Construction and Building Materials 127 (2016) 293–305

Contents lists available at ScienceDirect

Construction and Building Materials

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

Investigation of corrosion of steel stirrups in reinforced concrete structures

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HIGHLIGHTS

- A comprehensive experiment on corrosion of steel stirrups in concrete is presented.
- A micromechanical damage model for failure mechanism of corroded stirrups is proposed.
- A model for damage factor of corroded stirrups is derived.
- A hemispherical model for the pit shape is appropriate for corroded steel stirrup.
- A constitutive model for corroded stirrups is developed and verified.

ARTICLE INFO

Article history:
Received 18 May 2015
Received in revised form 29 August 2016
Accepted 28 September 2016

Keywords:
Corrosion
Stirrups
Mechanical behaviour
Micromechanical damage model
Constitutive model

ABSTRACT

Although extensive research on steel corrosion in concrete has been undertaken it is more on longitudinal reinforcing bars than stirrups as suggested in the review of published literature. The effect of corrosion of steel stirrups on structural behaviour can be significant for shear failure mode. This paper aims to investigate the degradation of mechanical behaviour of corroded stirrups. Details of a comprehensive experiment designed to examine the mechanical behaviour of corroded stirrups in concrete structural members are presented. A micromechanical damage model for failure mechanism of corroded stirrups is proposed and a model for damage factor is derived. Based on these models, a constitutive model for corroded stirrups is developed and verified with test results. It is found in the experiment that both the strength and ductility of corroded stirrups decrease with the increase of corrosion and that the hemispherical model for the pit shape is more appropriate for the prediction of strength reduction of corroded stirrups. The constitutive model developed in the paper can be used to predict the mechanical behaviour of corroded stirrups with reasonable accuracy, paving the way for the assessment of corrosion induced shear failure of reinforced concrete structures.

1. Introduction

Corrosion of reinforcing steel in concrete is regarded as the predominant cause for premature failures of reinforced concrete (RC) structures. The penetration of chlorides or carbonation would destroy the protective thin oxide film on the surface of reinforcing steel provided by high alkalinity of concrete pore solution, which leads to pitting or uniform corrosion of the steel. Numerous studies have shown that uniform corrosion has insignificant effect on constitutive, i.e., stress-strain (σ-ε), properties of corroded steel [1,2]. The pitting corrosion, however, may affect the mechanical properties of corroded steel due to possible localized change of microstructure of the steel, including stress concentration as confirmed in literature [3,4]. It is known that the corrosion products, whatever the type, can reduce the bond behaviour between reinforcing steel bars and concrete and the anchoring effect in concrete. This can eventually reduce the serviceability of corrosion affected structures, as characterized by concrete spalling and delamination. Therefore, accurate understanding of mechanical properties of corroded steel, both reinforcing bars and stirrups, is imperative for durability assessment, service life prediction and numerical simulation of the behaviour of RC structures subjected to corrosion.

Considerable research, both intensive and extensive, has been undertaken on mechanical properties of corroded reinforcing steel

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http://dx.doi.org/10.1016/j.conbuildmat.2016.09.128
0950-0618/

bars in the past few decades. Most of the published research, as confirmed in literature [5–10], concentrates on σ-ε curves of corroded steel in tension. The research suggests that the yielding plateau of σ-ε curves for corroded steel, taken out of aged structures, is shorter or even disappeared with the increase of corrosion rate [8,9]. As such, the ductility of corroded RC structures (e.g., beams) decreases significantly as also observed from the tests conducted by Almusallam [1], Azad et al. [5], Du et al. [6], Vidal et al. [7] and Zhu and François [10]. Based on test results, quantitative degradation models of mechanical parameters of corroded steel, such as yield strength, ultimate strength and uniform elongation, have been developed by Du et al. [11], Apostolopoulos and Papadakis [12], Lee and Cho [13], Apostolopoulos et al. [14] and Moreno et al. [15] with various methods. To determine the effect of whole process of corrosion on steel behaviour, constitutive models of corroded rebars under different conditions have also been established through comprehensive analysis of test results by various researchers, such as Apostolopoulos et al. [16], Zhang et al. [17] and Kashani et al. [18].

Although research on steel corrosion in concrete has been well trodden, it is more on longitudinal reinforcing bars (rebar). A review of published literature suggests that research on corrosion on steel stirrups and subsequent effect of structural behaviour has not been accorded much attention notwithstanding the fact that stirrups would be more prone to corrosion since they are closer to concrete surface and hence more fragile due to their smaller diameters [19,20]. In addition, the effect of corrosion of steel stirrups on structural behaviour can be significant for some types of structures; for example, RC flexural structures where shear failure can be critical and RC columns where the confinement of longitudinal bars are essential. There are many cases that the collapse of corrosion affected RC structures is triggered by the rupture of stirrups and subsequent shear failure without warnings, for example, the sudden collapse of Yanyue Bridge in Wujiang, China (see Fig. 1) [21,22]. Also, an experimental study on corroded RC beams conducted by Rodriguez et al. [23] has showed that the corrosion of reinforcement had altered the failure mode from bending for non-corroded beams to shear for corroded beams. It is in this regard that the present paper investigates the effect of corrosion on steel stirrups.

The review of literature also suggests that the existing constitutive models of corroded steel are almost based on factors with corrosion rate as the only independent variable, which is difficult to measure or estimate accurately in practice. Moreover, the accuracy of these models needs to be improved since they were developed based on methods of simplified mathematical regression without considering the fundamental mechanisms of corrosion and its effects on mechanical behaviour of steel. In addition, the degradation mechanisms of the mechanical properties of corroded steel are scantly investigated at microscopic level.

Fig. 1. Sudden collapse of Yanyue Bridge in Wujiang, China [21,22].

Therefore the objective of the present paper is to investigate the degradation of mechanical behaviour of steel stirrups subjected to corrosion. In this paper, details of a comprehensive test program designed to examine the mechanical behaviour of chloride-induced corrosion of steel stirrups in concrete structural members (exemplified by a concrete beam) are presented. Six factors deemed to affect the mechanical behaviour of the corroded stirrups are examined, including the concrete class, shear span ratio (λ), spacing of stirrups, steel grade, diameter of stirrups, and the degree of corrosion. These factors have not been investigated thoroughly up to date as shown in the literature [24–26]. Also in the present paper, a micromechanical damage model for failure mechanism of corroded stirrups is proposed and a model for damage factor is derived. Based on the developed damage models, a constitutive model for corroded stirrups is developed and verified with test results. Literature suggests that the developed constitutive model for corroded stirrups is the first of its kind. The model can be used for the assessment of corrosion induced shear failure of RC structures in corrosive environments.

2. Experimental program

2.1. Design of test specimens

There are many factors that affect the corrosion of reinforcing steel in concrete structures [27,28]. Some of these factors are observable and some not. The specimens of the test program were designed in such a way that observable factors can be quantified. There were six test variables investigated in the experimental program of RC beam series: (i) concrete class; (ii) shear span ratio (λ); (iii) spacing of stirrups; (iv) steel grade; (v) diameter of stirrups; and (vi) degree of corrosion, to be represented by a target corrosion rate, as summarized in Table 1. Concrete class was selected because different concrete density due to concrete class leads to different types of corrosion, and C30 and C40 are the most widely used grades in real structures. Shear span ratio (λ) is a key factor that affects the shear capacity of beams. Different λ from 2.0 to 3.5 were selected in the tests. The spacing of stirrups would affect the corrosion progression and different spacing from 150 to 250 mm were selected. Steel grades of HPB235 (A), HRB335 (B) and HRB400 (C) are widely used in practice and so are diameters of stirrup of 6 and 8 mm. Four target corrosion rates were selected for the test beams to study the effect of the degree of corrosion which ranges from zero to severe.

A total of 302 sets of stirrups with different grades of HPB235 (A), HRB335 (B) and HRB400 (C) were manufactured as specimens. They consist of 18 sets of un-corroded control specimens and 284 sets of corroded specimens embedded in concrete beams. Stirrup specimens were embedded in 24 sets of RC beams, which were cast with a same cross-section of 200 × 300 × 2400 mm and a concrete cover of 30 mm as shown in Fig. 2. Apart from investigating mechanical properties of stirrups embedded in concrete, the beams were also tested for studying the influence of corrosion on structural capacity and failure modes as part of the overall research program. Each type of beams was reinforced with steel bars of grades of A, B and C, and stirrups of diameters of 6 and 8 mm. Considering the mutual influence due to the same corrosion initiation times at the interface between transverse stirrups and longitudinal bars, wires were welded directly on the cleaned surface of longitudinal bars without any prime coating as shown in Fig. 3a. All welded parts were coated with epoxy resin to avoid disengagement of wires caused by corrosion during the accelerated process.