Corrosion Science 77 (2013) 308–321

Contents lists available at ScienceDirect

Corrosion Science

journal homepage: www.elsevier.com/locate/corsci

Experimental investigation of the relation between damage at the concrete-steel interface and initiation of reinforcement corrosion in plain and fibre reinforced concrete

A. Michel [a,c,*], A.O.S. Solgaard [a,b], B.J. Pease [a], M.R. Geiker [a,c], H. Stang [a], J.F. Olesen [a]

[a] Department of Civil Engineering, Technical University of Denmark (DTU), Kgs. Lyngby, Denmark
[b] COWI A/S Denmark, Kgs. Lyngby, Denmark
[c] Department of Structural Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway

ARTICLE INFO

Article history:
Received 7 January 2013
Accepted 22 August 2013
Available online 2 September 2013

Keywords:
A. Steel reinforced concrete
C. Atmospheric corrosion

ABSTRACT

Cracks in covering concrete are known to hasten initiation of steel corrosion in reinforced concrete structures. To minimise the impact of cracks on the deterioration of reinforced concrete structures, current approaches in (inter)national design codes often limit the concrete surface crack width. Recent investigations however, indicate that the concrete-reinforcement interfacial condition is a more fundamental criterion related to reinforcement corrosion. This work investigates the relation between macroscopic damage at the concrete-steel interface and corrosion initiation of reinforcement embedded in plain and fibre reinforced concrete. Comparisons of experimental and numerical results indicate a strong correlation between corrosion initiation and interfacial condition.

1. Introduction

Concrete reinforced with steel bars is nowadays the most used manmade construction material in the world. Embedding steel in concrete has several advantages and helps to overcome shortcomings of both materials. Concrete has a high compressive strength, but a low tensile strength and is therefore reinforced for structural purposes, while the steel is protected by the concrete from potentially harmful environmental exposure. Usually, the reinforcement in uncracked concrete is protected due to the high alkalinity (pH around 13) [1] and the concrete cover as a physical barrier itself against the ingress of corrosion initiating substances, such as water, chloride ions, carbon dioxide and oxygen. In the case of uncracked and uncontaminated concrete, the quality and thickness of the concrete cover are the most influential factors for reinforcement corrosion. In practice however, cracks can be found in nearly all reinforced concrete structures originating from hygral or thermal shrinkage and/or mechanical loading.

Within the past decades, numerous investigations on the impact cracks have on the ingress of corrosion initiating substances and reinforcement corrosion have generally concluded that cracks facilitate rapid ingress [2–9] and subsequently reduce the time to corrosion initiation. Both laboratory studies [10–15] and in situ observations [16–20] have noted an expedited corrosion initiation in cracked concrete compared to pristine concrete. Commonly used approaches, see e.g. [10,11,13–17,19,20], attempt to relate corrosion initiation and propagation to the concrete surface crack width. Thus, controlling concrete surface crack widths has become the norm to attempt to minimise the impact of cracks on corrosion-induced deterioration in structural design codes and recommendations [21–27]. Various probabilistic, empirical, and quasi-analytical cracking models are utilised in these structural design codes to predict crack widths based upon numerous geometric and stress (or strain) parameters. However, predicted and observed crack widths can vary significantly [28]. Further, a number of studies (both from laboratory and in situ observations) indicate that the concrete surface crack width alone cannot accurately assess the impact of cracks on reinforcement corrosion as other factors, such as concrete cover thickness [13,17], concrete composition (in particular water-to-cement ratio [11,13,29–31] and addition of supplementary cementitious materials [10,32,33]), stress level in the reinforcement [34], and crack orientation [35] alter the influence of the crack width on reinforcement corrosion.

One possible explanation for the lacking relationship between concrete surface crack width and reinforcement corrosion behaviour is that the surface crack width alone does not reliably describe the condition of the concrete-reinforcement interface [36,37]. The condition of the concrete-reinforcement interface appears to be a more fundamental criterion than the concrete surface crack width influencing the corrosion protection ordinarily provided by

* Corresponding author at: Department of Civil Engineering, Technical University of Denmark (DTU), Kgs. Lyngby, Denmark. Tel.: +45 4525 1656; fax: +45 4588 3282.
E-mail address: almic@byg.dtu.dk (A. Michel).
URL: http://www.dtu.dk (A. Michel).

0010-938X/$ - see front matter
http://dx.doi.org/10.1016/j.corsci.2013.08.019

concrete. Several references report accelerated corrosion initiation and relatively excessive cross-sectional reductions (compared to reinforcement with good cohesion with concrete) take place at sites of various interfacial defects, including entrapped or cast-in voids [38–41], casting joints [42], spalled concrete [20], and interfacial slip and separation caused by mechanical loading [43]. Results of experimental studies indicate that such interfacial defects at the concrete-reinforcement interface reduce the critical chloride threshold for corrosion initiation, see e.g. [38,41]. This, coupled with the increased ingress of corrosion-initiating substances associated with concrete cracks described above, clearly illustrates the potential deleterious impact of concrete cracks on reinforced concrete structures.

The main focus of this study was to test the hypothesis that controlling the concrete-reinforcement interfacial condition can be used as a single indicator for the impact of cracks on the risk of corrosion initiation along the reinforcement. The relation between interfacial damage and risk of corrosion initiation along the reinforcement was investigated for plain (PC) and steel fibre reinforced concrete (SFRC) beams subjected to flexural loading. A numerical model, developed and calibrated using specimens with similar geometries and identical materials, provided estimates on the extent of interfacial damage for the applied loads and measured surface crack widths. The impact of concrete cover thickness, concrete composition, stress level in the reinforcement and crack orientation on the mechanical response of the beam, i.e. cracking and interfacial damage was directly accounted for in the numerical model. Location- and time-dependent corrosion measurements along the reinforcement were performed using recently developed "instrumented rebars", which have a largely similar mechanical behaviour as conventional reinforcement [43]. For each beam, the open circuit corrosion potential (OCP) was measured at 17 locations and the macrocell current at 8 locations along the instrumented rebar. Comparisons of the cracking behaviour in [43] indicated the formation of interfacial damage due to flexural loading, i.e. slip and separation between the concrete and steel, is very similar for the conventional and instrumented rebar. Therefore, the instrumented rebar is a useful tool to investigate a potential link between mechanically-induced concrete-reinforcement interfacial damage and the corrosion response of the reinforcement. However, it should be mentioned that a practical application of instrumented rebars may be difficult due to the intensive monitoring equipment required for continuous OCP and macrocell current measurements. Nevertheless, previous results [36,43] and results of the present study indicate that instrumented rebars are suitable for laboratory investigations to study the effect of load-induced damage on reinforcement corrosion and to strengthen the hypothesis that load-induced interfacial damage can be used as an indicator for the risk of reinforcement corrosion.

2. Experimental investigations

To investigate the impact of cracks and the associated interfacial damage between concrete and reinforcement on the initiation of corrosion, reinforced concrete specimens were prepared, cracked, and tested in a corrosive environment. Experimental studies included mechanical and electrochemical testing as well as destructive visual investigation of plain (PC) and steel fibre reinforced (SFRC) specimens. During mechanical testing, photogrammetric investigations were performed to monitor load-induced cracking, slip, and separation between concrete and reinforcement. In addition, fracture mechanical properties of the different concrete compositions were determined using inverse analysis of experimental results obtained from three point bending tests (3PBT) as described in [44]. The 3PBTs were conducted in accordance with [45,46]. Electrochemical testing included time- and location-dependent OCP and macrocell current measurements with so-called instrumented rebars, which were embedded in each of the tested specimens along with a conventional rebar. The test matrix for the various experimental investigations is given in Table 1, including information on the naming convention and numbers of tested specimens. For each concrete composition, three specimens (MSF) were tested to determine fracture mechanical properties by inverse analysis of 3PBT results. Results of individual specimens of one concrete composition were then averaged. Four specimens (MSA) were tested for each concrete composition, i.e. two different concrete cover thicknesses (20 and 60 mm), to investigate load-induced cracking and associated interfacial damage by means of photogrammetry and subsequent digital image correlation. However, for simplicity, only results of specimens with a concrete cover thickness of 60 mm are presented in this study. Finally, one specimen (ESE) was tested for each concrete composition to study the influence of cracking and interfacial damage on the initiation of reinforcement corrosion using instrumented rebars, which allow for continuous OCP and macrocell current measurements. After termination of electrochemical testing, the electrochemical test specimens (ESE) were used for destructive visual investigations.

2.1. Materials and specimen preparation

Beams of plain (PC) and steel fibre reinforced concrete (SFRC) with a water-to-cement ratio of 0.43 were cast. Aalborg Rapid® Portland cement (type 52.5N cement [47]) was used and the mix designs for the different concrete compositions are given in Table 2. DRAMIX 65/35 fibres (hooked ended and made from cold drawn black steel) were used for the SFRC mixes with a length of 35 mm and diameter of 0.55 mm. As reinforcement, two rebars with 12 mm diameter, i.e. one conventional rebar and one instrumented rebar (described in Section 2.2), were embedded in each of the $290 \times 310 \times 650\ mm^3$ (height × width × length) prisms. The steel fibre reinforced beams were cast in oversize to avoid fibre orientation caused by the sides of the moulds. After casting, the beams were stored for 24 h in laboratory conditions under a plastic sheet (i.e. 20 ± 2 °C) and then demolded. Upon demoulding, the beams were stored in lime rich water for additional 28 days at 20 ± 2 °C until testing. Prior to cracking and testing, the SFRC beams were cut using a water-cooled concrete saw. Unreinforced MSF beams, i.e. specimens used for the determination of fracture mechanical properties, were cut to $150 \times 150 \times 650\ mm^3$ in accordance with the size recommended in [45]. Specimens used for photogrammetric investigations (MSA) were cut to $150 \times 120 \times 650\ mm^3$, where part of the concrete covering the reinforcement was removed to allow for monitoring of load-induced cracking and interfacial damage. However, a minute concrete cover remained (approximately 3–5 mm) to, among others, avoid damaging the concrete-reinforcement interface during the cutting process. Finally, a stochastic black and white speckle pattern was applied to the remaining concrete cover, which was used later for photogrammetric investigations. The final dimensions of the ESE beams, i.e. specimens used for electrochemical testing, were $190 \times 150 \times 650\ mm^3$ with 60 mm

Table 1
Test matrix for experimental investigations.

Experimental investigation	Concrete composition		
	PC	SFRC	
	Fibre content (vol.%)		
	0.0	0.5	1.0
Fracture mechanical properties	MSF 1-3	MSF 4-6	MSF 7-9
Photogrammetric investigations	MSA 1-4	MSA 5-8	MSA 9-12
Electrochemical testing	ESE 1	ESE 2	ESE 3