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Effect of bond and corrosion within partial length on shear behaviour and load capacity of RC beam

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ABSTRACT

This paper describes an experimental investigation into the effect of corrosion damaged partial length in one shear span on the shear behaviour and load capacity of reinforced concrete (RC) beams, where 14 RC beams were tested in four-point bending. Two shear span-to-effective depth ratios 2.0 and 3.0, two different partial lengths and three bond characteristics within the designed partial length were considered. Test results of the RC specimens were compared with theoretical results of the corresponding noncorroded bond-perfect RC beams, and the differences were analyzed to deduce the influence of the bond and corrosion within partial length on behaviour and load capacity of RC beams. The results indicate that the mechanical behaviour and load capacity of the test specimens are greatly influenced by the bond characteristics and high corrosion-induced damage within the partial length. Artificial elimination of the bond and neglecting of the corrosion-induced damage in the longitudinal bars and the connected stirrups within the partial length may lead to overestimate the residual capacity of the corrosion damaged RC beam. In assessing the residual life span and reliability of the in-service RC structures, it is very important to consider the severe corrosion damage within certain length of the RC elements.

1. Introduction

The problem of the deterioration of safety-related reinforced concrete (RC) structures due to corrosion of the steel reinforcement has received worldwide attention since it has been identified as one of the most predominant factors for the degradation the RC structures. Whereas current codes of practice adopt recommendations and precautions to avoid corrosion, evidence of the corrosion of steel in concrete continues to be reported in field situations. Up to now, two issues relative to the steel corrosion in RC elements have been studied comprehensively. One is to study its initiation and propagation as well as the related factors affecting the initiation of steel corrosion. Another is to study its influences on mechanical characteristics of reinforcing bar, bond between corroded steel and concrete as well as on the performance of corroded RC members in terms of their stiffness and deformation, ductility, failure modes, and load carrying capacity.

In previous experimental research related to the effect of steel corrosion on mechanical characteristics and load carrying capacity of corroded RC structural elements, the whole lengths of the longitudinal bars of the RC structural elements were designed to corrode by using the accelerated corrosion method at the laboratory [1–6]. However, for the corrosion damaged RC structural elements in-service, only a fraction length of the RC structural elements is corroded. Although long-term mechanical behaviours of the corroded RC beams kept in a confined salt fog were studied to take into account the actual conditions of the RC structures [7,8], the very long period consumed in preparing the test specimens is still a problem.

In order to simulate the case where only a fraction of the structural length is corroded in a relative short time, experimental works on the mechanical behaviour and load capacity of RC structural elements with partial damaged length were also carried in the laboratory. In the early experimental research works, the longitudinal tensile reinforcements were exposed or unbonded over a partial length of the RC beam and not suffered any corrosion damage within this partial length [9–13]. Due to the complete loss of bond between the longitudinal tensile steel and concrete was assumed and no cross section loss in the longitudinal tensile reinforcements and the contacted stirrups, the residual strength of the corrosion deteriorated RC elements may be different from the experimental results obtained by this simulation method. So, in the latter research works, experimental tests were carried out and the longitudinal tensile reinforcements and/or the contacted stirrups within the partial length of the RC structural elements were corroded just like their actual situation in the field [14–21].

In the above mentioned experimental research works, the continuously partially unbonded or corroded length was symmetrically arranged about the mid-span of the simply supported RC

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beam [9,14,17,19,21]. The residual strength or capacity of the RC beam with continuously partially unbonded length, were also theoretically predicted. Eyre and Nokhasteh [22] presented an algebraic formulation; Cairns and Zhao [9] developed a simplified numerical model by assuming the plane-section behaviour of the concrete section; Zhang and Raoof [23] proposed an iteration procedure to calculate the ultimate moment of the RC beams with exposed reinforcement on the basis of plane-section bending; Wang and Liu [24] proposed a compatibility condition of deformations of the RC beam with partially unbonded length and predicted the flexural capacity of this kind of RC beam. While in theoretical predicting the residual flexural strength of the RC beam with continuously partially corroded length, EI Maaddawy et al. [25] proposed an analytical model to predict the nonlinear flexural behaviour of corroded RC beam with partial length corrosion; Wang and Liu [26] presented a simplified methodology capable of providing estimates of the residual life of corroded RC beams with partial length. The proposed method used damaged material properties, and accounts for the length of partial corrosion and the amount of corrosion, concrete loss and change of bond strength within this specified length.

However, in existing RC elements, corrosion of the reinforcing bars may also occur within a partial length located in the areas close to the supports. In addition, in the in-service RC elements, if the RC elements are suffered corrosion damage within certain partial length located in the shear span, the longitudinal reinforcements and the contacted stirrups may corrode simultaneously. Thus, test studies regarding behaviour of RC beams with partially unbonded length in shear span [10–13] neglected the corrosion damage in reinforcements; the situation that only the longitudinal reinforcements were corroded within the designed partial length [15,16] or only the stirrups within one whole shear span were subjected to corrosion [18] was not a typical case.

In the present paper, 14 RC beams including two noncorroded RC beams, four RC beams with partially unbonded length and eight RC beams with partially corroded length were designed to investigate the effect of corrosion damaged partial length in one shear span on the shear behaviour and load capacity of corrosion damaged RC beam. Both the longitudinal reinforcements and the stirrups were subjected to corrosion within the partial length of the corroded RC test specimens. Test results of the specimens were compared with results of the corresponding noncorroded bond-perfect RC beams, and the differences were analyzed to deduce the influence of the bond and corrosion within partial length on behaviour and load capacity of RC beams. Influence of various variables on the performance and load capacity of the corrosion damaged RC beam was discussed.

2. Experimental program

2.1. Design of test specimens

All test specimens were designed with a rectangular cross section of $b \times h = 150 \times 180$ mm (Fig. 1). The overall length of the specimen was designed about 1800 mm with a 1200 mm distance between supports. All the specimens were designed to fail in shear by providing three 16 mm diameter deformed bars as flexural reinforcements to exclude premature flexural failure. Two top 6 mm-diameter plain bars were used to serve as stirrup-holders in the compression zone. 6 mm-diameter plain bars were also served as the shear reinforcements. Two different shear span-to-effective depth ratios 2.0 and 3.0 were chosen and two series RC beams were designed. For the shear span-to-effective depth ratio 2.0 series RC beams, the double-legged 6 mm diameter bars were spaced uniformly at 150 mm within the shear span (Fig. 1a); while for the 3.0 series RC beams, the double-legged 6 mm bars were spaced uniformly at 200 mm within the shear span (Fig. 1b).

The partial lengths, which were located in one of the shear span of the test specimens, were namely 200 mm and 300 mm long for 2.0 series RC beams (see Fig. 1a); while for 3.0 series RC beams, those partial lengths were namely 300 mm and 450 mm long (see Fig. 1b). The starting section of the partial lengths was exactly located under the load point, extending from the load point to the support direction, see Fig. 1.Within the designed partial length, three different bond characteristics were chosen, i.e. complete loss of bond, moderate reduction in bond strength and large reduction in bond strength. According to the test results of Almusallam et al. [27], the corresponding corrosion levels for moderate and large reduction in bond strength were chosen as 10% and 25% average weight loss of the longitudinal bars, respectively. The whole test specimens are shown in Table 1, where the beams were identified with letters and numbers designation: the first letter indicating beam, the first series numbers indicating the shear span-to-effective depth ratio, the second series numbers corresponding to the designed partial length and the last series numbers corresponding to the bond characteristic within the designed partial length. For example, specimen B2.0-300-25 implies a beam with shear span-to-effective depth ratio 2.0, having 300 mm target partial length and designed corrosion level of "25%"; specimen B3.0-450-0 implies a beam with shear span-to-effective depth ratio 3.0, having 450 mm target partial length and complete loss of bond within the target partial length.

2.2. Materials and fabricating the test specimens

The concrete was made in laboratory with target strength of 30 MPa and water-to-cement ratio of 0.55. Normal Portland cement and coarse aggregate with maximum aggregate size of 20 mm were used in the concrete mixture. The concrete mixture proportion by weight was as follows: cement: water: sand: gravel = 1:0.55:1.56:2.90. The average yield and ultimate strengths of 16 mm diameter deformed bars were 339.5 MPa and 550.8 MPa, respectively; while the 6 mm diameter plain bar had average yield strength of 441.5 MPa.

Before casting the concrete, the reinforcements used in the different test specimens were respectively prepared. For the specimens with designed partial length, the locations and the dimensions of the designed partial length along the longitudinal reinforcements were marked with red. For the stirrups used in partially corroded lengths of the corroded specimens, half of the top-part was epoxy-coated to avoid the corrosion of the top plain bars served as stirrup-holders (see Fig. 1). In making the steel cage, the epoxy-coated part of the stirrups was connected with the top plain bars, while the uncoated part was connected with the longitudinal tensile steel to represent the practical case in which stirrups are also subjected to corrosion. As further protection, plastic tapes and nylon strings were wrapped around the contact points between the top plain bars and the stirrups within the designed partial length.

In order to provide detailed strain readings of the stirrups and the longitudinal tensile bars, before the casting of the concrete, strain gages were installed in the designed position of the stirrups and the tensile bars (see Fig. 1), where for the longitudinal bars in all the test specimens, the strain gages were installed in the mid-span of the two lateral ones. The same designation was used for the steel bar and the strain gage installed on it. For instance, "St1" was the name of the stirrup located just below the loading point position and the strain gage installed on it. For the RC beam with partially unbonded length, besides the same strain gages shown in Fig. 1, within the partial length, two strain gages were installed in the mid-point of the partial length of the two lateral longitudinal bars, named as Go1 and Go2 in the cast surface and back of cast surface, respectively. For the RC beam with partially corroded length, considering the next corrosion process of the steel within the partial length, two white polyfoam cubes having a dimension of $50 \times 50 \times 22$ mm were banded at mid-point of the partial length of the two lateral longitudinal bars. If the whole shear span was the corroded length, since the strain gage may be damaged during the corrosion process, strain gage was not installed in stirrup St3. Thus, besides the banded polyfoam cubes within the design corroded length, in beams B2.0-200-10, B2.0-200-25, B3.0-300-10 and B3.0-300-25, the same strain gages shown in Fig. 1 was presented; while in beams B2.0-300-10, B2.0-300-25, B3.0-450-10 and B3.0-450-45, the installed strain gages were Lc1 (Lc2), St1–St2 and St4–St6. After the installing of all strain gages, anti-corrosion epoxy resin was used and anti-water adhesive tapes were wrapped to protect them from any damage.

At the structural laboratory, wood molds were used to horizontally cast the test specimens to minimize the variation of concrete strength. Each test specimen was cast respectively. Companion three $100 \times 100 \times 100$ mm concrete cubes were also cast for each test specimen to measure the corresponding compressive strength of concrete at the time of loading test.

2.3. Corrosion of RC beams

After the 28-day curing of the test specimens, the accelerated corrosion of the specimens with different corrosion levels was started The longitudinal bars were connected to the positive terminal of an external power supply to act as an anode while the copper plate was connected to the negative terminal of the power supply to act as a cathode, as shown in Fig. 2, where copper plate and wet sponge were immersed in 5% sodium chloride solution in a tank, the bottom of the wet sponge was wrapped around the designed partial length to ensure the necessary oxygen and moisture during the corrosion process. By applying Faraday's law, the total current required for each specimen was calculated based on their respective steel surface area and design corroded lengths. The current supplied to each concrete specimen was checked three times a day and any drift was corrected.