all three types of HSS, resulting probability of failure $P_f$ for first 75 years of structural operation.*

The Tab. 3 includes a table with numerical values for the ten final inspection times (times for the second inspection and subsequent inspections resulting from the conditional probability) of each type of HSS focused on detection of fatigue crack from the edge.

## 4. Conclusions

The contribution describes methods dealing with propagation of fatigue cracks from the edge in HSS structures and bridges, which are subject to cyclic loads. The theoretical model of fatigue crack progression is based on a linear fracture mechanics. The method of Direct Optimized Probabilistic Calculation ("DOProC") was applied for the probabilistic prediction of fatigue damage with subsequent design of the system

*Tab. 3: Calculated times for the 1st and subsequent inspections of the structural element focused to the fatigue damage, propagation of the fatigue cracks from the edge.*

| | Time of inspection [years] | | |
|---|---|---|---|
| Inspection No. | S460 | S690 | S960 |
| 1 | **35** | **42** | **41** |
| 2 | 39 | 46 | 46 |
| 3 | 43 | 49 | 49 |
| 4 | 47 | 51 | 52 |
| 5 | 50 | 53 | 54 |
| 6 | 52 | 54 | 55 |
| 7 | 54 | 55 | 56 |
| 8 | 55 | 56 | 57 |
| 9 | 56 | 57 | 58 |
| 10 | 57 | 58 | 59 |

of inspections focused on the critical detail of the supporting structure. The probability of propagation of fatigue cracks from the edge was calculated in FCProbCalc code.

On the basis of measured data, the probability of failure has been calculated for each year of operation of the structure. Times of the first ten structural controls have been specified in study based on this determination and the defined required degree of reliability. It was found that fatigue damage in HSS load-bearing elements occurs more slowly with increasing strength of the material. Further research will focus on situations where the nominal stress in element will be closer to the values of the yield strength of the material. Due to the time-consuming nature of the calculation, ways will be searched to develop a computational algorithm usable on parallel systems and supercomputers.

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