Engineering Structures 163 (2018) 409–425

Contents lists available at ScienceDirect

Engineering Structures

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

The effect of fibres on steel bar corrosion and flexural behaviour of corroded RC beams

Carlos G. Berrocal[a,b,*], Ingemar Löfgren[a,b], Karin Lundgren[a]

[a] Chalmers University of Technology, Division of Structural Engineering, Göteborg SE-41296, Sweden
[b] Thomas Concrete Group AB, Södra Vägen 28, Göteborg 41254, Sweden

ARTICLE INFO

Keywords:
Corrosion
Cracking
Fiber reinforced concrete
Rotation capacity
Crack width

ABSTRACT

This paper reports the results of an experimental programme aimed at investigating the influence of fibre reinforcement on the corrosion process of conventional steel rebar embedded in cracked concrete and on the flexural behaviour of reinforced concrete beams. Un- and pre-cracked reinforced concrete beams were subjected to natural corrosion through cyclic exposure to a 10% chloride solution for a period of three years. Subsequently, flexural tests were carried out under three-point bending configuration. Gravimetric measurements showed higher corrosion levels for bars in plain concrete compared to fibre reinforced concrete, and visual inspection of the bars revealed that fibres promoted a more distributed corrosion pattern. From detailed examination of the bars through 3D laser scanning technique, the main parameter controlling the local corrosion level of individual pits appears to be the local interfacial conditions; grater loads during pre-cracking and repeated load cycles yielded greater cross-sectional losses. Moreover, there was a tendency for more localized corrosion in beams with open cracks, indicating a possible impact of crack width on the extension of corrosion. The results from the flexural tests showed a consistent increase of load capacity for fibre reinforced beams compared to their plain concrete counterparts but only a marginal influence of the fibres on the rotation capacity. Furthermore, the rotation capacity of the beams was found to decrease several times faster than the load capacity with increasing loss of rebar cross-sectional area.

1. Introduction

Degradation of reinforced concrete (RC) due to corrosion of reinforcement is a widespread problem that today affects structures worldwide. The most common causes of reinforcement corrosion are the loss of alkalinity in the concrete cover due to carbonation and the local break-down of the steel passive layer due to the ingress of chloride ions [1]. In uncracked concrete, the corrosion process is governed by the depth and quality of the concrete cover [2]. However, cracks are inherently present in most RC members due to e.g. mechanical loading, temperature gradients, shrinkage, etc. Such cracks are known to have a negative impact on reinforcement corrosion as they provide a preferential path for external agents to penetrate into the concrete [3]. Although general agreement exists that corrosion of reinforcement initiates earlier for larger crack widths [4–6], the role of crack width during the corrosion propagation phase has been a subject of debate among researchers. A correlation between crack width and corrosion rate has been reported in several experimental studies [7–9], whereas others have claimed that such correlation may be only observed in the short term, provided cracks are not excessively large [10–13].

Even though the importance of the crack width on reinforcement corrosion is not completely clear yet, current codes, e.g. Eurocode 2 or ACI 318-14 [14,15], dictate minimum cover depth requirements and crack width limitations as a way to minimize corrosion of reinforcement. The imposition of those requirements on civil engineering structures exposed to marine environment or de-icing salts, e.g. harbour piers or bridges, is often very restrictive, leading to congested reinforcement layouts that cause difficulties in production. In such cases, the use of fibre reinforced concrete (FRC) in combination with conventional rebar could be of special interest for crack control purposes. Indeed, over the past years, the influence of fibre reinforcement on the mechanical response of conventionally reinforced concrete members has been extensively investigated [16–23]. As a result, today it is widely accepted that incorporating fibres into RC elements results in an improved mechanical performance in terms of increased load capacity and tension-stiffening, enhanced bond behaviour and particularly with regard to crack control. However, experimental investigations on both tensile [24] and flexural [19] members, have reported that combining fibres and conventional reinforcement may lead to a reduction of the deformation capacity.

---

* Corresponding author at: Chalmers University of Technology, Division of Structural Engineering, Göteborg SE-41296, Sweden.
E-mail address: carlos.gil@chalmers.se (C.G. Berrocal).

https://doi.org/10.1016/j.engstruct.2018.02.068
Received 30 May 2017; Received in revised form 29 November 2017; Accepted 21 February 2018
0141-0296/

Furthermore, it has been shown that steel fibres embedded in concrete possess a much higher corrosion resistance compared to conventional rebar [25–29]. Although the use of fibres is currently limited to a number of applications, such as industrial floors, slabs on grade, precast tunnel linings, sprayed concrete or thin shells, the incorporation of design rules for FRC in recently released structural codes, e.g. [30], could lead to a more generalised deployment of FRC in a broader range of structural applications. However, for the usage of fibres to be viable in RC structures exposed to chloride environments, a sound understanding of how the fibres may influence the corrosion process of conventional rebar in concrete is needed.

Several researchers have shown that using FRC can be advantageous to delay the initiation of reinforcement corrosion in cracked concrete elements [31–33]. In a previous work by the authors, it was observed that fibres could contribute to a delayed corrosion initiation even for RC elements featuring the same surface crack width [34]. Several studies have also reported a beneficial effect of the fibres on the corrosion rate. However, those studies used either uncracked concrete specimens [35–39], artificially accelerated corrosion through impressed current [40] [37,41,42], high fibre contents (>1.5 vol%) leading to pseudo-strain hardening behaviour [32,35,42,43] or reduced exposure times (<1 year) [32,33,35]. Moreover, the surface crack width is not the only crack feature affected by the addition of fibres. The crack spacing, the internal crack morphology and the degradation of the steel-concrete interface, all of them parameters which have been suggested to have a more important influence on the corrosion rate than surface crack width [3,11,44–47], can be also altered due to the presence of fibres [16,48,49].

This paper presents the results of an investigation aimed at determining whether the use of low fibre contents (<1 vol%) may influence the corrosion process of reinforcing steel bars embedded in concrete. Experiments were carried out on uncracked and cracked RC beams with varying fibre reinforcement, subjected to different loading conditions and exposed to cyclic immersion in chloride solution for a period of three years. The corrosion rate was monitored during the exposure period using a device based on the galvanostatic pulse technique and the results were later compared to corrosion levels determined at the end of the experiments by means of gravimetric measurements. The corrosion patterns were also documented and local corrosion levels at critical pits were examined using a 3D laser scanning technique. Furthermore, the effect of corrosion and fibre reinforcement on the flexural performance of the beams, i.e. the load and deformation capacity, was assessed through quasi-static three-point bending tests carried out after the corrosion experiments.

2. Description of experiments

The present study had two main objectives. The first objective was to investigate whether fibre reinforcement, at low dosages, might influence the corrosion process of steel rebar embedded in uncracked and cracked RC beams subjected to different loading conditions. The second objective was to experimentally assess the contribution of fibre reinforcement on the structural performance of the RC beams after corrosion of the conventional reinforcement had occurred. A general description of the experiments is provided in this section. For a thorough description and motivation of the different parameters chosen in this investigation the reader is referred to the following report [50].

A total of 54 beam specimens were cast. Six of the beams were kept uncracked and stored in potable water to be used as reference samples, while the remaining beams were subjected to different loading conditions and subsequently exposed to chlorides. The four conditions considered were: (a) uncracked specimens, which were never loaded; (b) specimens that were loaded only once to induce cracking; (c) specimens subjected to five load cycles to promote greater damage at the rebar-concrete interface; and (d) specimens initially pre-cracked and subsequently reloaded with a sustained load to keep cracks open. The beams, when referring to their loading conditions, are denoted throughout the paper as *uncracked*, *unloaded*, *cyclic* and *loaded*.

Table 1
Summary of experimental programme.

Load conditions			Series[a]	Target crack widths	Number of beams
Reference beams stored in potable water					
Uncracked			PL	–	3
			ST	–	3
Corroded beams exposed to cyclic immersion in chloride solution					
Uncracked			PL	–	3
			ST	–	3
			HY	–	3
			SY	–	3
Cracked	Unloaded	1 cycle	PL	0.1, 0.2, 0.3, 0.4	4
			ST	0.1, 0.2, 0.3, 0.4	4
			HY	0.1, 0.2, 0.3, 0.4	4
			SY	0.1, 0.2, 0.3, 0.4	4
		5 cycles	PL	0.1, 0.2, 0.3, 0.4	4
			ST	0.1, 0.2, 0.3, 0.4	4
			HY	0.1, 0.2, 0.3, 0.4	4
	Loaded		PL	0.1, 0.2, 0.3, 0.4	4
			ST	0.1, 0.2, 0.3, 0.4	4

[a] PL = Plain, ST = Steel, HY = Hybrid, SY = Synthetic.

Moreover, four different series of specimens were used, one without fibre reinforcement referred to as plain (PL) series and three FRC series with different types of fibre reinforcement, referred to as steel (ST), hybrid (HY) and synthetic (SY) series. In addition, crack widths ranging from 0.1 to 0.4 mm were investigated. However, only results from the beams exhibiting intermediate crack width, i.e. 0.2 and 0.3 mm, are presented here; thus, results from 32 beams are reported in this paper. The remaining beams were kept to characterize the relationship between the geometry of corrosion pits and the mechanical properties of individual rebars. A summary of the experimental programme is shown in Table 1 whereas the notation used to refer to individual specimen results is presented in Fig. 1.

2.1. Materials, mix composition and characterisation tests

A self-compacting concrete mix with a water cement ratio (w/c) of 0.47 was used for all the series in the present study. The concrete mix proportions are presented in Table 2. Fibre reinforcement was introduced in the mix design by replacing the corresponding aggregate volume fraction. The type of fibres used in the different series were: 35 mm end-hooked steel fibres for the steel series; 30 mm straight PolyVinyl Alcohol (PVA) fibres for the synthetic series; and a combination of steel fibres and 18 mm long PVA fibres for the hybrid series. The main characteristics of the different fibres used in the study are summarized in Table 3.

As for the main reinforcement, reinforcing bars made of B500B steel grade were used, which is defined in the Eurocode 2 [14] as normal ductility steel. The average values of the yield stress, ultimate strength, ultimate strain and elastic modulus, obtained through tensile tests, were $f_y = 546$ MPa, $f_u = 626$ MPa, $\varepsilon_u = 12\%$ and $E_s = 204$ GPa, respectively. No surface treatment was applied to the steel bars prior to casting.

The mechanical properties of the different mixes were assessed both before and after the corrosion tests. Compressive strength tests were carried out according to [51] on 150 mm cubes at 28 days and on Ø100 × 100 mm core cylinders after 3.6 years. Note that according to EN 13791:2007 [52], both specimen geometries give an equivalent compressive strength. Additionally, the flexural strength of the fibre reinforced concrete mixes was assessed through three-point bending tests on 150 × 150 × 550 mm beams according to [53] at 20 weeks and 3.6 years. Furthermore, two series of wedge splitting tests in accordance to [54] were carried out on 150 mm cubes after 3.6 years of being stored in either potable water or 10% chloride solution, to assess the