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Time-varying relative displacement field on the surface of concrete cover caused by reinforcement corrosion based on DIC measurement

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HIGHLIGHTS

- Full-scale observation of the relative displacement variation using DIC measurement.
- The cracking process due to corrosion of reinforcement.
- Influence of stirrups and longitudinal reinforcement on corrosion cracking.
- A probable cracking zone identification.

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ABSTRACT

To investigate the cracking process of concrete cover due to corrosion of reinforcement for concrete specimens subjected to semi-immersed accelerated corrosion, digital image correlation (DIC) was applied to quantitatively and visually characterize the development of relative displacement on the viewed surface. The impacts of stirrups and concrete cover thickness on the evolution of relative displacement were interpreted. And a detailed analysis covered the initial cracking time, position and relative displacement distribution on the surface during the cracking procedure. The study indicates that the corrosion of stirrups is prior to longitudinal reinforcement as the longitudinal reinforcement is cathodic protected by stirrups. The full-scale monitoring on the relative displacement reveals that a thicker concrete cover can retard the initial cracking but will promote the propagation speed of corrosion cracks. The investigation on the initial cracking zone implies that the initial cracking has high probability to appear within a region and its width is approximately close to the concrete cover thickness.

1. Introduction

The durability deterioration of reinforced concrete structures has drawn more and more attention in the last decades. Chlorides erosion should induce corrosion of reinforcement which is believed to be one of the main reasons that will cause durability deterioration of structures [1–3]. The volume expansion of corrosion products changes the stress state of concrete around reinforcement, and furtherly leads to cracking of concrete cover. Reinforcement corrosion-induced cracks can undermine the bearing capacity of structures. Meanwhile, cracks provide quick and effective passages for corrosive medium from outside into concrete. Thus, the research on the whole cracking process of concrete cover induced by corrosion is of great importance for the performance analysis and service life prediction of reinforced concrete structures.

Among all the influential factors, damaged stirrups and concrete cover thickness were believed to have very significant impacts on corrosion cracking of concrete structures. In 2006, Christopher [4] experimentally investigated the characteristics of stirrups corrosion-induced crack and proved that stirrups corrosion reduced shear capacity of beams. Coronelli et al. [5] studied the relationship between stirrups configuration and cracking patterns through experiments in which both longitudinal reinforcement and stirrups were corroded simultaneously. Their study clearly addressed the importance of stirrups for the assessment of deteriorated structures. Saeki [6] and Ravindrarajah [7] evaluated the influence of concrete cover thickness on the initial cracking time qualitatively. Afterwards, the research of Rasheeduzzafar [8] and Alonso [9,10] implied that the corrosion crack width was linearly related with corrosion rate. But for a long time, the measuring technique of corrosion cracks was always a difficult issue during the research.

In some early studies, scholars [5,10] detected the corrosion-induced cracks mainly through naked eyes and microscopes. These

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methods are very effective in observing the crack patterns, but they can't quantitatively represent the change of displacement on the surface of specimen before initial cracking, which is extremely important for the assessment of the deterioration of concrete structures indeed. In last decade, Goitseone Malumbela [11–14] evaluated and monitored the generation and propagation of corrosion-induced cracks of reinforced concrete utilizing strain gauges. While the data collected from a strain gauge essentially reflect the average strain variation within the length of the gauge. Therefore, a strain gauge matrix is always applied, covering the whole surface of concrete specimen, to exhibit a complete strain distribution. Meanwhile, the direction and value of the principle strain at a measuring point can't be obtained from one stain gauge and a gauge rosette is usually necessary to achieve the complete information of the strain field on the surface. Furthermore, the strain gauge technique is merely workable on measuring the continuous displacement of concrete. Once corrosion cracks generate or expand across a strain gauge, the measurement will be invalid. In summary, both the naked-eye observation and strain gauge technique belong to passive measuring methods. The measuring results highly depend on the corrosion cracking process and cracking path which is proved to be unpredictable. As a result, some scholars proposed innovative methods to replace strain gauge technique among which the digital image correlation (DIC) method had caused raising concern recently.

DIC measurement was proposed By Yamaguchi [15] and Peters [16] in the early 1980's. It is a modern optical method for non-contact measurement of overall displacement on the surface of materials. It gets the displacement field on the object's surface by tracking the movement of exterior markers, using method of image correlation matching to obtain speckle image before and after distortion. Due to the advantages of real-time, dynamic and non-contact measurement, many scholars have used DIC to study the damage [17,18], displacement [19] and destruction [20,21] of concrete. But the DIC-based study of the evolution of relative displacement field on the exterior surface of corroded reinforced concrete is still rare.

In this research, the influence of stirrups and the cover thickness on the relative displacement field for the surface of corroded reinforced concrete was investigated based on three-dimensional DIC measurement, covering the entire process of corrosion-induced cracking. And the moment and position corresponding to initial cracking were discussed in considering the corrosion of reinforcement.

2. Three-dimensional DIC measurement

The three-dimensional DIC measurement is established based on digital image correlation and stereovision technologies. The displacement analysis using DIC consists of comparing two images, a reference image and a target image, respectively. Before calculation of relative displacement, a region of interest (ROI) should be set on the reference image. And local displacements are determined at points in the ROI by correlating small sets of pixels through grey level and relative location. The correlation scores are assessed by measuring the similarity of the fixed subset window in the reference image to a shifting window in the target image [22]. It is reasonable that the matching accuracy of the two subset windows increases with the growth of similarity, which is quantitatively indexed by the correlation coefficient K as:

$$K = \frac{\sum\sum[f(x,y)-\bar{f}]\cdot[g(x',y')-\bar{g}]}{\sqrt{\sum\sum[f(x,y)-\bar{f}]^2\cdot\sum\sum[g(x',y')-\bar{g}]^2}} \tag{1}$$

where f(x,y) is the grey value of the point (x,y) at the reference image; g(x′,y′) is the grey value of the point (x′,y′) at the target image; $\bar{f}$ and $\bar{g}$ correspond to the average grey value of the subset window in ROI of the reference image and target image, respectively.

Once the correlation coefficient K exceeds a threshold value which is usually set as 0.95, a one-to-one correspondence between two points in the reference and target images may be established. Then, the displacement can be calculated from the distance of these two points. The stereovision applied here is to eliminate the influence of out-of-plane displacement on measuring results. The three-dimensional displacement can be reconstructed from the point correspondences using triangulation, and the corrected data is furtherly used to calculate the displacements field on the viewed surface. In derivation of the displacement at a measuring point in ROI, a partial least squares method is mathematically applied to reduce noise of the measured results [23,24]. In this research, the DIC measurement covered the whole cracking process including the generation and propagation of corrosion cracks. Strictly speaking, a strain analysis can't demonstrate the discontinues displacement around corrosion cracks. As a result, the relative displacement, instead of strain, is used to evaluate the measuring results collected from different specimens. It should be emphasized that the relative displacement has the same meaning as strain at the area containing no cracks. The relative displacement μ can be expressed as:

$$\mu = \frac{\varepsilon'_x + \varepsilon'_y}{2} + \sqrt{\left(\frac{\varepsilon'_x - \varepsilon'_y}{2}\right)^2 + \left(\frac{\gamma'_{xy}}{2}\right)^2} \tag{2}$$

where ε'_x is transverse relative displacement; ε'_y is longitudinal relative displacement; γ'_{xy} is shear relative displacement.

3. Experimental procedure

3.1. Specimen preparation

Influence of stirrups and concrete cover thickness on the relative displacement field was studied utilizing orthogonal test. Four kinds of specimens were designed including specimens with and without stirrups, as well as the specimens with cover thickness of 20 mm and 30 mm respectively. The details of the specimens are listed in Table 1. All specimens have the same size as 100 × 100 × 400 mm. Each specimen is reinforced with a plain steel bar whose diameter is 10 mm. To connect the external power supply, the plain bar extends out of the specimen for 20 mm on both ends. The stirrups consist of 6 mm plain steel bars spaced for 100 mm. And the detailed configuration of reinforcement in specimens can be seen in Fig. 1.

The cement used in this research is Portland cement with the grad of PO52.5. River sand with the fineness modulus of 2.64 is utilized as the fine aggregate. And the coarse aggregate is crashed gravel with a continuous grad ranging from 5 mm to 20 mm. The mix proportion of cement: water: fine aggregate: coarse aggregate is 1:0.53:2:3 for the concrete used in this experiment. The compressive strength of concrete at 28 d is 46.3 MPa.

Before the experiment, the air voids on the surface of concrete specimen was filled with a layer of plaster to achieve a smooth

Table 1
Details of reinforced concrete specimens.

Specimen No.	Thickness of concrete cover/mm	Stirrups configuration	Duration of corrosion/h
L20Y	20	Yes	298
L20N	20	No	81
L30Y	30	Yes	336
L30N	30	No	93