Construction and Building Materials 38 (2013) 846–853

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

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

Determination of residual cross-sectional areas of corroded bars in reinforced concrete structures using easy-to-measure variables

Xiao-gang Wang [a,b], Wei-ping Zhang [b], Xiang-lin Gu [b,*], Hong-chao Dai [b]

[a] School of Civil Engineering, Yantai University, 30 Qingquan Road, Yantai 264005, PR China
[b] Department of Building Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, PR China

HIGHLIGHTS

- ▶ Virtual modeling of corroded bars using 3D laser scanning technology.
- ▶ Precise sampling of severely corroded rebar cross sections aided with computer.
- ▶ Convenient and efficient models were built for area loss of rebar cross sections.

ARTICLE INFO

Article history:
Received 12 June 2012
Received in revised form 31 August 2012
Accepted 19 September 2012
Available online 29 October 2012

Keywords:
Reinforced concrete structure
Area loss
Carbonation
Pit corrosion

ABSTRACT

Area loss of corroded rebar cross sections is a crucial variable that is difficult to measure. In this paper, virtual models of corroded bars were built using 3D laser scanning technology; and, 693 severely corroded sections were screened to explore a practical way for the area loss determination. The results show that residual sections can be simplified into ellipses for general corrosion; otherwise, it can be ascribed to combined pit and general corrosion. Four spot penetration depths were taken as independent variables which can be easily measured. Based on the variables, regression models were developed and proven to be effective.

1. Introduction

Corrosion of reinforcement steel bars plays a harmful role in the service life of reinforced concrete (RC) structures. Intensive investigations have been focused on the deterioration of corroded RC structures in the last few decades, and abundant valuable results have been achieved [1–4]. In all these contributions, critical variables were necessarily employed to quantify the corrosion level. These variables usually took the forms of corrosion penetration depth, a weight loss ratio (percentage weight loss compared to the sound rebar for a certain length) and a cross-sectional area loss ratio.

In laboratory studies, corroded bars can be easily retrieved from specimens and cut into segments. Their weights are then measured after rust products have been cleaned. The corresponding weight loss ratio can be calculated through:

$$\eta_s = (m_0 - m_s)/m_0 \tag{1}$$

where η_s is the mass loss ratio or average cross-sectional area loss ratio, m_s is the weight of a corroded rebar segment and m_0 is the weight of a sound steel bar of the same length.

Based on the weight loss measurement, the average corrosion penetration depth can also be approximately calculated through:

$$P_{av} \approx \frac{m_0 - m_s}{m_0} \cdot \frac{D_0}{4} \tag{2}$$

where P_{av} is the average corrosion penetration depth, and D_0 is the diameter of the sound steel bar. Herein error of the equation should be noted in the situation of severe corrosion when the ratio of P_{av}/D_0 getting greater.

These variables represent the average corrosion level of corroded bars over a certain length. However, due to the non-uniform corrosion characteristic, the area loss of severely weakened cross sections (e.g., at a pitting site) could be several times higher than the average value determined through the method described above. It has been observed that the maximum pit depth could reach as high as 8–10 times the average penetration depth [5,6]. As shown by previous studies, performance degradation of corroded rebar is correlated better with the weakening of severely

---

* Corresponding author. Tel./fax: +86 21 65982928.
E-mail addresses: wxgnet@163.com (X.-g. Wang), weiping_zh@tongji.edu.cn (W.-p. Zhang), gxl@tongji.edu.cn (X.-l. Gu), dhc_111@126.com (H.-c. Dai).

0950-0618/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.conbuildmat.2012.09.060

corroded sections than the average corrosion level [7,8]. Ignoring this effect of spatial variability of corrosion would consequently lead to an overestimation of structural reliability [9].

It is also of great importance to find a method for the determination of area loss of a single severely corroded cross section in field applications. In reliability assessments and service life predictions for existing corroded RC structures, concrete cover can be readily removed to ascertain the real corrosion situation of the reinforcing steel bars. In this case, the average corrosion variables are inconvenient to be implemented, because cutting of the corroded bars for weight loss measurements would impose great damage to the structures. Certainly, spot corrosion depths can be easily measured with instruments, such as vernier calipers; however, there is no easy way to calculate the area loss based on these data. Although some relevant mathematic models have been proposed in previous studies, they have all been based on rather simple hypotheses of pit configuration and are far from being precise [9,10]. Additionally, ascribing cross-sectional area loss merely to a single pit seems to be inappropriate, according to Yuan's research results [11].

In this investigation, rebar specimens under carbonation-induced corrosion and chloride-induced contamination were first obtained. An advanced three-dimensional (3D) laser scanning technique was then employed to build virtual models for the corroded bars with the aid of a computer. These virtual models were the exact duplicates of real bars, through which any required physical dimensions, such as pit depth, cross-sectional area loss and weight loss ratio, could be measured precisely and conveniently. The aim of this research work, thus, was a practical way to determine the area loss of severely corroded cross sections based on easy-to-measure variables, namely the spot corrosion penetration depths, which can be easily measured using instruments.

2. Specimen preparation

Corroded rebar specimens in this research work came from two sources. The first source were 14 corroded bars, with original diameters of 12 mm and lengths varying from 300 to 600 mm, from RC slabs of a small inland culvert that was constructed about 19 years ago and suffering from poor concrete quality. The average weight loss ratios of the bars ranged from 1% to over 40%. It can be said that the corrosion was caused by carbonation, rather than chloride attack, considering that measured carbonation depths far surpassed (about 12 mm on average) the cover thickness and that the inland culvert of a low-grade highway was not subjected to deicing salt.

The second source was an accelerated corrosion test using the impressed current method. Fig. 1 shows a schematic drawing of the 12 concrete slabs (150 × 300 × 400 mm) in which 36 steel bars were embedded. The diameter of these bars varied from 14 to 20 mm; and, they all extended out of concrete for 50 mm at one end of the slab, in order to be connected with the direct current (DC) supply. The concrete of the slabs was mixed with Portland cement, coarse aggregates with a maximum diameter of 25 mm, sand and tap water. The adopted water-to-cement ratio was 0.55, and the ratio of cement: sand: coarse aggregate equaled 1:1.47:3.29. Additionally, sodium chloride (NaCl), 3% by weight of cement, was premixed during the concrete casting.

The concrete slabs were cured at room temperature for 28 d before the accelerated corrosion started. Fig. 2 shows the test setup. The embedded stainless steel bars were used as cathodes, and the reinforcing bars to be corroded acted as anodes. During the corrosion process, the slabs experienced dry and wet recycles; simultaneously, a constant current was applied to generate a current density of 200 $\mu A/cm^2$.

The maximum predefined weight loss ratio was 30%; therefore, the required time duration can be calculated using Faraday's law:

$$t = \frac{ZF \cdot r \cdot \rho \eta_s}{2A \cdot i} \tag{3}$$

where t is the required time duration (seconds); Z is the valency of the reacting anode, which is 2 in this case (iron); F is Faraday's constant ($F = 96{,}500$ A s); r is the radius of the corroded bar (cm); ρ is the density of iron ($\rho = 7.87\ g/cm^3$); A is the atomic mass of iron ($A = 56$ g); and, i is the current density (A/cm^2). The designed weight loss ratio of the rebars ranged from 5% to 30%. After the accelerated corrosion finished, all the bars were retrieved, and the rust was cleaned.

3. Virtual modeling and cross section sampling

After the rebar specimens had been prepared, surface scanning was run on all specimens using a 3D laser scanning instrument. After this operation, the 3D coordinates of each point (i.e., the point cloud) on the surface of the corroded rebar were acquired. Data not belonging to the corroded rebar were rejected by using Geomagic Studio® software to get more realistic point cloud files with the higher signal-to-noise ratios of the data. The acquired point cloud data were processed using Unigraphics NX3.0® software to construct lattice-planes, which were subsequently curved and seamed into shell models. Finally, solid models were formed in PRO/E software after the materialization process, as shown in Figs. 3 and 4, which illustrate the typical segments taken from the virtual models at different corrosion levels.

Through observation of the virtual models, it was clear that the corrosion was not evenly distributed circumferentially and longitudinally, regardless of whether it was induced by carbonation or chloride penetration. Additionally, pits of different shapes and sizes were quite obvious for the second case, as seen in Fig. 4.

As previously mentioned, the severely weakened cross sections are of the most concern in this investigation. These sections can only be determined by visual inspection when dealing with real corroded bars. To avoid possible subjective error and take full advantage of established 3D models, this process was done in a more elaborate way. First, planes perpendicular to the corroded bar were used to cut the bar into slices at intervals of 1 mm using PRO/E software. The areas of the obtained sections were then measured by the software and subsequently plotted into a distribution

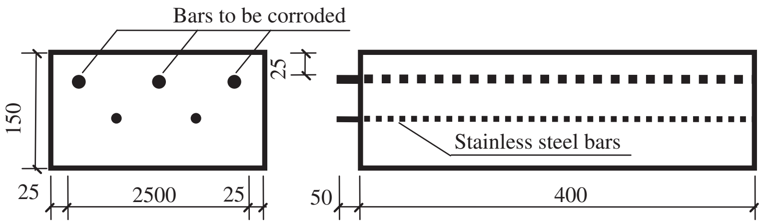

Fig. 1. Geometry of concrete slabs (unit: mm).