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Corrosion of the reinforcement and its influence on the residual structural performance of a 26-year-old corroded RC beam

Wenjun Zhu, Raoul François *

Université de Toulouse, UPS, INSA, L.M.D.C. (Laboratoire Matériaux et Durabilité des Constructions), Toulouse, France

HIGHLIGHTS

- We have tested in 3-points bending, two 27 old beams: one corroded and one control.
- Corrosion results of natural process and then corresponds to in situ conditions.
- The loss of ductility of corroded beam is a major phenomena.
- Ultimate elongation of steel bar is highly reduced by corrosion.

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ABSTRACT

This paper presents the reinforcement corrosion process and the results of experiments on a highly corroded beam subjected to a chloride environment for 26 years so as to assess the residual performance of long-term-corrosion-damaged beams. A cracking map was drawn for the corroded beam, which was then tested by a three-point loading system until failure, as was a control beam of the same age. Force displacement curves were recorded for both beams. The corrosion distribution and loss of diameter of the steel bars were studied for the reinforcement. Tension tests of the tensile bars were carried out, and stress strain curves of the tension experiments were also plotted. From the results, it appears that corrosion has a significant impact on the reinforcing bar behavior, and on the load-bearing capacity, stiffness and deflection of the beam.

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1. Introduction

The corrosion of reinforcement induced by the presence of chloride ions in concrete is considered to be one of the most common reasons for the deterioration of reinforced concrete (RC). During the last few decades, a considerable amount of research has been conducted on the corrosion of concrete beams [1–6]. In the corrosion process, the steel is transformed into rust, which leads to: (1) reduction of the cross-section of the reinforcing bars; (2) loss of the bond between bars and concrete; (3) volume expansion which can generate splitting stress in the concrete near the rust, resulting in cracking and spalling of the concrete cover [7,8], and (4) change in ductile properties of steel bars.

Hanjari et al. [9] have described the effect of corrosion on the behavior of RC structures by analyzing the causes and mechanisms of the reinforcement corrosion. In the same way, Stewart [10] has studied the mechanical effects of pitting corrosion, including on flexural and shear reinforcement, which can significantly affect the mechanical behavior and ductility, while greater corrosion loss can lead to brittle fracture. Nevertheless, relatively less research has been performed to assess the practically important aspect of evaluating the residual structural performance of corroded concrete structures. Torres-Acosta et al. [3] have focused on an experimental investigation of the relationship between the loss of bending capacity and loss of steel cross-section of corroded beams, and reached the conclusion that the maximum pit depth was the most important factor reducing the load bearing capacity of the corroded beams.

But the weak point of most of the corrosion processes used in the research cited above is that they were accelerated either by the application of an impressed current or by including an admixture of $CaCl_2$ in the concrete [11]. Very limited studies dealing with the behavior of naturally corroded structures can be found at this moment. A summary of tests done to assess the residual capacity of corroded beams is shown in Table 1. Almost all studies use impressed current to accelerate corrosion. One main difference between the behavior of RC beams artificially corroded and

* Corresponding author. Tel.: +33 561559901; fax: +33 561559900.
E-mail address: raoul.francois@insa-toulouse.fr (R. François).

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Table 1
Summary of research work done on the mechanical behavior of corroded concrete members.

Authors	Time	Specimen	Environment	Corrosion condition	Loading condition
Tachibana et al. [14]	1990	RC beams		Galvanostatic corrosion	Corrosion prior to loading
Ting et al. [15]	1991	RC Beams		Numerical simulation	
Cairns et al. [16]	1993	RC beams		Simulation of corrosion through reinforcement exposed	
Almusallam et al. [17]	1996	RC slabs		Impressed current	Corrosion prior to loading
Rodriguez et al. [5]	1997	RC beams		Impressed current	Corrosion prior to loading
Mangat et al. [18]	1999	RC beams		Impressed current	Corrosion prior to loading
Castel et al. [19]	2000	RC beams	Chloride environment	Natural corrosion	Simultaneous corrosion and load
Yoon et al. [20]	2000	RC beams		Impressed current	Simultaneous corrosion and load
Capozucca et al. [21]	2003	RC beams		Impressed current	Corrosion prior to loading
Torres-Acosta et al. [22]	2004	RC beams		Impressed current	Simultaneous corrosion and load
El Maaddawy et al. [23]	2005	RC beams		Impressed current	Simultaneous corrosion and load
Du et al. [2]	2007	RC beams		Impressed current	Corrosion prior to loading
Azad et al. [24]	2007	RC beams		Impressed current	Corrosion prior to loading
Torres-Acosta et al. [3]	2007	RC beams		Impressed current	Corrosion prior to loading
Vié D. et al. [25], Petre-Lazar et al. [26]	2007	RC and pre-stressed beams	Chloride environment	Natural corrosion	Corrosion prior to loading
Vidal et al. [27]	2007	RC beams	Chloride environment	Natural corrosion	Simultaneous corrosion and load
Zhang et al. [28]	2009	RC beams	Chloride environment	Natural corrosion	Simultaneous corrosion and load
Malumbela et al. [29]	2009	RC beams		Impressed current	Simultaneous corrosion and load
Ababneh et al. [30]	2011	RC beams	Chloride environment		Loading prior corrosion
Khan et al. [31]	2011	RC beams	Chloride environment	Natural corrosion	Simultaneous corrosion and load
Dang and François [32]	2013	RC beams	Chloride environment	Natural corrosion	Simultaneous corrosion and load

naturally corroded is the ultimate deflection which is not modified in case of artificial corrosion but strongly reduced in case of natural corrosion. The reason can be that artificial corrosion leads to uniform corrosion which is not the case for natural corrosion [12]. Moreover, Otieno et al. [13] and Yuan et al. [12] have concluded that corrosion accelerated in artificial chloride environment such as cycle of wetting–drying is similar to that of corrosion in natural environment. This point is very important since different corrosion characteristics on the surface of steel are the main reasons that cause differences of structural behaviour between methods of inducing corrosion [12].

Corrosion rate is also an important parameter to predict the actual performances of corrosion affected RC structures. Impressed current used in accelerated corrosion study varies [2,3,5,17,18,20–24,29] from 80 $\mu A/cm^2$ to 10,400 $\mu A/cm^2$ leading to different consequences on the corrosion pattern. For natural corrosion, the corrosion rate also varies from one structure and exposure condition to another. Nevertheless, the variation of Icorr [13] is in a limited range from 0.1 $\mu A/cm^2$ to 1–2 $\mu A/cm^2$. Then results obtained from exposition to cyclic wetting and drying with NaCl are closed from natural corrosion [12,33].

With the goal of studying natural corrosion, François et al. [34] have built a long-term program concerning the corrosion of concrete beams stored in a chloride environment under service load in 1984. The corrosion situation is much closer to the conditions affecting real structures than that of accelerated tests. The effect of sustained loading was clearly established in terms not only of the presence of mechanical cracks but also of damage at the interfaces between re-bars and concrete. Nevertheless, the effect of the load intensity was only reported for the short term and was not significant at long term. The effect of load on the corrosion process has also been studied by Yoon et al. [20] and Malumbela et al. [35], whose studies demonstrate not only the influence of the load but also an effect of the load level. In their tests, the control beams failed by steel bars yielding followed by crushing of concrete as expected. Nevertheless, it was quite surprising that all corroded beams failed also by yielding of steel bars following by concrete crushing. These results seem to indicate that impressed electrical current used in the experimental process has led to generalized corrosion. This does not allow putting in evidence the loss of ductility due to corrosion pits which appears with natural corrosion process.

The aim of this paper is to present the effect of chloride corrosion on the reinforcement bars and the influence of corrosion on the residual mechanical performance of a corroded beam B2Cl2 at the age of 26 years by loading it in a three-point loading system until failure. The same mechanical test was carried out on a control beam B2T2. The main interest is that the corrosion results from a natural process (no impressed current) over a long period of propagation since corrosion was initiated after 6 years of aging in the chloride environment [27]. One objective of the paper is also to extend the experimental data base concerning the residual mechanical behavior of corroded RC members, to promote the validation of future mechanical models and reduced uncertainties due to numerical simulations.

2. Experimental context

This program of long-term corrosion experiments has been in progress since 1984 at Laboratoire Matériaux et Durabilité des Constructions (L.M.D.C.) in Toulouse, in southwestern France. The aim was to further identify the steel corrosion process in the concrete beams and the influence of corrosion on the mechanical performance.

In this program, 36 reinforced concrete beams were cast with dimensions of $300 \times 28 \times 15$ cm. They were divided into Group A and Group B by the different depth of the concrete cover and the diameter of the steel bars, then stored in a chloride environment under service load in order to consider the influence of flexural effects. Another 36 beams were cast with the same composition and layout of the

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