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Structural effects of simultaneous loading and reinforcement corrosion on performance of concrete beams

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HIGHLIGHTS

- ▶ Tests done on concrete beams under simultaneous loading and corrosion (SLC).
- ▶ SLC causes a beam to exceed its limiting deflection for service prematurely.
- ▶ SLC decrease beam strength and especially, its ductility much more rapidly.
- ▶ SLC causes a beam to fail less ductile and even in a brittle way.

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ABSTRACT

The paper presents an experimental investigation into the structural performance of concrete beams under simultaneous loading and reinforcement corrosion. Four out of five concrete beams were subjected to an accelerated corrosion of their tensile bars, while they sustained a constant point load and their self-weight, until they failed in their load-bearing capacity. On the basis of the experimental results, it has been found that, under the same service loads, the time-dependant deflection of a corroded beam increases more rapidly than that of a non-corroded beam, and is likely to reach the limiting deflection for its serviceability requirements prematurely. Under simultaneous loading and reinforcement corrosion, both ultimate strength and maximum deflection of a concrete beam decrease more than those of the beams tested under a separate loading and corrosion condition. Either a further development of corrosion or an occasional over-loading or both are likely to cause a corroded beam under service loads to fail and even collapse suddenly without significant warning in term of its deflection. Hence, attention should be paid to the inspection and maintenance of corroded structures that are being used in our society to avoid any loss of life and property.

1. Introduction

Corrosion of reinforcement is one of the major causes for structural deterioration of reinforced concrete buildings and bridges. For the purpose of cost-effective decision-making in respect of their use and maintenance, mechanical performance, residual strength and service life of these structures with corroding reinforcements should be fully understood.

Over the past few decades, many experimental investigations have been carried out to address the structural effects of reinforcement corrosion on the performance of concrete beams. On basis of the experimental results, it has been reported that, in contrast with the ductile failure of a non-corroded beam, a corroded beam would possibly fail either in shear, or in shear–compression, or by bond ineffectiveness with a less ductile mode [1–5]. With regards to the magnitude of the reduction of beam strength due to corrosion, however, completely consistent results have not been achieved from the previous tests. In particular, all the above experimental investigations were carried out in such a way that concrete beams were first corroded to an expected extent, before they were loaded to failure to assess the variation of their mechanical behaviour due to corrosion [1–5]. This clearly does not reflect the real world of corroded structures in which corrosion of reinforcement occurs simultaneously with service loads that are being applied on the structures.

Recently, Yoon et al., Ballim et al., Vidal et al. and Malumbela et al. conducted the tests on concrete beams which were subjected to simultaneous loading and reinforcement corrosion [6–10]. It has

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reported that, under simultaneous loading and reinforcement corrosion, the longitudinal tensile strain, surfacing cracks and flexural deflection of a corroded beam increased more than those of a non-corroded one [9,10]. Due to a simultaneous loading, there were faster initiation of the corrosion of reinforcements and a shift of failure mode of a concrete beam [6].

However, these investigations are mainly focused on beam behaviour at its service stage on aspects of corrosion imitation, corrosion propagation, surface cracks and the time-dependant deflection, etc. In addition, the level of sustained loads that were applied on the beams with corroding reinforcements was only about 8% and 12% of beam ultimate strength [9,10], which seems too small when compared with the level of service loads that are commonly applied on most concrete beams in actual structures.

Hence, this paper presents an experimental investigation with an aim of studying the structural behaviour of reinforced concrete beam subjected to simultaneous loading and reinforcement corrosion. A particular attention will be paid to their ultimate strength, maximum deflection and failure modes at its ultimate limit state.

2. Experimental work

2.1. Beam specimen and materials

Five reinforced concrete beams with the dimensions of 100 mm wide by 150 mm deep by 1300 mm long were made for an anticipated flexural failure, prior to corrosion of their reinforcements, as shown in Fig. 1. The measured yield and ultimate strengths of the H8 rib bars were 478 N/mm^2 and 557 N/mm^2, while those of the R6 plain bars were 286 N/mm^2 and 335 N/mm^2. All concrete beams were cast using the same batch of the concrete mix and had the same thickness of concrete cover of 20 mm. The measured cubic strengths of the concrete were 25.6 N/mm^2 after 28 days cure in the water tank, and 39.2 N/mm^2 when beams failed under simultaneous loading and corrosion.

2.2. Test programme and techniques

Following both 28 days cure in the water tank and further 29 days natural exposure, all concrete beams were subjected to three points bending over a 1000 mm span, as illustrated in Fig. 1.

In addition to beam self-weight, a point load was applied at the mid-span of each beam and progressively increased up to 15 kN, 60% of their design ultimate load of 25 kN, and then kept constant. The loading was implemented by using two screwed rods that stood on each side of a beam. Each rod had its one end fixed to the floor of the laboratory and the other end projected above the test beam, as shown in Fig. 2. The point load was measured and monitored using a load cell that was positioned between a loading distribution steel beam linking the two rods and the top surface of each beam. The deflection of the beam was measured using a dial gauge that was located in the middle span of each beam adjacent to the point load.

While keeping the above point load at the constant level of 15 kN, four out of five beams, except for the control beam CB5, were then subjected to accelerated corrosion on the parts of their H8 bottom tensile bars simultaneously for the remaining 50–60 days, as shown in Fig. 3.

To ensure uniform moisture condition of different beams and to improve the electrical conductivity of the concrete, 3.5% sodium solution was sprayed for 24 h to the part of a beam to be corroded. After this initial 'wet' phase, the power suppliers were immediately switched onto impress the currents of 0.25 mA/cm^2 and 0.50 mA/cm^2 onto the H8 bars during the first two weeks and the remaining six weeks, respectively, when the beams were under a cycle of 'wet' and 'dry' conditioning. This cycle of wet and dry conditions was established by having 2 h of sodium–chloride solution spraying and the remaining 22 h of indoor natural exposure of the beam every day. A timer was used to control the turn on and off of water-spraying while the current was kept at a constant level.

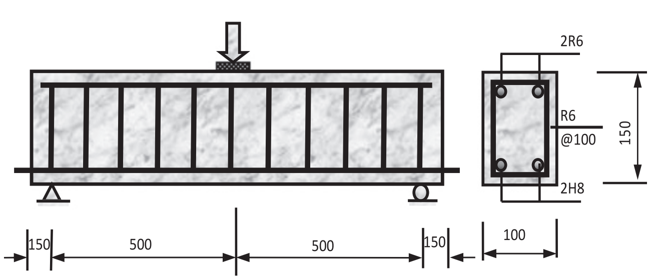

Fig. 1. Specimen of reinforced concrete beam.

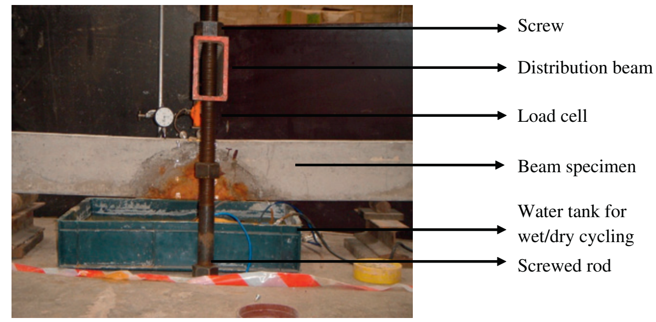

Fig. 2. Test rig for beam loading.

At the end of the above process, both the control beam CB5, which was only subjected to the applied loads without corrosion, and the corroded beam CB4 were further loaded to failure using Mand Testing Rig under displacement control to measure their ultimate strength and maximum deflections. A beam was deemed to have failed in its load-bearing capacity, if either its tensile steel bar fractured or its post-peak load decreased by 50% of its ultimate strength.

At the end of the test, both corroded bars and non-corroded bars were removed from the tested specimens. The amount of corrosion of reinforcing bars was calculated on the basis of its weight loss, which represents an average loss of steel cross-sectional area and is about 1–5 times less that is determined using its minimum residual cross-section area [12].

3. Results and discussion

The main experimental results of concrete beams subjected to simultaneous loadings and reinforcement corrosion are shown in Figs. 4–6 in terms of their load-dependant and time-dependant deflections, respectively. Here, the deflections of the beams under the initial loading of up to 15 kN and under simultaneous loading of 15 kN and reinforcement corrosion were shown in Figs. 4 and 5. The increased deflections of the beams CB4 and CB5 under the further loading of up to 20 kN and 25.6 kN, respectively, were added to Fig. 5, while those under the simultaneous loading and reinforcements only in Fig. 6.

3.1. Structural performance of concrete beam under loading and corrosion

As shown in Figs. 4 and 5, the structural performance of reinforced concrete beams subjected to simultaneous loading and reinforcement corrosion can be divided into three different stages, i.e., stage A for initial loading, stage B for time-dependant deflection and stage C for final failure.

Initially, when the point load was gradually increased to between 5.0 and 7.0 kN, the deflections of all concrete beam almost linearly increased to between 0.28 mm and 0.51 mm and the first set of flexural cracks occurred in the middle span of the concrete beams. When the point load was increased to the designated level of 15 kN, the development of the flexural cracks on beam surface tended to stabilise and the deflections of the five beams increased to between 1.46 and 2.03 mm with an average value of 1.70 mm, as shown in Figs. 4 and 5. During the 24 h of the initial 'wet' phase, the average deflection of the five beams increased from 1.70 mm to 2.72 mm with an average value of 2.7 mm. This was still well below the limit deflection of 4.0 mm in term of L/250 specified in the BS EN 1992-1-1 for a concrete beam at its serviceability limit state [11], as shown in Fig. 5.

Following the initiation of the corrosion of reinforcements in the beams CB1–CB4, some rust stains and corrosion cracks appeared on beam surfaces along the length of the longitudinal