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Behaviour of RC beams corroded under sustained service loads

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ABSTRACT

This paper presents the results of an experimental study conducted to characterize the structural behaviour of reinforced concrete beams corroded whilst subjected to constant sustained service loads. Corrosion of tensile steel bars was induced by an accelerated corrosion process using a 5% solution of NaCl and a constant impressed current. Four RC beams were tested, each with a width of 153 mm, a depth of 254 mm and a length of 3000 mm. Beams were tested whilst under a load equivalent to 1%, 8% and 12% of the ultimate load. Longitudinal tensile and compressive strains were monitored during the corrosion process and used to determine the variation of the depth of the neutral axis, the curvature and the second moment of area of beams with the time of electrolysis. The results indicate that the longitudinal strains, the depth of the neutral axis and the curvature of beams depend on both the level of corrosion and the applied service load whilst the second moment of area is mostly influenced by the level of corrosion.

1. Introduction

Corrosion of steel bars embedded in concrete is a worldwide problem that affects numerous reinforced concrete (RC) structures [1]. It is accepted that as corrosion of steel bars occurs there is a corresponding reduction in the area of the bars and corrosion products deposited around the steel bar occupy a larger volume than the volume of steel lost. The expansive corrosion products apply tensile stresses in the concrete surrounding the corroding steel bar, which can cause cracking and spalling of concrete. The structural integrity of a RC structure undergoing corrosion damage is reduced by the loss of bond between the steel and the concrete as well as the loss of area of reinforcing steel [2].

A great deal of research has been done on the effects of corrosion of tensile steel bars on the structural performance of RC members. The majority of the work done has focussed on corrosion damage under no sustained load [3]. In real structures, however, steel corrosion normally takes place whilst the structure is under a sustained load. The limited work where RC beams were corroded under a constant sustained load mainly investigated the interaction between the applied load, the level of corrosion and central deflections of beams [3–5]. In spite of the limited work, the results by the researchers clearly indicate that deflections of beams increase with an increase in the level of corrosion as well as the magnitude of the applied load. Whilst deflections of beams can be used as an indicator of structural performance of corroded beams, general models of structural behaviour of RC members (including deflections) require variations of strains in various elements due to applied stresses, depths of neutral axis along beams, curvatures and stiffness of the RC members as input parameters. Research is therefore needed to clarify the variation of these input parameters with the level of corrosion in the presence of a sustained load. This paper presents an experimental programme and a summary of the research findings on the interactions between longitudinal strains, the depth of the neutral axis, curvatures and stiffness of beams with various service sustained loads and the corrosion of tensile steel bars. Depth of the neutral axis in this paper defines the distance from the compression face of beams to the position of the neutral axis.

1.1. Behaviour of RC beams under service loads

Models for flexural behaviour of RC beams under service loads often consider their behaviour to be made up of two distinct stages namely the uncracked stage and the cracked stage [6]. Whilst there are different types of cracks that can be found in a structure under load, these models are often limited to flexural cracks caused by the sustained load and are nearly perpendicular to the longitudinal axis of the beam under pure bending. It is not well understood how corrosion cracks which normally propagate in the longitudinal axis of the reinforcing bars affect the flexural behaviour of beams that are at the different cracking stages, especially when they occur whilst the beams are under load.

1.1.1. Uncracked stage

In this stage, the tensile stresses applied on the concrete are lower than the tensile strength of the concrete. Sectional properties of RC beams in this stage are such that the majority of applied stresses on the beam are balanced by the concrete and

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not by the steel bars. Loss in area of tensile steel bars due to corrosion on a beam in this stage is therefore unlikely to disturb the equilibrium of the internal forces and moments resisted by the beam. There is little published work to describe the behaviour of uncracked RC beams under simultaneous load and corrosion of steel bars. Previous work on RC beams corroded under load has focused on beams under high loads (23–75% of their ultimate capacity [3–5]). Ancient structures which are often more susceptible to corrosion due to their extended time of exposure to aggressive environments in addition to poor concrete that was used in the past, were, however, mostly overdesigned such that they continue to experience very low applied stresses and may be free from flexural cracks. The cracking stage that should be used in their analysis to predict their residual strength after steel corrosion is unclear.

1.1.2. Cracked stage

In this stage, the tensile stresses applied on the concrete are larger than the tensile strength of concrete and therefore concrete is cracked in tension. Local curvatures in the beam vary along the beam with high curvatures occurring at the crack location and lowest curvatures occurring midway between cracks [7]. This is because at the location of a crack, tensile stresses resulting from the beam loading are balanced only by the tensile steel bars. The increased stresses resisted by the tensile steel bars causes increased strains in the steel bars. To ensure equilibrium of a section, the depth of the neutral axis reduces and consequently the curvature increases and the stiffness at the section reduces. Between adjacent cracks tensile forces are transmitted from the steel to the surrounding concrete by bond stresses. A reduction in the stresses in steel due to bond stresses disturbs the newly established equilibrium and hence causes a subsequent increase in the depth of the neutral axis, a decrease in the curvature and an increase in the stiffness. Despite the variation of local curvatures in cracked concrete, deformations of steel and concrete over the cracked region must be compatible [8]. Consequently mean curvatures and/or effective second moment of areas along the cracked region are normally used to calculate deflections of cracked RC beams [6,7,9].

Since the majority of tensile stresses on the cracked stage are balanced by the tensile steel bars, a loss in area of the steel bars due to corrosion as well as a loss in the bond between the steel and the surrounding concrete is likely to disturb the equilibrium of the system. The depth of the neutral axis is likely to decrease with an increase in the level of corrosion so as to maintain equilibrium of internal forces and moments. Consequently the mean curvature is likely to increase and the effective stiffness is likely to reduce with an increase in the level of corrosion of cracked beams.

2. Experimental programme

2.1. Test programme

Four beams were used in the test programme. For each beam tested, a second beam was tested under the same regime not only to increase the reliability of the research findings but to later assess the influence of interventions such as repair and strengthening on the behaviour of corroded beams. Beam 1 was tested under a sustained load equivalent to 1% of the ultimate capacity (low deflections); beam 2 was tested under a sustained load equivalent to 8% of the ultimate capacity (anticipated medium deflections but no flexural cracks); and beams 3 and 4 were tested under a sustained load equivalent to 12% of the ultimate capacity of a virgin beam (anticipated high deflections and flexural cracks). Beams 1–3 were corroded under their respective loading systems whilst beam 4 was not corroded. A summary of the test programme is shown in Table 1.

Table 1
Experimental programme.[a]

Beam	Load as % of ultimate capacity	Corrosion	f_c (s.d.) (MPa)	E_c (s.d.) (GPa)
1	1	Yes	35 (0.9)	22 (4)
2	8	Yes	34 (0.2)	23 (5)
3	12	Yes	44 (1.1)	33 (9)
4	12	No	44 (1.1)	33 (9)

[a] f_c = compressive strength of concrete at the time of testing; E_c = modulus of elasticity of concrete at the time of testing; and s.d. = standard deviation.

2.2. Specimen configuration

Quasi-full scale RC beams were tested in this programme each with a width of 153 mm, a depth of 254 mm and a length of 3000 mm. The reinforcement details of the beams are shown in Fig. 1. Each beam was reinforced with three 12 mm deformed bars in tension with a cover of 40 mm, and two 8 mm plain bars in compression also with a cover of 40 mm. Stirrups with a diameter of 8 mm were used as shear reinforcement and were spaced at 100 mm centre-to-centre within the shear span. No stirrups were placed in the middle span; instead compression reinforcement bars in the middle span were tied together by 8 mm diameter hooks at 200 mm spacing.

2.3. Material properties

The concrete mix was designed to yield a 28 days compressive strength of 35 MPa. Maximum aggregate size of the concrete was 13.2 mm and w/c ratio was 0.7. Cement, fine sand and coarse aggregate contents were 300 kg, 909 kg and 950 kg/m^3, respectively. Due to the limited number of test frames, it was not always possible to test the beams at their 28 days strength. The compression strengths and the elastic modulus of the beams were therefore measured at the time of testing the beams and are shown in Table 1. The strength of the beams at the time of testing was therefore expected to vary as shown in Table 1. The elastic modulus of the concrete at the time of testing was tested in compression using three 100 mm cylinders of 200 mm length.

Tensile pull tests were carried out on the reinforcing steel bars used in the programme. The 12 mm deformed bars had yield strength of 549 MPa (s.d. = 3 MPa) and ultimate strength of 698 MPa (s.d. = 4 MPa) whilst the 8 mm plain bars had yield strength of 385 MPa (s.d. = 1 MPa) and ultimate strength of 451 MPa (s.d. = 2 MPa).

2.4. Sustained loading

Beam 1 was tested whilst supported on two concrete blocks of $100 \times 100 \times 200$ mm placed in the middle third of the beam span. The beam was tested with the tensile face up. Fig. 2 shows a photograph of the loading frame used in the research programme to test beams 2–4. The frame was designed and built at the University of Cape Town. Support columns of the frame were bolted to a strong floor to provide adequate reaction force. Weights were hung on a loading beam and transferred to the load distribution beam using a frictionless bearing support and pinned struts. From the load distribution beam, the load was transferred to the test specimen to produce four points bending with a constant moment in the middle third of the beam, using rollers. The loading beam had a lever arm to magnify the hung weights. Ball joints were used at the supports of the test specimens to allow for free rotations. The overall design of the frame was such that tension was applied on the top face of the beams. This was done especially to enable; the monitoring of tensile strains and corrosion cracks on the tensile face of beams during the corrosion process; the construction of a NaCl pond for the corrosion process on the tensile face of the beam; and the patch repair and strengthening of corroded beams whilst under a constant sustained load.

2.5. Accelerated corrosion

Before the corrosion process, beams were inverted such that the tensile steel bars were at the top. Corrosion of tensile bars was concentrated over a region of 700 mm in the middle of the beams. A pond with a depth of 50 mm and a length of 700 mm was built on the tensile face of the mid span of beams to be corroded by bonding 5 mm thick polyvinyl (pvc) sheets to the concrete such that the pond did not offer any restraint to the expansion of the concrete. The pond in each corroded beam was filled with a 5% solution of NaCl, and a 12 mm stainless steel bar of length 250 mm was placed in the NaCl solution. The tensile steel bars and the stainless steel bar were connected to a power supply to induce a constant current of 150 mA which corresponds to a current density of 189 μA/cm^2. The current density was calculated by assuming that only the portion of the tensile steel bars within the region bound by the NaCl pond act as anode and corrodes. According to [10] a current density lower than 200 μA/cm^2 is small enough to prevent accelerated damage found at high current densities. The direction of the current was such that the tensile steel bars served as an anode while the stainless steel bar served as a cathode. The corrosion process consisted of a ponding cycle of 4 days wetting and 2 days drying under natural air to promote corrosion. Current was only applied during the wetting period.