Engineering Structures 56 (2013) 8–21

Contents lists available at SciVerse ScienceDirect

Engineering Structures

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

Finite element analysis of cracking and delamination of concrete beam due to steel corrosion

Y.G. Du [a,*], A.H.C. Chan [b,1], L.A. Clark [b], X.T. Wang [c], F. Gurkalo [a], S. Bartos [d]

[a] Department of Engineering and Built Environment, Anglia Ruskin University, Chelmsford CM1 1SQ, United Kingdom
[b] School of Civil Engineering, The University of Birmingham, Birmingham B15 2TT, United Kingdom
[c] Department of Civil Engineering, Ningbo University, Ningbo, China
[d] Faculty of Civil Engineering, University of Zagreb, Zagreb, Franje Hermana 16E, Croatia

ARTICLE INFO

Article history:
Received 9 September 2012
Revised 25 February 2013
Accepted 8 April 2013

Keywords:
Corrosion
Steel bar
Cracking
Concrete cover
Bar clear distance
Bar diameter
Beam
Finite element
Deterioration
Penetration

ABSTRACT

This paper presents the analytical results to investigate cracking and delamination of concrete beam due to steel corrosion. A series of concrete beams were idealised as two dimensional models via their cross section and analysed using the finite element software – LUSAS. The corrosion of steel bars was simulated using a radial expansion. The FE results show that cracking of beam section due to steel corrosion can be clarified into four types, i.e., *Internal Cracking*, *Internal Penetration*, *External Cracking* (HS) and *External Cracking* (VB). The amount of corrosion in term of radial expansion required to causes *Internal Cracking*, *Internal Penetration*, *External Cracking* (HS) and *External Cracking* (VB) varies almost linearly with bar diameter d, bar clear distance s and concrete cover c, respectively. If the ratio s/c was less than the critical value of about 2.2, the delamination of concrete cover could occur before the cracks can be visualised on the concrete surface, which does concern engineers.

1. Introduction

Steel corrosion is one of the most dominant causes for the premature degradation of reinforced concrete structures. It has been a topic of widespread interest to those concerned with the service performance and residual life of existing concrete structures. Although the collapse of reinforced concrete structures directly as a result of steel corrosion has rarely been reported, maintenance of these deteriorated structures has been a heavy burden on owners and users of such structures.

One of the principal effects of steel corrosion on structures is the cracking of concrete, which is caused by the volumetric expansion of corroded steel bars. As an electrochemical process initiated by concrete carbonation and/or chloride intrusion, corrosion of a steel bar in concrete involves both dissolution of iron ions from bar surface and transformation of the dissolved metal into corrosion products, i.e., rusts. Some of these rusts may possibly migrate into any voids inside the concrete, and even permeate the concrete cover and remain on the concrete surface as stains, which do not damage the integrity of the concrete. However, other rusts might accumulate between the corroding bar and its surrounding concrete. Since the rusts occupy a larger volume than their parent metal, a radial expansion of a corroding bar would take place around its circumference, which causes a hoop tension and radial compression strains within the surrounding concrete. As corrosion of a steel bar continues both hoop tension and radial compression strains of concrete increase. Once the maximum tensile strain of the concrete due to its hoop and radial strains exceeds its deformation capacity, cracking, spalling and even delamination, of concrete cover can occur.

Cracking of concrete due to steel corrosion has substantial influences on performance and safety of a concrete structure. It not only affects structural aesthetics and serviceability, but also accelerates the corrosion process of steel bars by providing ample oxygen and water through the developed cracks [1], which in turn promotes the further development of cracks in the concrete. In addition, the cracking and, in particular, the delamination of concrete cover

---

* Corresponding author. Tel.: +44 0845 1963945.
E-mail addresses: yingang.du@anglia.ac.uk (Y.G. Du), a.h.chan@bham.ac.uk (A.H.C. Chan), l.a.clark@bham.ac.uk (L.A. Clark), wxt196322@126.com (X.T. Wang), filip.gurkalo@anglia.ac.uk (F. Gurkalo), bartos@gmail.com (S. Bartos).
[1] Tel.: +44 0121 414 5100.

http://dx.doi.org/10.1016/j.engstruct.2013.04.005

can impair the bond between corroded bar and its surrounding concrete and decrease the effective sectional area of structural members. As a result, it will very likely alter the mechanical behaviour of a structure and may even reduce its residual capacity and service life.

Over the past decades a number of experimental investigations have been conducted to study the effect of corrosion on both performance and cracking of concrete structures [2–14]. In these investigations, the corrosion of a steel bar in the concrete was reproduced artificially either by applying an internal pressure or conducting accelerated corrosion tests. Both the occurrence of the first cracks and their further development on the concrete surface were monitored and recorded externally. On basis of the experimental results, it was found that internal pressure and/or amount of corrosion required for cracking almost increase linearly with the thickness of concrete cover. Owing to corrosion of multiple bars, cracks occur not only on the external surface of the concrete along the longitudinal corroded bars, but also between two adjacent corroded bars, which eventually causes the delamination of concrete cover, as typically shown in Fig. 1. However, the magnitudes of the internal pressure or amount of corrosion for cracking were less consistently reported by different researchers because of the different concrete mixes and different testing techniques adopted. In addition, the above experimental results are mainly based on the external observation of the physical specimen. They were unable to reveal both initiating mechanism and propagation process of the corrosion-induced cracks in the concrete.

As a result, finite element method was brought into this research field, and facilitated an effective tool to study the corrosion-induced cracks in the concrete [15–21]. In these FE analyses, reinforced concrete beams or slabs were idealised as three or two dimensional analytical models. The expansive behaviour of corrosion products was modelled either as an internal pressure or a prescribed displacement or a volumic expansion of the joint interface element between concrete and steel bar. According to FE results, it has been found that the cracking of concrete initiates and develops as a result of an increase of the radial expansion of corroding bars. If the permeation of corrosion products from a corroding bar into its surrounding concrete cover and into the developed cracks were taken into account, both critical amount of corrosion for concrete cracking and the width of concrete cracks could be well estimated [21]. Otherwise, the FE results would under-estimate the above critical value [15,17]. However, most of the analytical results reported so far were obtained using individually developed finite element package, and were validated using galvanostatic experimental results, which actually differ from those in real world of corrosion damaged concrete structure [21]. In particular, little attention has been paid to the engineering interpretation of FE results and the effect of key parameters of a concrete beam on its cracking and delamination.

Fig. 1. Corrosion cracks on surface of concrete beam.

Hence, this paper aims to discover the mechanism of cracking and delamination of concrete beam due to steel corrosion and to study its variation with the main parameters, i.e. bar diameter, concrete cover and bar clear distance using the commercial software package – LUSAS [22]. A series of reinforced concrete beams were idealised as a 2-D model via its cross-section. The corrosion of steel bars in concrete beams was simulated using an increasing radial expansion. The FE analytical results are validated using the experimental results of corroded concrete beams, before their engineering implications are summarised.

2. Research significance

In addition to corrosion stains, cracks on the concrete surface along a corroded steel bar are another sign of corrosion of steel bars embedded in concrete members, which not only affects external appearance and serviceability of structures, but can also impair their residual capacity and service life.

An improved understanding of the initiating mechanism, development and controlling parameters of beam cracking would help design engineers to minimise the risk of corrosion cracks occurring in new structures. Particularly, it would assist practising engineers in their selection of the appropriate management strategy for corroded structures.

3. Analytical model and methods

Concrete beams that were analysed in this work were assumed to have rectangular cross-sections, be singly reinforced using four round steel bars with the same diameter, and be subjected to corrosion of the four steel bars simultaneously.

It was noted that both cracking and delamination of concrete beams due to steel corrosion are mainly caused by the radial expansion of corroded steel bars. The main purpose of this research was to understand the mechanism of initiation and development of beam cracking with particular reference to the influences of the relevant parameters. Therefore, the above three dimensional (3-D) reinforced concrete beams were idealised as two-dimensional (2-D) analytical models via their cross sections. Furthermore, taking into account of both symmetry of a beam section about its central line and the assumption that its four steel bars had the same diameter and corroded simultaneously, only one half of the beam cross section was taken as the analytical model, as shown in Fig. 2.

The vertical symmetrical line of the beam section was assumed to be restrained against rotation and horizontal displacement, but its other three sides were free. Each steel bar with a round circle of circumference within the beam section was modelled as a polygon with its 64 nodes equally distributed around the bar 'circumference' and mechanically pinned. The radial expansive behaviour of corroded steel bars was modelled by an increasing radial uniform displacement that takes place simultaneously at each of these nodes around each bar, as shown in Fig. 2. Such a radial expansion actually is imposed onto the internal surface of concrete cover around each bar and subjected confinement from surrounding cover concrete before its full cracking.

Three key design parameters, i.e., bar diameter, bar clear distance and concrete cover, as indicated in Fig. 2, which affect the corrosion cracking of concrete beams with the given properties of steel and concrete, were considered analytically. As summarised in Table 1, the bar diameters of concrete beams were taken as $d = 8$,