Construction and Building Materials 151 (2017) 208–219

Contents lists available at ScienceDirect

Construction and Building Materials

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

Crack propagation and flexural behaviour of RC beams under simultaneous sustained loading and steel corrosion

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HIGHLIGHTS

- Simultaneous loading and corrosion lead to more severe and faster cracking damage.
- Simultaneous loading and corrosion reduce the ductility of the beams.
- The corrosion of tension reinforcement occurs more slowly than that of stirrups.
- Tension-reinforcement corrosion near stirrups is slighter than at other parts.

ARTICLE INFO

Article history:
Received 31 October 2016
Received in revised form 24 March 2017
Accepted 23 May 2017

Keywords:
Sustained loading
Corrosion-induced cracking
Flexural behaviour
Stirrups corrosion
Tension reinforcement corrosion

ABSTRACT

This paper investigated the cracking behaviour and flexural capacity of beams under simultaneous sustained loading and steel corrosion. Chloride ions were electro-migrated into the concrete beams, and then DC current, coupled with wetting and drying cycles, was applied to accelerate the steel corrosion. During the steel corrosion, the beams were subjected to sustained loading at different levels. The cracking maps were drawn and crack width was measured periodically. The flexural capacity and the steel corrosion degree were measured after seven wetting and drying cycles. The results show that simultaneous loading and corrosion lead to more severe and faster cracking damage on the beams and reduce the beams' ductilities. The corrosion of the tension reinforcement occurs more slowly than that of the stirrups, while the tension-reinforcement corrosion at the areas connecting with the stirrups is slighter than the corrosion at the other parts of the tension reinforcement.

1. Introduction

Corrosion-induced cracking is the major cause of durability deterioration in reinforced concrete (RC) structures [1,2]. As the steel corrosion develops, the corrosion product, which is approximately two to six times the volume of the original steel [3,4], produces an expansive pressure on the surrounding concrete and leads to concrete-cover cracking. The cracks provide paths for rapid ingress of aggressive agents into the reinforcement and accelerate the corrosion process [5,6], which will reduce the load-bearing capacity and ductility of the structure [7] and result in progressive deterioration and even spalling of the concrete cover [8]. Therefore, investigation of corrosion-induced cracking is important for the prediction of the serviceability and durability of reinforced concrete structures.

A considerable number of experimental studies have been conducted on corrosion-induced concrete cracking [8–19], revealing that the crack widths on the concrete-cover surface increase with the growth of the steel-corrosion degree. These models mainly investigated the influence of the geometric variables of concrete and steel bars [8–11] and the mechanical properties of concrete [12–15] on the concrete-cracking process, while the improved models considered more parameters, such as the corrosion rate [16], and the properties of corrosion products [17].

All the works mentioned above have two aspects in common. One is that the corrosion process was accelerated by chloride pre-blending, impressed current or both; as a result, the steel bar was normally uniformly corroded on its whole surface [20,21]. In the real case, however, the steel-corrosion products normally accumulate at the bar surface facing the concrete cover, which result in non-uniform corrosion. The other is that the models were derived from specimens without loads. In real cases, the structures are always under service loads. To gain an overall understanding of the cracking behaviour of in situ structures, a number of beams

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http://dx.doi.org/10.1016/j.conbuildmat.2017.05.193
0950-0618/

were cast in 1984, and then simultaneously subjected to sustained loading and corroded in a confined salt environment. Theses beams were studied after 14 [22,23], 17 [24], 23 [23,25], 26 and 28 years [26]. The crack-propagation behaviours of the beams under different loading levels and corrosion levels were described and compared [22,23,25]. However, all the beams in these studies were loaded under either 50% or 80% of the failure load, and the differences of the crack-propagation behaviour between the loaded beams and unloaded beams were not compared.

The mechanical performances of the corroded RC specimens were also widely studied. Researchers [27–31] have found that when the corrosion degree was relatively small (<4%) [28], the steel corrosion showed a slight effect on flexural load capacity; when the corrosion degree was greater, the deflection and crack width increased significantly during the sustained loading, the flexural load capacity decreased and even the failure mode was modified [31]. A strong limitation of the above works [27–31] is that all the specimens were firstly corroded to an expected extent in the absence of loading before the mechanical test was applied. To improve which, the following works [32–36] studied the ultimate capacity and the serviceability of beams under the loading and steel corrosion simultaneously. Results show that loading history and loading level have significant effects on both corrosion initiation and the rate of corrosion propagation, and eventually change the failure mode from a shear failure to bond splitting [32]. Simultaneous loading and steel corrosion could increase the deflection of the beam during loading and corrosion, and decrease the ultimate strength and maximum deflection of a concrete beam significantly when monotonically loaded, compared to only steel corrosion before the mechanical test [33–36]. However, most of these studies focused on the corrosion of the tension reinforcement; the stirrup corrosion was not considered in most previous studies. In engineering practices, both the tension reinforcement and the stirrups are used to form reinforcing skeletons in reinforced concrete structures, and stirrups are more vulnerable to corrosion than tension bars, as the concrete cover is thinner for stirrups [37].

This study was conducted to investigate the crack propagation and flexural behaviour of RC beams under simultaneous sustained loading and steel corrosion. To produce non-uniform corrosion of the steel bar, chloride ions were electro-migrated into the concrete before the constant current and wetting and drying cycles to accelerate the steel corrosion. Both the stirrups and tension reinforcement were corroded. During the steel corrosion, the beams were subjected to sustained loading at different levels. The cracking maps were drawn periodically and the flexural capacities were measured after the target steel-corrosion levels were reached. The results of this study are helpful for understanding the crack propagation, the flexural behaviour, and the stirrup and tension-reinforcement corrosion behaviour of the RC beams under simultaneous loading and corrosion.

2. Experimental program

2.1. Concrete beams

The concrete mix shown in Table 1 was used for the reinforced concrete beams. The cement CEM I – 42.5 MPa and coarse aggregate with a maximum gravel diameter of 25 mm were used. The slump value was 135 mm. The 28-day compressive strength of the concrete was 35.4 MPa.

Deformed HRB335 with a diameter of 16 mm was used as the tension reinforcement. Three deformed steel bars were used in each beam and they were hooked at the ends of the beams to avoid any premature bond failure. Smooth HPB300 with a diameter of 8 mm was used for the stirrups and the top-layer steel bars. Stirrups were spaced at 100 mm within the shear span, and at 150 mm within the constant-moment zone, where the U-type stirrups were used. The dimensions and material properties of the reinforcing steel bars are given in Table 2.

Fig. 1 shows the dimensions and the reinforcement information of the beams. Seven beams were cast with dimensions of 180 mm in depth, 250 mm in width and 1200 mm in length. The labels of the seven beams are shown in Table 3. In Table 3, the first letter, "C" or "F", indicates whether the beam is used to study the "Cracking propagation" or "Flexural behaviour", respectively; the following letter, "C" or "N", represents "Corrosion" or "No corrosion", respectively; the last letter, "L" or "N", indicates whether the beam is "under Loading" or "No loading", respectively; and the following number, "00", "03" or "06", indicates whether the loading level is 0%, 30% or 60% of the peak load, respectively. After casting, all the beams were covered with damp burlap and wetted once a day for 28 days, during which, the temperature ranged from 3 °C to 23 °C, with an average value of 12.6 °C.

2.2. Electro-migration on the beams

All the beams, except for the control beam FNN00, were subjected to electro-migration, i.e., the chlorides were electro-migrated into the concrete cover by means of an electro-chemical method, similar to that of Xia et al. [38]. The targeted electro-chemical area was the on the bottom surface, i.e., the tension surface (the surface near the longitudinal reinforcement) on the beam in the constant-moment zone.

As shown in Fig. 2, the sponge materials immersed in 5% NaCl solution, a stainless-steel net and damp burlap were applied to the target corrosion area. Sponge materials immersed in 0.3 mol/L NaOH solution, a stainless-steel sheet and damp burlap were placed on the surface opposite the target corrosion area. After 24 h of moistening the concrete, the direction of the current flow was adjusted so that the stainless-steel net became the cathode and the stainless-steel sheet served as the anode. A constant voltage of 25 V was applied between the stainless-steel net and the stainless-steel sheet using a direct-current (DC) power source. The electro-migration time used in the accelerated-corrosion tests was determined using the following equation [39].

$$t = \frac{RT}{Z_{Cl}FED_{nssm}} \cdot \left[x_d - 2\sqrt{\frac{RTx_d}{zFE}} erf^{-1}\left(1 - \frac{2c_d}{c_0}\right) \right] \quad (1)$$

where t is the electro-migration time; $R = 8.314$ J/(mol·K) is the molar gas constant; $T = 298$ K is the average absolute temperature of the concrete beams; $Z_{Cl} = 1$ is the charge number of the chloride ions; $F = 96{,}480$ J/(V·mol) is the Faraday constant; $E = U/h$ is the applied electric-field strength, where $U = 25$ V, and h is the distance between the stainless-steel net and stainless-steel sheet, i.e., the sum of the height of the beam (180 mm) and the thickness (2 × 20 mm) of the two sponge materials; D_{nssm} is the non-steady-state diffusion coefficient, which was determined to be

Table 1
Compositions of the concrete used in the beams (kg/m^3).

Cement	Fly ash	Slag	Water	Fine aggregate	Coarse aggregate	Water reducing agent
282	41	53	184	752	985	7.5