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INFLUENCE OF THE LONG TERM EXPOSURE TO AGGRESSIVE ENVIRONMENT ON THE FATIGUE PERFORMANCE OF CONCRETE SPECIMENS

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Abstract: *High stress ranges caused by cyclic loading can result into accelerated crack propagation, higher deflection, structural stiffness reduction and consequently into fatigue failure. Aggressive environment (soluble salts, acids etc.) causes a different kind of deterioration. Agents contained in the aggressive environment penetrate into the structure of concrete and reduce its matrix stiffness. The combination of these effects occurs e.g. at bridges in urban environment or at crane tracks in chemical plants and leads to higher long-term structural damage. This paper presents outcomes of a long-term experimental program focused on the fatigue performance of reinforced concrete specimens stored in aggressive environment. The specimens are stored in an acidic lotion for more than 5 years.*

Keywords: ***Fatigue, aggressive environment, concrete, deterioration, deflection.***

1. Introduction

Fatigue can be defined as a process of permanent progressive changes in the structure of material subjected to cyclic loading. Research related to fatigue of metals started in 1840's with the construction of railways. Fatigue of concrete and concrete structures was first described at the beginning of the 20th century and became a significant topic in 1920's with the development of highways. Strain development due to fatigue loading was firstly examined in late 1970's by Holmen (1979). This effect was further extended by Foglar (2008).

The effect of concrete deterioration on its fatigue performance on has not been properly quantified yet. The most material models of concrete consider the characteristics of an undamaged material (strength, elastic modulus) despite the fact that many experiments carried out (Fan et al., 2010; Huang et al., 2005; Kong et al., 1987) show large reduction of material properties due to concrete deterioration. The interaction between cyclic loading and the effects of aggressive environment cause deteriorative processes and leads to faster element deterioration and subsequently into its failure.

This paper presents experimental investigation of performance of reinforced concrete specimens exposed to cyclic loading and aggressive environment.

2. Experimental program

2.1. Materials and specimen preparation

Several reinforced concrete specimens were made for the experimental program. The C25/30-X0 strength class of concrete was chosen; the low grade of resistance against the influence of environment was intentionally chosen to increase the effect of the aggressive environment. The dimensions of the specimens are 300x150x1300 mm. Cubes with dimensions of 150x150x150 mm from the same concrete grade were made for evaluation of compressive strength of deteriorated concrete specimens.

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Specimens are designed as over-reinforced (6ø16 grade B500 reinforcing steel), thus failure by compressive-zone crushing should occur and the fatigue failure of concrete is assumed. The reinforcement scheme can be seen in Fig. 1.

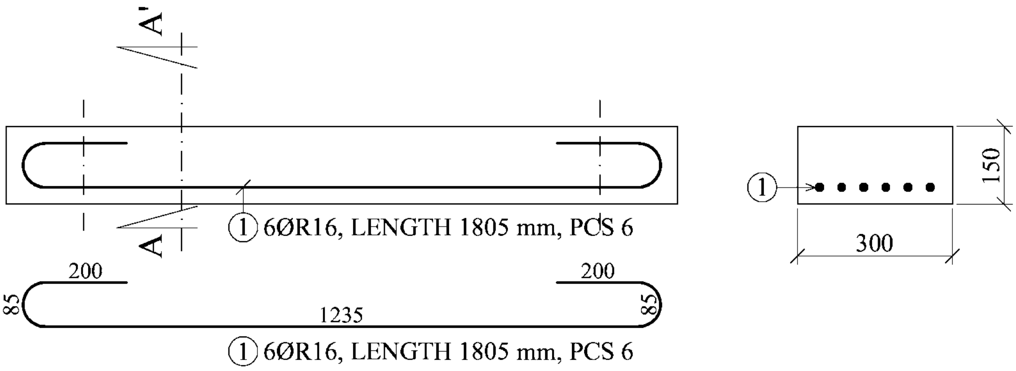

Fig. 1: Scheme of specimen reinforcement

2.2. The simulation of the aggressive environment

Due to the nature of investigated phenomena, it was necessary to design an appropriate environment for storing the specimens. Firstly, a solution of sodium chloride (*NaCl*) with concentration of 5%, corresponding to de-icing salts used for winter maintenance of roads was chosen. This environment appears mainly at bridge structures with damaged insulation. To obtain faster deterioration of specimens, the saline lotion was later substituted by hydrochloric acid solution (*HCl*) with pH = 4. Two reference specimens were made. The first specimen was stored in dry conditions; the second one was placed in water from the day it was cast and during the rest periods.

2.3. Fatigue testing

The arrangement of the cyclic loading is four-point bending with mid-span length 1000 mm and overhangs with the length of 150 mm. The testing layout can be seen in Fig. 2. Loading frequency, maximum / minimum force, its eccentricity and number of cycles applied to each specimen can be seen in Tab. 1. Experimental testing was conducted in laboratories of Faculty of Civil Engineering, CTU in Prague.

Tab. 1: Specification of loading and total number of applied cycles

Loading frequency	**Cyclic force** [kN]		**Eccentricity e**	**Load cycles applied**
[Hz]	Min.	Max.	[m]	[$\cdot 10^3$]
5	5	80/100	0,3	600/200/400/250

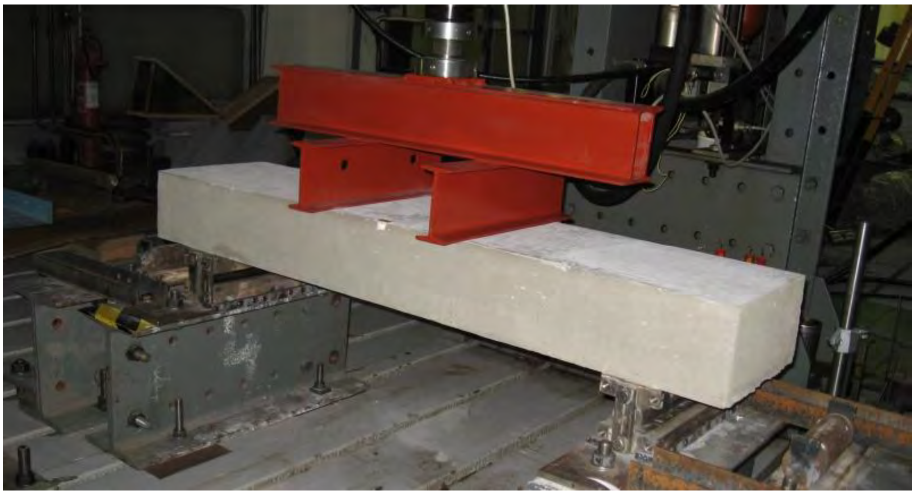

Fig. 2: The arrangement of the fatigue loading

2.4. Deflection measurement

Two types of deflection measurements were conducted within fatigue testing. The first type was static deflection measurement which took place each hour of the cyclic loading (circa 18000 load cycles). The fatigue testing was stopped during the measurement. The second type was dynamic deflection measurement which was carried out during the fatigue testing at least once between two static deflection measurements.

Due to the time constraints of laboratories (fatigue testing can run only between 7 a.m. and 3 p.m.) the fatigue testing was conducted in several consecutive days to achieve the required number of cycles. For this reason, the additional static measurements were executed after the end of fatigue testing and before another testing on following day.

3. Results and discussion

The first four specimens were tested. The dry specimen (n_1 = 600 thousand cycles, age 29 days), the wet specimen (n_2 = 200 thousand cycles, age 61 days), the specimen stored in saline lotion (n_3 = 400 thousand cycles, age 383 days) and the specimen stored in saline lotion and subsequently in acidic solution (n_4 = 250 thousand cycles, age 564 days). The effect of water, saline lotion and acidic solution treatment on the fatigue performance of concrete was evaluated.

3.1. Deflection calculation

The procedure of evaluation of measured data sets is based on the fatigue damage function (1) (Foglar, 2008). In addition to the data derived from the experimental testing, the calculation of the fatigue damage function requires the compressive strength and the modulus of elasticity as the input data. The compressive strength was evaluated from the tests performed on cubes corresponding to each deteriorated specimen. The value of modulus of elasticity was calculated from the first static deflection measurement of the specimen and from equation for deflection in four-point bending test. Modulus of elasticity is then multiplied by the fatigue damage function (1). The results of the experiments can be seen in Fig. 3.

$$\omega_{F_i} = 1 - \left\{ \left[a^{c_4 \cdot \frac{1}{S_{\max}^{c_3}}} \cdot \frac{n_i}{c_1 \cdot N} \right]^{\frac{1}{c_4 \cdot \frac{1}{S_{\max}^{c_3}}}} + b \cdot \exp\left[\left(\frac{n_i}{N} - 1 \right) \cdot c_2 \right] \right\} \qquad (1)$$

where ω_{Fi} = fatigue damage function after n_i load cycles; n_i = number of load cycles the structural element has already resisted; N = total number of load cycles the structural element is able to resist (this value can be calculated by formulas given in Eurocode 2 or more conservatively in Model Code 2010); a, b = constants dependent on load level; c_1 = 0.1, c_2 = 70; c_3 = 2.72; c_4 = 1.0 for S_{max} from (0; 0.377), = 2.1436S_{max} + 0.19037 for S_{max} from (0.377; 0.736), and = 1.771 for (0.736; 1).

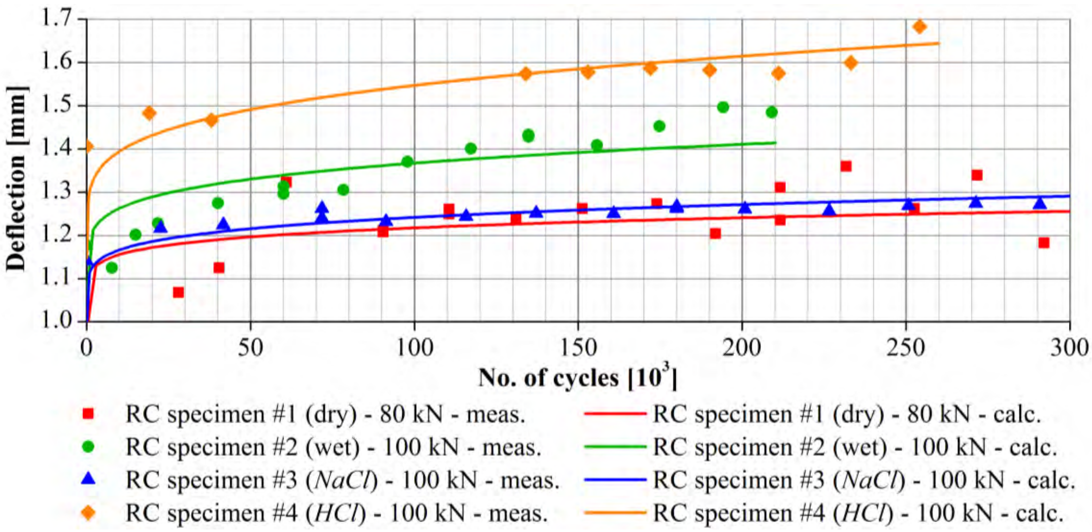

Fig. 3: Deflections of all evaluated specimens. Comparison of calculated and measured deflections

3.1. The comparison of the fatigue performance of dry and wet specimens

The dry specimen show bigger scatter of measured values, see Fig. 3. Also the "healing" effect of the rest periods (3 p.m. to 7 a.m.) seems to be higher. The influence of "healing" effect of concrete on static deflections before another day of fatigue testing was up to 10%. This fact can be attributed to decreased shear resistance of the bond between aggregate and the cement paste in wet specimens as referred in Barr and Lee (2004).

3.2. The effect of aggressive environment

When comparing specimens no. 2 stored in water and no. 3 stored in saline lotion, it can be observed that specimen no. 3 shows smaller deflections in comparison to specimen no. 2. This fact can be attributed to time-dependent increase of compressive strength and elastic modulus with low-rate deteriorative effect of the saline lotion which is primarily physical and has bigger effect in changing dry/wet condition. Nevertheless, the spotted lime leaching is assumed due to greater solubility of calcium hydroxide ($Ca(OH)_2$) in sodium chloride solution than in water as presented by Tuthill (1978).

For the specimens stored in the acidic solution (no. 4), the increase of the deflections caused by material deterioration is significant. The decrease of the modulus of elasticity can be observed comparing the first deflection measurements in Figure 7, 8, 9 with the first value in Figure 10. The influence of the compressive strength decrease is included in fatigue damage function by S_{max} which influences the total number of cycles and constants a, b, c_4.

To remove the influence of the increase of the material characteristics (compressive strength, modulus of elasticity) in time, the deflections of the specimens no. 2, 3 and 4 were multiplied by the in Eurocode 2 presented time-dependent function for development of the compressive strength β_{cc} (the modulus of elasticity is calculated from the compressive strength of concrete). The ratio was calculated using measured compressive strengths of the specimens. For better comparison of the deflections of specimen no. 1, the deflections were modified to the 100 kN cyclic force used for other specimens. The calculated ratios of β_{cc} are summarized in Tab. 2. The deflections were multiplied by modulus of elasticity ratios according to equation (2):

$$E_i = \left(\beta_{cc,i} / \beta_{cc,1}\right)^{0\,3} E_1 \tag{2}$$

Tab. 2: Comparison of calculated ratio and ratio according to Eurocode 2

Specimen no.	Age [day]	Compressive strength [MPa]	$\beta_{cc,1} / \beta_{cc,i}$ calculated [-]	$\beta_{cc,1} / \beta_{cc,i}$ Eurocode 2 [-]
1	29	39.0	1.000	1.000
2	61	43.0	1.103	1.063
3	383	49.0	1.256	1.153
4	564	31.0	0.795	1.164

With this approximation, the deflections of specimen no. 1 were similar to the deflections of the highly deteriorated specimen no. 4, as can be seen in Fig. 4. This behavior is improbable, thus another approximation was derived.

The second approximation was based on the ratios of modulus of elasticity fitted from deflection measurements for each specimen. For comparison, the modulus of elasticity of the specimen no. 1 was taken as the reference value. The deflections of others specimens were multiplied by the ratio between reference value and fitted value of modulus elasticity.

With this approximation, the deflection of the specimen no. 3 was similar to measurements of specimen no. 2 but not higher. This behavior is more realistic. For both approximations the deflections of specimen no. 4 were slightly decreased due to the measured compressive strength and fitted modulus of elasticity was lower than for specimen no. 1. The deteriorative effect of acidic solution is still significant. The results of this approximation can be seen in Fig. 5.

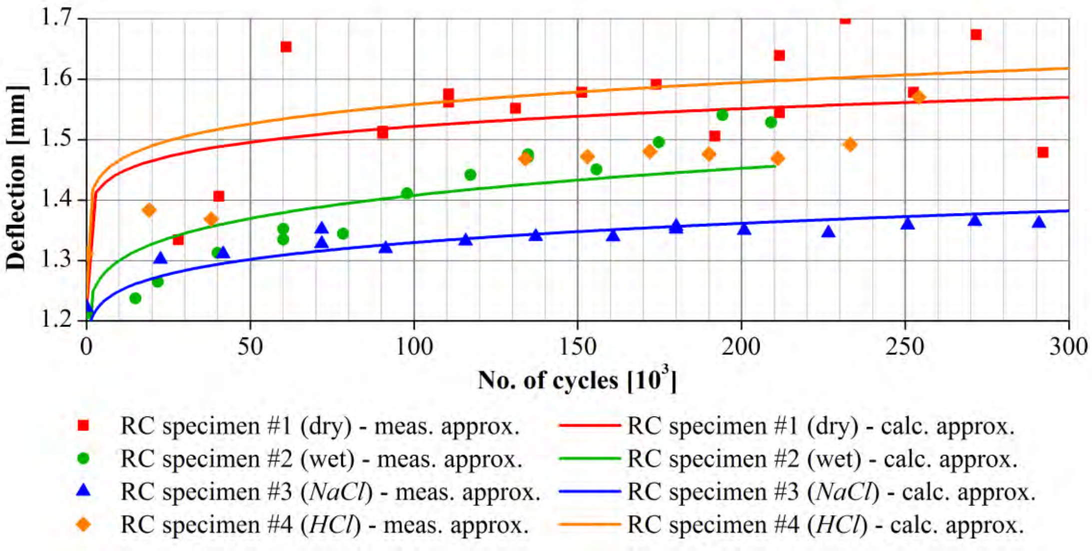

Fig. 4: Time-independent approximation of deflections using β_{cc} function

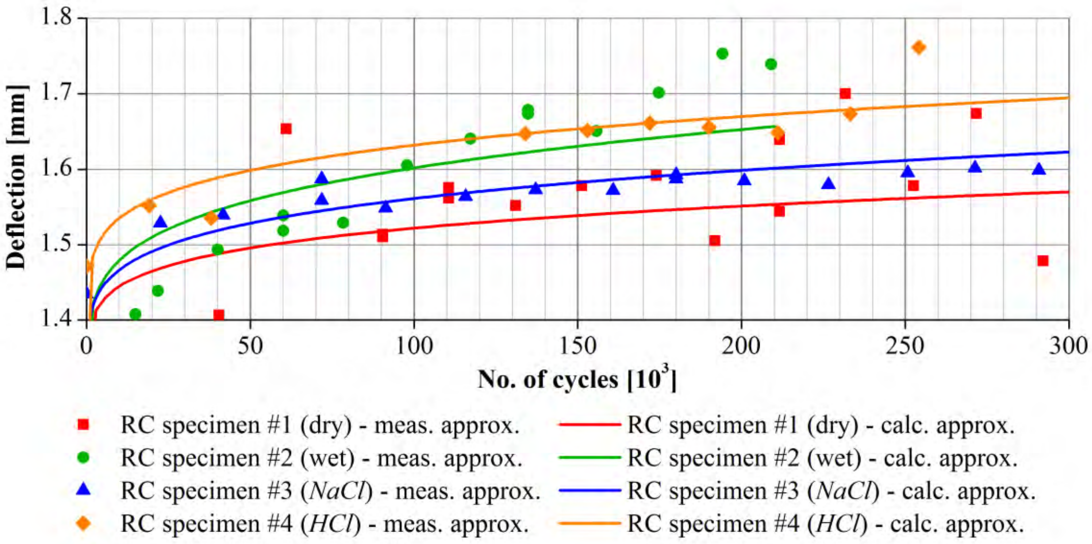

Fig. 5: The time-independent approximation of deflections using ratios of modulus of elasticity

The experimental program will continue with an extended set of specimens. The main goal of the experimental program is to propose an analytical tool for assessing the influence of $Ca(OH)_2$ mass loss on compressive strength, modulus of elasticity, thus on fatigue characteristics of concrete elements.

4. Conclusions

This paper described long-term experimental program focused on interaction between aggressive environment and cyclic loading. The effect of material deterioration on fatigue performance of concrete structures was investigated.

Within the testing of concrete beams, differences were observed in fatigue behavior of dry and wet specimen. Because of the nature of investigated phenomena these differences are not negligible and will be subject to further theoretical and experimental investigations as well as the influence or speed of sodium chloride deteriorative effect under wet and dry/wet conditioning.

The deteriorative effect of the hydrochloric acid solution on specimen deflections was of a significant influence. Lower, but not negligible effect of the sodium chloride solution on the increase of deflections was demonstrated with time-independent approximation.

Acknowledgement

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