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Service life analysis of corroded high strength concrete elements

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Abstract

High strength concrete is nowadays an optimum construction material, with excellent cost-effectiveness relationship with regard to physical-mechanical properties and durability. However, a reinforced element in service is generally exposed to more or less aggressive media, which reaches the embedded reinforcement through structural, inherent cracks and produces corrosion and loss of section. The following study is focused on reinforced high strength concrete elements subjected to one point loading, with and without induced artificial corrosion, taking into account vertical deformations and cracking pattern at a certain crack width.

Rezumat

În contextul actual, betonul de înaltă rezistenţă este un material optim, cu o bună relaţie cost-proprietăţi mecanice şi de durabilitate. Chiar şi în aceste condiţii, un element din beton armat, realizat din beton de înaltă rezistenţă, aflat în starea limită de serviciu, este expus la medii agresive prin intermediul fisurilor inerente, structurale, care ajungând la armătură, produc coroziunea acesteia, respectiv o pierdere de secţiune. Articolul următor se concentrează pe studiul elementelor din beton armat, realizate cu beton de înaltă rezistenţă, supuse la o forţă concentrată, afectate sau neafectate de coroziune accelerată artificială, din punctul de vedere al deformaţiilor şi al modului de fisurare la o anumită deschidere de fisuri.

Keywords: corrosion, reinforcement, crack width, vertical deformation, service

1. Introduction

Among certain well known effects of corroded embedded reinforcement, some are esthetically improper, such as color, but overall harmless, but some are more problematic, such as the loss of cross section, which leads to a reduction in overall strength, broader deformations and fatigue. Moreover, the bond between the reinforcement and the concrete is severed with structural degradations following shortly [1]. There are several corrosion products responsible for the exfoliation of the concrete cover, due to their expansion in the concrete matrix, causing tensile pressures which easily exceed the tensile strength. For example, 1 cm^3 of steel corrosion corresponds to 2.1 cm^3 of black colored Fe_3O_4, 3.8 cm^3 of white colored $Fe(OH)_2$, 4.2 cm^3 of brown colored $Fe(OH)_3$, and 6.4 cm^3 of yellow colored $Fe(OH)_3 \cdot 3H_2O$ [2]. Furthermore, the intensity of the current is related to section loss of the reinforcement. A moderate corrosion rises up to 0.5

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μA/cm^2 which can produce a loss of section of 5.7 μm/year and an oxide layering up to 17.3 μm/year, whereas a stronger corrosion is produced by an intensity current of 1 μA/cm^2, which corresponds to a maximum of 11.5 μm/year and an oxide layering of maximum 34 μm/year [2]. These values are important in assessing the rate of the corrosion and the possible effects, if they are considered properly for a complex reinforcement detailing, with both transverse and longitudinal reinforcement. The presence of structural cracks, dependent of the concrete matrix and the reinforcement ratio add further complexity to the problem at hand. Stirrup often causes a beneficial delay over corrosion cracks initiation and propagation. Deeper concrete covers lead to longer time periods for the same crack widths. This goes for smaller reinforcement diameters and smaller compressive strength [3]. The level of loading of the elements in service exacerbates corrosion, both for the initiation and the propagation periods and the failure of a severely corroded element is similar to creep failure [4]. But how the corrosion begins is best explained by Hansson et al. [5]. The micro cell and macro cell corrosion must be taken into consideration simultaneously, because they are both often met in practice. One refers to a self-employed corrosion on the same bar due to two different charged, but close locations and the other refers to an active bar connected to a passive bar due to exposure to different media [5].

Usually, in service reinforced concrete elements, crack widths are allowed to reach 0.1, 0.2 and 0.3 mm, dependent of the exposure class, according to Eurocode 2 [6]. Furthermore, the concrete cover and the concrete composition are the main resources in mitigating aggressive environments [6].
Therefore, the aim of the study is to assess the structural response of reinforced high strength concrete elements, with 25 mm and 50 mm concrete covers, pre-cracked to a service life crack width and subjected to accelerated artificial corrosion. Witness specimens non exposed to corrosion were also tested in order to produce comparisons to corroded elements. The bending capacity of the corroded beams was not severely diminished, compared to the non-exposed specimens. Furthermore, the 50 mm concrete cover did not address the corrosion problem. In fact, the overall bending behavior was negatively affected by it.

2. Materials and methods

The high strength concrete composition is presented in Table 1.

Table 1. Concrete composition - C80/95

Components	Quantity
Portland Cement CEM I 52.5R	520 [kg/m^3]
Silica fume	52 [kg/m^3]
River sand (0-4mm)	530 [kg/m^3]
Crushed gravel (4-8mm)	530 [kg/m^3]
Crushed gravel (8-16mm)	706 [kg/m^3]
Superplasticizer Glenium ACE 30	11.44 [l/m^3]
Water	140 [l/m^3]

The concrete characteristics are: the fresh state density ρ = 2458 kg/m^3, the water/cement ratio A/C=0.269, the water/binder ratio A/B=0.245. The physical-mechanical characteristics of the high strength concrete were determined on cube and prisms specimens, cast in the same batch as the reinforced elements, as followed: the medium compressive strength f_{cm} = 93.94 MPa, the medium flexural tensile strength $f_{ct,fl}$ = 9.596 MPa, and the medium splitting tensile strength $f_{ct,sp}$ = 6.951 MPa. The secant elasticity modulus was also determined: E_{cm} = 46905 MPa.

The specimens used in this study are one point loading, simply supported reinforced concrete beams, as showed in Fig. 1.

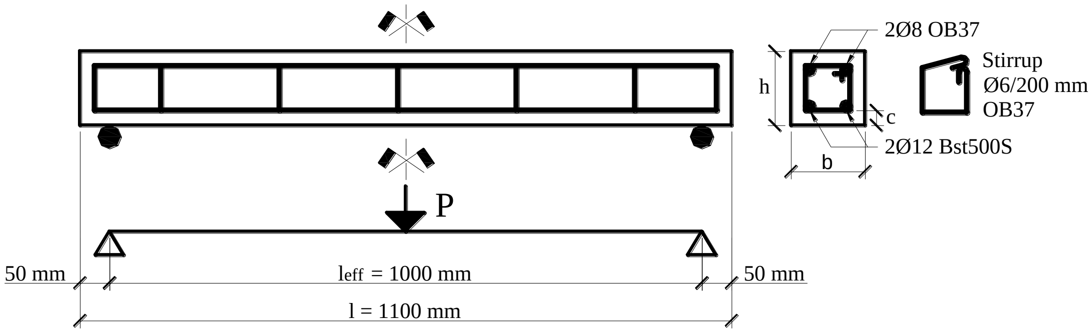

Figure 1. Reinforcement detailing and set-up test

Two types of reinforcement were used: Bst500S for the tensile reinforcement with f_{yk}=500 MPa and OB37 for the upper bars and for the transverse reinforcement, with f_{yk}=255 MPa. The strains were measured at midspan using digital (B, C, D and E) and mechanical (A) strain gauges with 0.001 mm precision and the vertical deformations were measured with a mechanical gauge with precision of 0.01 mm. The cracking pattern was monitored with optical instruments (precision 0.1 mm) (Fig.2).

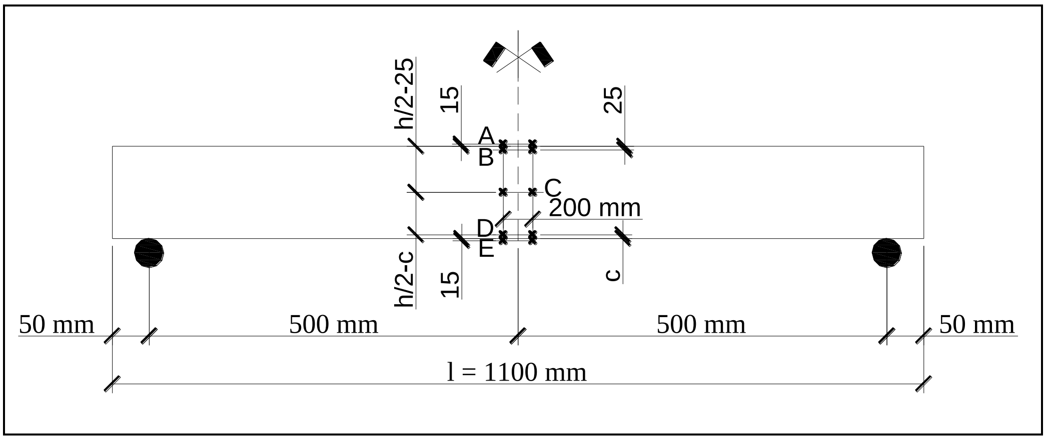

Figure 2. Placement of the measurement devices

The beams were different in concrete cover and cross-section, but with equal theoretical bending capacity, as described in Table 2.

Table 2. Description of the specimens

Element ID	**Cross section dimensions [mm]**	**Concrete cover [mm]**	**Type of the elements**	**Description of the set-up test**
GDA 1-1	125x125	25	“a”	Non exposed elements, tested to failure
GDA 1-2	125x125	25		
GDA 2-2	125x150	50		
GDS 1-1	125x125	25	“b”	Pre-cracked to a service limit state, exposed to accelerated corrosion, and then tested to failure
GDS 1-2	125x125	25		
GDS 2-2	125x150	50		

The set-up test for the accelerated corrosion is similar to other research [7]. A schematic view of the set-up test and a picture of the corrosion equipment are presented in Fig. 3.a, and 3.b.

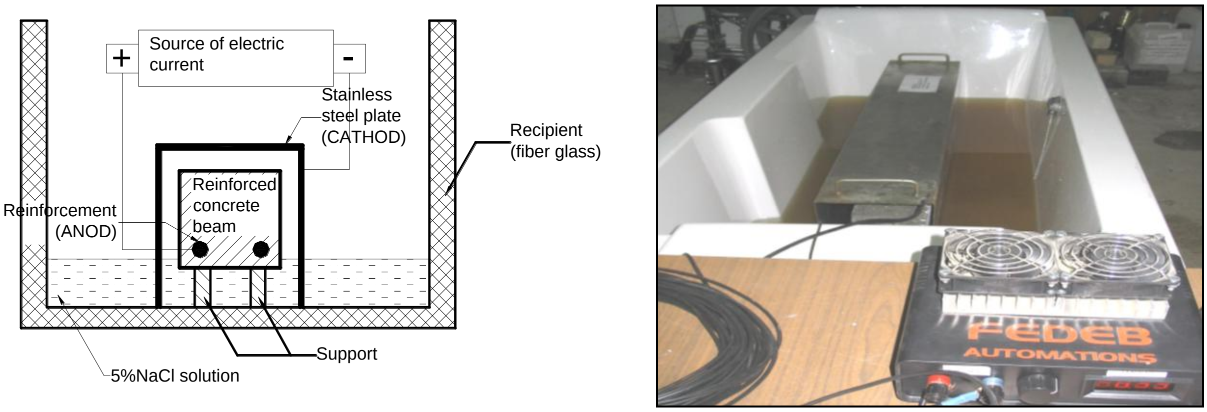

Figure 3. a. Schematic view of the corrosion process; b. Corrosion equipment

The circuit of the electric current generated by an external source consisted in anode (the embedded reinforcement), the cathode (a stainless steel plate covering 3 faces of the element) and the electrolyte, a 5% NaCl solution. The intensity of the current was set to 3 mA/cm^2 and the elements were exposed for 7 days.

3. Results and discussions

Some visual aspects after 7 days of induced corrosion are presented in Fig. 4.

Figure 4. a. GDS 1-1 (top left); b. GDS 1-2 (top right); c. GDS 1-2 (bottom)

Although the color of the electrolyte became brown-red as soon as the corrosion process started, as an indisputable sign of the corrosion products, which were also present on the surface of the elements, after testing, the reinforcement was removed and inspected. The conclusion was that

mainly the transverse reinforcement was affected and destroyed in the process, the longitudinal tensile reinforcement showing insignificant signs of corrosion or loss of section.
The service life analysis was performed when the maximum crack width reached 0.1 mm. A comparison between the beams with the concrete cover of 25 mm and those with 50 mm was made, considering the exposure to corrosion, in terms of bending moment M (Fig.5), level of loading M/Mu (Fig.6) and vertical deformation at mid-span (Fig.7). The ultimate bending moment is presented in Fig.8.

Although the beams were designed to have the same bending behavior, the experimental results show that, when reaching a 0.1 mm crack width, the bending moment for one of the type “a” beams GDA1-2 (non-exposed, 25 mm concrete cover) represents 45% of the other GDA1-1, possibly due to casting irregularities (Fig.5). However, GDA2-2, also a type “a” beam, but with 50 mm concrete cover, shows a minor difference of 5% from GDA1-1, in terms of the bending moment, but at this level of loading, it displays the least number of cracks, only one exactly, compared to GDA1-1 with 3 cracks and GDA1-2 with 4 cracks. With this in mind, higher concrete covers could affect negatively the overall bending behavior of small concrete beams, as a plastic hinge could form in the very few in number tensile cracks in the bending area sooner than expected.

GDS 1-1 and GDS 1-2, pre-cracked beams exposed to corrosion, and then tested again, with 25 mm concrete cover, show a difference of 17% between them, displaying 4 and 7 cracks at this level. GDS 2-2, pre-cracked beam exposed to corrosion, and then tested again, with 50 mm concrete cover, reaches a crack width of 0.1 mm at 4.425 kNm, representing 63% of GDS 1-2, with 3 cracks along the longitudinal surface (Fig.5). Again, the concrete cover negatively affects the number of cracks, which could lead to broader deformations.

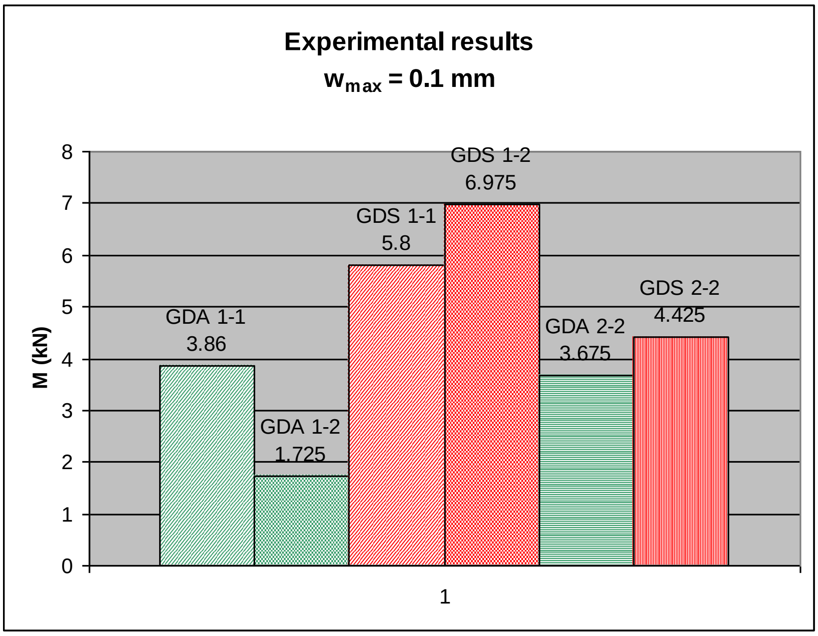

Figure 5. Experimental bending moment at w_{max} = 0.1mm

Furthermore, the corrosion process does not affect the bending behavior at this level of loading, as non exposed, 25 mm concrete cover beams registered an average bending moment with 56% less than the corroded beams, whereas at 50 mm concrete cover, the difference was 17%. During the corrosion process the previous cracks were filled with corrosion products and cement based mortar, due to the non-hydrated cement particles in the concrete composition, which were activated at the first contact of the electrolyte. The phenomenon was also seen when the intensity of the electric current in the 7 day corrosion exposure significantly dropped, as the salt bridge was no longer able to reach the reinforcement and close the electrolytic process. A crack width of 0.1 mm was therefore noted later, at higher levels of loading, for pre-cracked compared to non-exposed beams. Fig.6 describes the level of loading at which w_{max}=0.1 mm was reached compared to the ultimate experimental bending moment. GDA1-1 and GDA1-2, the non-exposed 25 mm concrete cover beams recorded the 0.1 mm crack width at an average of 18% of the ultimate bending moment Mu. In contrast, GDS1-1 and GDS1-2 recorded the same crack at 42%. Considering that GDS1-1 and GDS1-2 have by 6% smaller ultimate bending moments than GDA1-1 and GDA1-2, as seen in fig.8, a clear conclusion that the corrosion severely affects or does not affect at all the service life of high strength reinforced concrete elements cannot be drawn from this study. An explanation for this may lie in the presence of the stirrup, which were diminished by the corrosion, removing the danger from the longitudinal tensile reinforcement. In elements subjected to shear force, however, the stirrup, if affected, may lead to brittle, unwarned failures. In any case, further periods of exposure are considered in future studies to increase the exposure time for bending reinforcement.

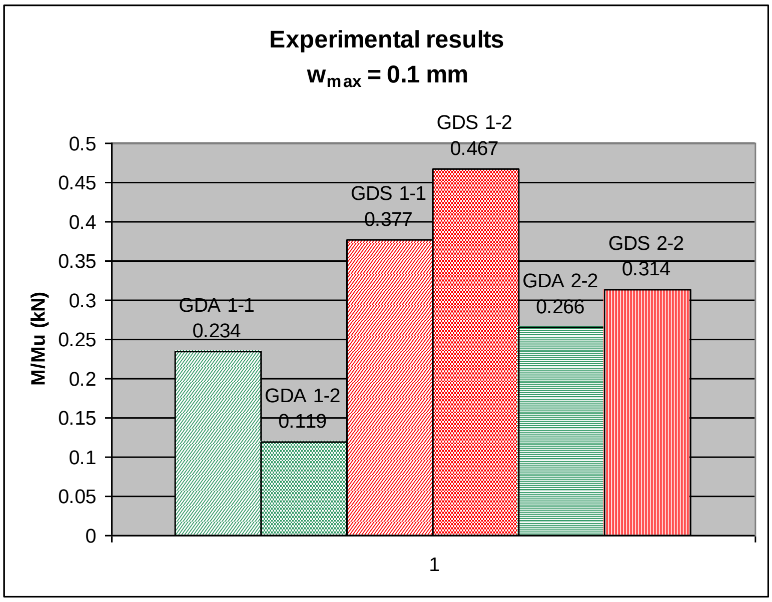

Figure 6. Experimental bending moment at w_{max} = 0.1mm / ultimate moment

The vertical deformations at midspan at the same level of loading are presented in fig.7. A conventional deflection is usually considered at service life, l_{eff} / 250. It can be seen that, even the weakest element with the higher deformations GDS1-2, is under l_{eff} / 500, showing a very good behavior in service.

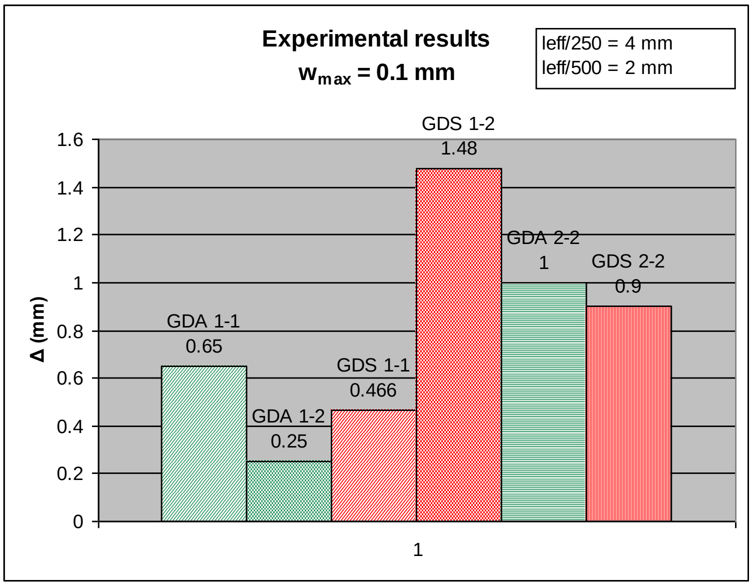

Figure 7. Experimental vertical deformations at w_{max} = 0.1mm

The average ultimate bending moment of the corroded elements represents 94% of the non-exposed elements with both concrete cover of 25 mm and 50 mm. The overall bending capacity of the elements is not significantly influenced by the corrosion process (Fig.8). The elements with 50 mm concrete covers displayed smaller ultimate bending moments, with up to 5% compared to the average bending moment calculated on 25 mm beams with and without corrosion exposure. They also displayed fewer bending cracks than their 25 mm counterparts.

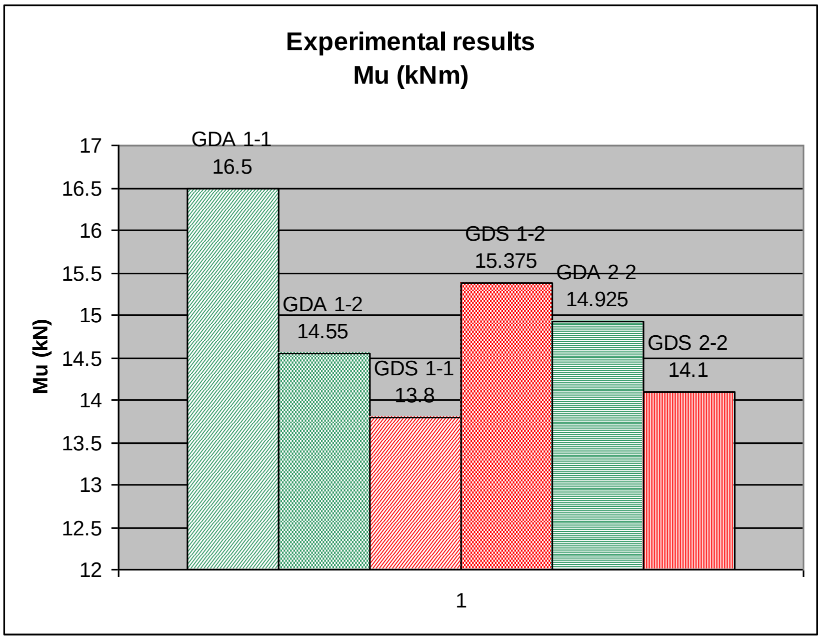

Figure 8. Experimental ultimate bending moments

4. Conclusions

The study was focused on the assessment of the structural response of reinforced high strength concrete elements, with 25 mm and 50 mm concrete covers, pre-cracked and subjected to accelerated artificial corrosion. The analysis was performed at a certain level of loading corresponding to a crack width of 0.1 mm, which is usually met in Eurocode 2 recommendations for aggressive exposure classes. The elements were assessed in terms of bending moment, bending moment over ultimate bending moment, and vertical deformations at midspan. It was found that the 7 day accelerated corrosion did not significantly affect the bending behavior of the beams. The ultimate bending capacity of the corroded elements dropped 6% compared to the non-exposed elements. This behavior is linked to the presence of the transverse reinforcement, which acts as protection for the bending bars, in spite of the presence of cracks that favor the intake and the propagation of the corrosion and to the composition of high strength concrete, which holds a residual hydration potential, with non-hydrated cement particles activating at the contact with the electrolyte from the corrosion process. However, these hypotheses need more study and proof and will be the focus point of future research.

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