A PRESTRESSED BRIDGE BEAM UNDER CORROSION ATTACK – PROBABILISTIC MODELLING

Dita Matesová, Jan Podroužek, Zbyněk Keršner, Břetislav Teplý

Summary

Presented here is an assessment of the limit state conditions of a prestressed bridge beam with its prestressing steel affected by corrosion. The proposed approach is based on probabilistic methods and simulation techniques, taking into account the uncertainties of the relevant variables while modelling hydrogen induced stress-corrosion cracking (SCC). The software package FReET-D [1, 2] for the stochastic assessment of degradation effects in reinforced concrete structures is utilized for SCC modelling and service life assessment. The deterministic model is based on the fracture mechanics approach. As an illustrative example, a precast prestressed bridge girder damaged by SCC is presented.

Keywords: Stress-corrosion cracking, analytical model, fracture mechanics, reliability, software

1 Introduction

In the last decade, considerable progress has been made in the realistic determination of the actual load carrying capacity and reliability of existing bridge structures. In this context, the deterioration of concrete due to corrosion of mild or prestressing reinforcement is a serious effect influencing the service life and reliability of concrete structures. Furthermore, a corrosion rate may arise in older bridge structures with quenched and tempered prestressing wires that are sensitive to hydrogen induced stress corrosion cracking (SCC). Despite the intensive research devoted to SCC, its underlying mechanisms are not yet fully understood as it depends upon complex chemical and mechanical interactions. In such cases large uncertainties are related to the deterioration of the materials, and consequently, structural member behaviour. Thus, the assessment of the load carrying capacity, serviceability, durability and reliability of a structure should be based on advanced methods taking into account the above mentioned uncertainties.

Computational models provide useful information about a structure and its behaviour in various phases of its life-time. This is important especially when the experimental investigation of the existing structure is unsuitable or even impossible. Prestressed bridges damaged by the hydrogen induced SCC of their wires may represent such a case. The effect of SCC cannot be simply described as a chemical or a mechanical effect. This paper presents the linear elastic fracture mechanics approach and the stochastic simulation technique applicable for the assessment of this problem.
2 FReET-D software

Metals can be generally subjected to various forms of corrosion. In our case, the interaction is studied of corrosion and mechanical stress leading to failure due to cracking. The development of damage due to the interaction of corrosion and mechanical stress may be faster than other types of deterioration. The consequences of SCC may be costly and destructive. Unfortunately, research concerning SCC modelling is rather rare and engineering tools suitable for the handling of such situations do not yet exist (to the best knowledge of the authors). Let us note that a stochastic nonlinear assessment of a precast prestressed concrete bridge girder has been performed recently [3] using the ATENA [4] and FReET [5] software packages that communicate through the SARA shell (Structural Analysis and Reliability Assessment). This package was specifically designed for the purpose of reliability assessment of the nonlinear behaviour of reinforced concrete structures. Results of numerical simulations of the prestressed bridge girder with ad-hoc corroded reinforcement were presented in [6] showing decreases in the load carrying capacity and in the reliability index compared to a beam with prestressing steel without corrosion. However, no degradation model was utilized in that case.

The aim of this paper is to refer to an effective mathematical model describing SCC in prestressed steel wires. This model has been implemented into the multipurpose probabilistic software FReET-D [1, 2] (Feasible Reliability Engineering Tool for Degradation effects assessment) which is based on FReET [5]. FReET-D involves 26 degradation models in the form of dll functions.

3 SCC modelling

Degradation models are generally time dependent mathematical functions describing the process of degradation during exposure to environmental and operational loading. While formulating the SCC model, the following basic assumptions were adopted: (i) although the real problem is practically a three-dimensional one, a two-dimensional approach is proposed for the sake of simplicity and computational efficiency; (ii) the corrosion develops in the form of pits that are considered to be stress concentrators; (iii) the position and range of pitting corrosion is random and the worst pit is taken into account here; and (iv) the geometry of the crack/pit is considered to be semi-elliptical and loaded via mode I opening.

The fundamentals of the model are adopted from [7]. The model proposed in this paper differs in the geometry function $F_I$ evaluation, and has been randomized by the authors. As already mentioned, the implemented model is based on the fracture mechanics approach and thus is determined only with the geometry of reinforcement and the corrosion pit (see Fig. 1), the exposure time, and the actual uniform tension. The time dependency is included through the depth of the pit $p(t)$ [mm] (Fig. 1) that can be expressed as [8]:

$$ p(t) = \psi \left( 0.0116 \ i_{corr} \ R_{corr} \ (t-t_i) \right) $$

(1)

where $t = t_i + t_p$ (see Fig. 2), $t_i$ [years] is the time to corrosion initiation, i.e. steel depassivation, and may be gained using appropriate models for carbonation or chloride ingress, see e.g. [9], and $t_p$ [years] is the time of corrosion propagation. $\psi$ is the uncertainty factor of the model [-], $i_{corr}$ is the corrosion current [$\mu$A/cm$^2$] and $R_{corr}$ is a
coefficient that expresses the corrosion type. The constant 0.0116 is a conversion factor from $\mu$A/cm$^2$ to mm/years under the assumptions that steel (Fe) has $n = 2$ (number of electrons freed by the corrosion reaction), $M = 55.85$ g (atomic mass) and $d = 7.88$ g/cm$^3$.

The output value of the proposed model, the stress intensity factor $K_I$ [MPa.m$^{1/2}$] is defined as:

$$K_I = \psi F_I (t, d_i, c) \sigma \sqrt{s(d_i, s_p, t)}$$  \hspace{1cm} (2)$$

A key parameter is the relevant geometry function $F_I$ designed according to [10], plotted in Fig. 3 and defined as:

$$F_I = 1.76 \exp \left( -1.054 s_p + 0.7072 \left( \frac{2p(t)}{d_i} \right)^2 \right) + 0.5548 \ln(s_p)$$  \hspace{1cm} (3)$$

In Eqs. (2) and (3) $d_i$ is the initial wire diameter, $s$ is the arc of a circle length given by the circle – ellipse intersection (see Fig. 1) and $\sigma$ [MPa] represents the uniform tension in the prestressed wire considered as time independent for the sake of simplicity. The relationship between the ellipse's primary half-axe, $c$ and the secondary half-axe that is the crack depth $p(t)$ (Fig. 1), is bonded by a shape parameter $s_p = p(t)/c$. The illustration of the influence of $s_p$ on $F_I$ is shown in Figs. 3 and 4.
4 Limit-state function

The model presented in section 3 may be effectively utilized while evaluating the limit state condition:

\[ P_f(t_D) = P \left( K_{ISCC} - K_i (t_D) \leq 0 \right) \leq P_d \]

Fig 4 Geometry function \( F_i \) vs. propagation time \( t_p \) for \( d_i = 20 \text{mm} \), and the rate of the pit depth increase \( p(t) = 0.2 \text{mm/year} \)

The growth of a crack becomes unstable.

5 Illustrative examples

**Example 1:** The analysis of the condition (4) has been performed for the following input data: \( d_i = 15.24 \text{ mm} \) (≈0.6 in), \( \sigma = \text{N}(1000; 80) \text{ MPa} \), \( s_p = 0.75 \) and \( \psi = \text{LN}(1; 0.15) \). The barrier \( K_{ISCC} \) was assumed to have Normal probability distribution with the mean values 40, 50 and 60 MPa·m\(^{1/2}\) and COV = 0.1 [7]. Pitting corrosion rate was assumed to be 0.2 mm/year. This value was determined on the basis of Eq. (1) for the following inputs: \( i_{corr} = 3 \mu\text{A/cm}^2 \), \( R_{corr} = 6 \) and \( \psi = 1 \). The chosen values of \( i_{corr} \) and \( R_{corr} \) indicate a high rate and the pitting type of corrosion, respectively. The influence of the \( K_{ISCC} \) value on the probability of the failure of a single wire, Eq. (4), vs. propagation time \( t_p \) is plotted in Fig. 5.

**Example 2:** As an application example, a precast prestressed bridge girder damaged by hydrogen induced SCC is simulated. The effect of corrosion on the load bearing capacity of the girder has been studied previously in [6]; the dimensions of the girder are similar to those of the AASHTO Type IV, capable of spanning distances in the 21 to 30 m range [11]. The influence of a rupture of 6 prestressing tendons out of a total of 26 due to SCC on the ultimate load and the probability of failure was shown in [6], utilizing nonlinear FE analysis and probabilistic assessment. From the study results, a 15% decrease in the bearing capacity can be compared to that of the girder with all prestressing tendons (the index of reliability \( \beta \) being equal to 3.8, as prescribed by EN 1990 as the target value at the 50-year reference period). No consequences for service life were studied in [6] as no time dependent model was available. To complete this is the reason why the same girder is investigated in the present study using the SCC model described in the previous sections.
The values input to Eq. (1) are: $i_{\text{corr}} = 3 \, \mu\text{A/cm}^2$, $R_{\text{corr}} = 4$ and $\psi = 1$; to Eq. (2): $d_i = \text{N}(11.2; 0.112) \, \text{mm}$, $\sigma = \text{N}(1020; 102) \, \text{MPa}$, $s_p = \text{N}(0.75; 0.075)$ and $\psi = \text{LN}(1; 0.15)$.

First, the value of $p(t)$ is studied, Eq. (1). The resulting corrosion rate used further for the SCC evaluation is 0.14 mm/year. In the next step the time to failure of the 6 prestressing tendons is calculated. Tensile stress $\sigma$ is taken from the nonlinear numerical simulation [6] for the reliability level $\beta = 3.8$. The threshold value of the stress intensity factor $K_{\text{ISCC}} = 60 \, \text{MPa}\cdot\text{m}^{1/2}$. The results are plotted in Fig. 6. It follows that the mean critical propagation time $t_p$ is about 7 years.

The initiation time $t_i$ has been studied under the assumption that chloride ingress is responsible for the steel’s depassivation. The model proposed by Papadakis et al. [12] implemented in FReET-D [1, 2] was used. The description of this model is out of the scope of this text; the resulting time to corrosion initiation has been found to be $t_i = 30$ years.

In this way, the partial results gained in [6], i.e. the decrease in the load-bearing capacity to 85%, are completed by the assessment of the time $t_S = t_i + t_p = 37$ years.

Acknowledgement
This outcome has been achieved with the financial support of the Czech Ministry of Education, project No. 1M0579, within the activities of the CIDEAS research centre.

References


Ing. Dita Matesová, PhD.
Jan Podroužek
Ing. Zbyněk Keršner, CSc.
Prof. Ing. Břetislav Teplý, CSc.

Brno University of Technology
Faculty of Civil Engineering
Vevěří 331/95
602 00 Brno, Czech Republic

+420 5 4114 7368
matesova.d@fce.vutbr.cz
limajuliet@seznam.cz
kersner.z@fce.vutbr.cz
teply.b@fce.vutbr.cz

http://www.fce.vutbr.cz