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Prediction of ductility factor of corroded reinforced concrete beams exposed to long term aging in chloride environment

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ABSTRACT

An experimental study using a three-point bending test on RC beams with dimensions of $150 \times 280 \times 3000$ mm, naturally corroded over many years was conducted to evaluate the influence of steel corrosion on structural performance and, in particular, to better understand the change in ultimate deflection in bending and then in ductility. Some previous works by different authors are also discussed. The results show that the conventional ductility factor hardly applies to the assessment of ductile behaviour of corroded beams. A new ductility factor, based on the ratio between ultimate deflection of corroded and non-corroded beams, is proposed. In addition, the relation between ductility factor of corroded beams and cross-section loss in the corroded reinforcing steels was studied on the RC beams tested. The service life of corroded structures appears to be limited by the reduction of ductility in bending behaviour, which is more pronounced on the reduction of load-bearing capacity. This was linked to the change in mechanical properties of corroded steel bars in comparison with non-corroded steel bars.

1. Introduction

Corrosion of the reinforcing steel embedded in concrete is a very serious problem for Reinforced Concrete (RC) structures exposed to a saline environment as the penetration of chloride ions can locally ruin the passive oxide layer existing on the reinforcement surface. Reinforcement corrosion not only reduces the cross-sectional area of the reinforcing steel but may also induce cracking, delamination and/or spalling of the concrete cover, loss of bond strength with surrounding concrete, and deterioration of the anchoring of longitudinal steel bars. All of these factors can act individually or in combination, leading to greater damage. Corrosion-induced damage may also adversely affect the load bearing behaviour of members during their service life. It is very important to have reliable information on both the load bearing capacity and the serviceability of corroded RC beams. The mechanical performance of corroded RC beams has been studied by many authors since the 1970s and this research has contributed significantly to the increase in knowledge of the behaviour of corroded RC structures. Almost all investigations show that corrosion can reduce both the deflection and ultimate strength of RC members and these reductions can lead to premature failure of beams. Nevertheless, there are very limited studies dealing with the behaviour of naturally corroded structure. Almost all studies use impressed current to accelerated corrosion or experimental simulation of corrosion, which lead to a corrosion induced damage different from natural corrosion. Indeed, research performed by Yuan et al. [24], Poursaee and Hansson [27], Otieno et al. [28], have highlighted the discrepancies between corrosion resulting from accelerated corrosion using impressed current and corrosion resulting from climate accelerated conditions which is closed to the one observed during natural process. As a result, artificial corrosion and natural corrosion lead to different ductile response of steel bars [26] and then different response of artificially or naturally corroded RC members. The objective of this paper is then to study the ductility of naturally corroded members and then propose a prediction model of ductility in relation to the corrosion damage. In the next section, the works of several researchers will be presented. The ductility and modes of failure of the beam specimens corroded under loading or without loading will be discussed in detail.

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2. Previous works on the change in ductility of corroded RC beams

2.1. Change in failure mode for corroded RC members

Ductility is the ability of the structures to sustain large deformations and it is necessary for RC beams to provide an early warning of failure. The type of collapse of concrete members is largely dependent on the amount of steel, and the yield stress and ultimate strain it undergoes in tensile zones, because the tensile strength of concrete is very low. Six failure modes can occur, as follows:

- Shear failure taking place before an RC member reaches its flexural load-bearing capacity.
- Anchorage failure occurring before an RC member reaches its flexural load-bearing capacity.
- Concrete crushing in the compression zone before the tension reinforcement yields. This happens if the tensile force capacity of the steel is high (i.e. high ratio of reinforcement), so the steel does not yield at all.
- Steel and concrete yielding simultaneously. If the tensile force capacity of the steel is moderate, yielding of the steel is accompanied by simultaneous crushing of the concrete.
- Steel yielding first and fracturing prematurely, before the compressive concrete reaches the maximum permissible strain of 0.0035. This situation occurs if the tensile strength of the steel is too low.
- Steel yielding first but still maintaining its strength despite its increasing elongation. If the ultimate tensile strength of the steel is low, steel will be yielded before the strain in the concrete at the top fibre reaches the maximum permissible strain of 0.0035. This is the most desirable type of failure because there is plenty of warning before it occurs. In this case, both the materials reach their ultimate load limit state at the same time.

A failure due to shear is always sudden compared to a failure due to flexure. For RC beams with low span-to-depth ratio or inadequate shear reinforcement, the failure mode can be due to shear.

Many researchers have reported a significant change in the flexural behaviour of corroded specimens, which means that the loading capacity and mode of failure are modified in the presence of steel corrosion. Cairns et al. [10] observed that, for almost all specimens with corroded under-reinforcement, the mode of failure was mainly accompanied by flexure, which meant that the ductility was enhanced. For several corroded specimens with a high reinforcement ratio, failure was imputed to slipping between the reinforcement and the concrete, which could result in lower ductility. Almusallam et al. [11] and Rodriguez et al. [13] indicated that the mode of failure of corroded, under-reinforced flexural members was dependent on the magnitude of the reinforcement corrosion. Failure by sudden longitudinal splitting along the steel bars [11] was recorded and was probably caused by failure of the shear bond between the reinforcing steel and the surrounding concrete. The failure in shear of corroded beams [13] was recorded in most cases, which contrasted with the failure in flexure of the corresponding control beams. According to [13], the two main explanations for this behaviour were the significant reduction in stirrup cross-section and a reduction in the effective depth of the concrete section at the shear span. Clearly, corrosion shifts the failure mode from ductile to brittle. For over-reinforced beams, however, corrosion caused a change from brittle to ductile behaviour [8].

In an important experiment that has been running on corroded beams at LMDC since 1984, various authors [3,6,19] have found a change in the bending failure mode of RC beams corroded in a chloride environment, from concrete crushing in the compressive zone of control beams to tensile steel brittle failure at the mid-span of corroded beams. Even though all the beams showed the flexural mode of failure, their ductility varied. The mechanical properties of the corroded steel bars inside beams affected the failure mode of these beams. In other words, the change in corroded steel ductility had a marked influence on the ductility of the beams. It appears that there is a link between the change in bending failure mode and a loss of ductility of the reinforcement steel taken from corroded beams. The studies mentioned do not indicate what this relation is.

2.2. Evaluating the change in ductility of RC corroded beams

The ductility of RC beams is generally measured by a ratio called the ductility factor (μ). The ductility factor is determined as the ratio of rotation (θ), curvature (Φ) or deflection (Δ) at failure to the corresponding property at yield [21], as shown below:

$$\mu = \theta_u/\theta_y; \quad \mu = \Phi_u/\Phi_y; \quad \mu = \Delta_u/\Delta_y \tag{1}$$

The ductility factor is believed to depend on the failure mode. In the present study, the deflection of members will be used as a measure of the ductility factor.

El Maaddawy et al. [5] tested nine RC beams using impressed current to accelerate the corrosion process. One beam was kept as a control beam, 4 beams (group A) were corroded in the absence of loading and 4 beams (group B) were corroded under a sustained load. These beams were under-reinforced ones with 1.24% tension steel. The ductility factors of the control beam and corroded beams are shown in Fig. 1a. It can be seen that the ductility of corroded beams is higher than that of the non-corroded beam irrespective of corrosion level. Interestingly, beams corroded with loading proved to be more ductile than beams corroded without loading, even when steel corrosion was increased to 31%. In El Maaddawy's study, it seems that applying load to beams during the corrosion process significantly affects the ductility of the beam rather than the ratio of tensile reinforcement. Fig. 1b presents the ductility factor of corroded beams extracted from the results of Cairns et al. [10]. With the tension steel percentage less than the percentage of balanced steel, the ductility of beams was improved as the loss of cross-sectional area due to corrosion increased. The authors attributed this to changes in bond stress in the shear span caused by corrosion. However, the rate of ductility increase was different in the two groups. By studying the impact of reinforcement corrosion on the ductile behaviour of RC beams, Du et al. [8], who accelerated the steel corrosion by impressing a direct current on individual sets of bars, concluded that for corroded, over-reinforced beams (balanced reinforcement $\rho_s = 3.1\%$), ductility improved as the corrosion developed. In contrast, the ductility of corroded under-reinforced concrete beams was slightly impaired as shown in Fig. 2a. Torres-Acosta et al. [23], who accelerated corrosion by adding chlorides during casting and impressing an electrical current, tested 10 beams until failure (8 corroded and 2 control beams). The ductility factor resulting from these tests is shown in Fig. 2b and does not indicate a clear ductility trend in relation to the degree of corrosion.

It should be noted that the tests mentioned above used different procedures to accelerate the corrosion process, such as mixing the concrete with chloride then applying a current to the steel bar [5] or partially immersing the samples in sodium chloride solution and then applying a current to reinforcement [8]. Generalized corrosion along the whole steel bar was thus expected to occur in a short time. However, such a corrosion pattern would take tens of years to build up in service structures. If the current density significantly