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Strain Field of Reinforced Concrete under Accelerated Corrosion by Digital Image Correlation Technique

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Abstract

The strain evolution and crack pattern of reinforced concrete attacked by accelerated corrosion have been studied using strain gauges and the digital image correlation (DIC) technique. Results show that there was good consistency between DIC and the classical strain gauges in the strain evolution of corroding reinforced concrete. Moreover, the strain field and crack behaviour of reinforced concrete could be tracked by DIC image pattern intuitively and its stress could also be calculated by DIC quantitatively. However, the micro-deformation of reinforced concrete could not be obtained by DIC because of its test accuracy. When reinforced concrete was attacked by accelerated corrosion, the expansion stress was applied to the upper zone of reinforced bar, and the compressive stress was applied to its bottom zone. And the failure model of reinforced concrete was mainly in a brittle manner.

1. Introduction

In marine environment, reinforced concrete is widely used as a construction material for infrastructures. But the chloride and sulfate ions in marine environment would penetrate into the concrete cover and induce the depassivation and corrosion of the reinforced bar (Cheewaket al. 2012; Yu 2004), which could result in corrosive cracking and carrying bearing capacity loss, and ultimately damage the concrete structures (Jin et al. 2015; Bilcik et al. 2012). Therefore, the corrosion of reinforced bar induced by salinity has been considered a major threat to the durability of structures. The deterioration of the steel bars due to corrosion has contributed to more than 80% of all the damages in reinforced concrete structures (Biezma et al. 2005; Hou 2012; Moradillo et al. 2012). In severe environments such as marine tidal zone, corrosion rates even exceed 500 μm/year (Costa 2002).

The tensile strength of concrete and expansion stress induced by the corroded reinforced bar are key parameters to the crack time of reinforced concrete, which has directly relation to the service life of the concrete structure in a marine environment (Jin et al. 2016). It is extremely tough to test the expansion stress of the reinforcement corrosion in concrete directly, but the elasticity modulus and deformation evolution induced by reinforcement corrosion could be tested, which is helpful to this issue. Ballim et al. (2003) and Malumbela et al. (2009, 2010) have preliminarily proven the possibility of the considerations above toward midspan and lateral deformation in concrete using strain gauges. The classic measurement techniques, such as strain gauges extensometers and linear variable differential transformer sensors (LVDTs) could not provide precise estimations of strain fields or for an early crack detection. The strain gauges usually break locally at critical sections close to failure. In addition, strain gauges only measure strains at fixing points and in the direction of the gauges alignment, and therefore, they do not provide a full-field analysis. Additionally, the crack pattern and process tracking of reinforced concrete induced by corrosion of steel bar are helpful to reveal the performance evolution and predict residual service life of concrete structure. The crack pattern of concrete induced by non-uniform and localized corrosion of steel bar has been studied by Qiao (2016). And the electro-mechanical model for evaluating the corrosion—induced damage in reinforced concrete has also been proposed by Qiao (2016), which provides an accurate means to continuously monitoring the crack developing process of corroded reinforced concrete.

Digital image correlation (DIC) is a fully non-destructive and non-contact measurement tool that is used to track the surface displacements of deforming materials. It is simplicity in use and the continuous measurements up to failure of concrete. And DIC has also proven to be an ideal tool for a wide range of applications, including the identification of the mechanical material behavior, structural health monitoring (Sas et al. 2012) and the study of the deformation characteristics of a wide range of materials. With the DIC technique, the deformation and crack process of reinforced concrete...
exposed to corrosion environment could be tracked, and the deformation and strain value would be used to calculate the expansion stress on the surface of reinforced concrete induced by corrosion of reinforced bar. And then the relationship between expansion stress and corrosion time could be proposed. When the expansion stress is higher than tensile stress of reinforced concrete, crack would be inevitable. Therefore, the crack time and crack process of reinforced concrete induced by corrosion of reinforced bar could be gained based on monitoring data of DIC. It also means that the propagation stage of service life of reinforced concrete could be proposed by DIC technique.

With the aim of continuously monitoring the strain field developments and the cracking process of reinforced concrete under accelerated corrosion, the Digital Image Correlation technique is used. The results of this study are useful for corrosion expansion stress calculation and service life prediction of reinforced concrete in the severe environment.

2. Experiment and materials

2.1. Materials and specimen preparation

P.I.52.5 Portland cement in accordance with Chinese standard GB175-2007, with a compressive strength of 59.8 MPa at the age of 28 days, was used in this study. Table 1 shows the chemical composition of cement.

The coarse aggregate are crushed granite with a maximum size of 25 mm. River sand with a fineness modulus of 2.6 was used as the fine aggregate. A polycarboxylic ether-based superplasticizer was used, and its modulus of 2.6 was used as the fine aggregate. The mixture proportions for the reinforced concrete were 1:1.58:2.37:0.33 for cement: sand: aggregate: water, respectively, and the compressive strengths of the concrete were 36.5MPa and 63.9MPa at the age of 7d and 28d, respectively.

The size of reinforced concrete specimens was 100×100mm×300mm. A carbon steel bar with 10 mm diameter was casted in the middle of the concrete specimen along its long side. The carbon steel bar was cleaned and coated with cement paste followed by epoxy coating at the concrete-air interface. The surface of the carbon steel bar was polished by 200# sand paper. The steel bars were degreased by acetone just before it was placed in the mold. Reinforced concrete samples were cast and placed at room temperature in the mold, which were subsequently removed after 48 h. Finally, all the specimens were cured under the condition of 20°C±3 °C and 95% relative humidity for 28 d.

2.2 Accelerated corrosion of reinforced concrete

The corrosion process of reinforced concrete exposed to marine environment is long term and imperceptible. So, constant potential accelerated corrosion system was often used to study the corrosion process of reinforced concrete. In order to simulate the actual situation and accelerate the corrosion process, the external electric field was applied and driven the chloride ions in seawater migrate to the surface of reinforced bar. A groove with size of 150mm×30mm×15mm was reserved on the upper surface of reinforced concrete and used to store seawater and place the stainless steel plate. And the carbon steel bar in reinforced concrete was connected to the positive electrode of potentiostatic power; the stainless steel plate placed into the seawater was connected to its negative electrode. Further, the electric potential was kept at a constant 30 V, and the current was checked every 1 h.

2.3 DIC technique for whole-field strain measurement

DIC is an optical-based whole field surface displacement and strain measure method. It’s based on pattern matching between two images of the specimen coated by random speckle pattern in the undeformed and deformed state. The basic principle of DIC method is to search for the maximum correlation between small zones (subsets) of the specimen image in the undeformed and deformed states. In deformation identification, a small part of the reference image is defined as the reference subset and the corresponding part on the deformed image as the target subset. The target subset can be searched by gray scale distribution. Thus, deformation measurement is transformed into digital correlation calculation and the displacements at the various points in the reference subset are obtained by subtracting the new coordinates from the original ones. The simplest image-matching procedure is the cross-correlation, which provides the in-plane displacement fields \( u(x,y) \) and \( v(x,y) \) by matching different zones of the two images. The cross correlation coefficient is given in Eq. (1) and for correlation, small sub regions over the digital image are compared (Kolanu et al. 2016).

\[
\frac{\sum_{i,j} f(x,y)g(x+i,y+j)}{\sqrt{\sum_{i,j} f(x,y)^2} \sqrt{\sum_{i,j} g(x+i,y+j)^2}}
\]

where \( f \) is mean intensity value of reference subset, \( g \) is mean intensity value of deformed subset; \( m \) is the subset width in pixels.

And the subsets coordinate of the specimen image in

| Constituent (wt%) | SiO\(_2\) | Al\(_2\)O\(_3\) | Fe\(_2\)O\(_3\) | CaO | MgO | TiO\(_2\) | Na\(_2\)O | K\(_2\)O | SO\(_3\) | Cl |
|------------------|---------|--------------|-------------|-----|-----|---------|--------|--------|--------|----|
| Cement           | 21.8    | 5.42         | 3.44        | 66.01| 1.26| 0.36    | 0.57   | 0.33   | 0.66   | 0.00|
the undeformed and deformed states is \((x, y)\) and \((x', y')\), respectively. And their relationship is as following.

\[
\begin{align*}
  x' &= x_0 + u + \frac{\partial u}{\partial x} \Delta x + \frac{\partial u}{\partial y} \Delta y \\
  y' &= y_0 + v + \frac{\partial v}{\partial x} \Delta x + \frac{\partial v}{\partial y} \Delta y
\end{align*}
\]

(2)

where \(u\) and \(v\) are the displacement of center of subsets along \(x\) and \(y\) direction respectively, \(\Delta x\) and \(\Delta y\) are the distance from \((x, y)\) to \((x_0, y_0)\). \(\partial u/\partial x\), \(\partial u/\partial y\), \(\partial v/\partial x\), \(\partial v/\partial y\) are the first derivative of the displacement, that is the strain of subset of specimen image.

The DIC is affected by the lightning conditions, surface roughness, angle and distance change of the focused point, off-plane displacement and noise of digital camera. A reasonable way to decrease even eliminates the error caused by off-plane displacement and correction factor ‘k’ has been investigated by researchers (Dai et al. 2013; Wang et al. 2012). And previous studies using DIC and strain gage measurements by the authors have shown the errors in DIC strain measurements are less than 50 micro strains (Kashfuddoja et al. 2015). The experiment results from Hamrat et al. (2016) and Wang et al. (2012) suggest that the classical measurement techniques (strain gauges, LVDT sensors) and the DIC technique are suitable for the analysis of strain components. And the DIC technique is an efficient measuring tool for obtaining displacement and strain fields during all the loading process from the start until failure. DIC has been successfully applied to various mechanics and deformation measurements by other researchers (Aggelis et al. 2013; David et al. 2007; Liu et al. 2014; Wu et al. 2011).

In the DIC test, two digital cameras with 75 mm macro lens were mounted to capture images of 100×100mm² cross section and the upper surface of the specimen. And an image half hour was grabbed using software. The digital cameras have a resolution of 1200×1600 pixels and give 256 levels of gray output. For this resolution, one pixel in the image represents approx. 80 μm square on the specimen, which is considered sufficient to determine displacement measurement with 4μm accuracy. Two LED light sources were placed above the testing area of concrete specimens to get an adequate image contrast. The LED light sources, cameras and reinforced concrete specimens were fixed on shockproof desk and didn’t move throughout the testing processing. The shockproof desk could barrier against 93%, 99% and 99.7% of vibration with frequency of 2Hz, 5Hz and 10 Hz. And a uniform/random speckle pattern was applied on the upper surface and cross section of the specimens, as shown in Fig. 1.

In order to compare the strain value measured from conventional measurement devices with those of the DIC system, the conventional measurement devices, strain gauges were employed to measure the deformation around the reinforced bar. The testing measurement system of reinforced concrete under accelerated corrosion with DIC and strain gauge were shown in Fig. 2.

3 Results and discussion

3.1 Electric current

Reinforced concrete specimens were polarized by a constant voltage of 30 V, and the current change with time was shown in Fig. 3. The electric current decreased fast at the early stage, and kept stable to concrete cracks. And then the electric current increased quickly due to the seawater penetration into the surface of reinforced concrete through the crack. With the crack filled with increasing corrosion production, the electric current increased slowly again. When the penetrating crack was shown in the reinforced concrete, the electric current jumped to about 2.5 times of the initial value. According to the evolution of electric current, the time of initial crack and penetrating crack of reinforced concrete was 160 h and 256 h respectively.

3.2 Strain field evolution around reinforced bar

The area around reinforced bar in 100×100mm² section of reinforced concrete with pixel coordinates 600×600 in the image was selected, which is shown in Fig. 4. The strain field evolution in these areas was calculated by DIC technique and was plotted in Fig. 5. Obviously, the strain field evolution of reinforced concrete under accelerated corrosion could be tested by DIC.
The value of strain could be ignored before 248 h corrosion. When reinforced concrete corroded for 256 h, the maximum value of strain on the surface of reinforced concrete increased to 15000 με sharply. And the maximum strain increased to 800000 με when the sample corroded for 304 h.

Based on the strain cloud maps, the strain evolution in location of the strain gauge was calculated and plotted as shown in Fig. 6. Obviously, the expansion tension stress induced by the corrosion of reinforced bar was applied to concrete in the upper zone (Area No.1) and the right zone (Area No.2) of reinforced bar, and compressive stress was applied to concrete in the bottom zone (Area No.3) of reinforced bar. The concrete in the left zone (Area No.4) of reinforced bar bears compressive stress firstly, and when penetrating crack occurred in concrete it bears tension stress.

Fig. 3 Electric current evolution of reinforced concrete.

Fig. 4 The location of reinforced bar and strain field analysis area (1 pixel=0.11 mm).

Y. Jiang, Z. Jin, T. Zhao, Y. Chen and F. Chen / Journal of Advanced Concrete Technology Vol. 15, 290-299, 2017
Fig. 5 The strain field around reinforced bar in different corrosion time (symbols 'H'-hours).

Fig. 6 Strain evolution in Area No.1-4 around reinforced bar under accelerated corrosion.
The strain measurements obtained by electrical resistance strain gauges around reinforced bar are shown in Fig. 7. The rule of strain/stress field evolution around reinforced bar tested by DIC and the strain gauge are consistent. The accuracy of the strain gauge and DIC was about $1 \mu \varepsilon$ and $80 \mu \varepsilon$ respectively. The micro-deformation of concrete was reflected by the strain gauge, and the crack process of concrete could be tracked by DIC after the strain gauge was broken when crack occurred on concrete. Figure 8 presents a comparison between the strain obtained by electrical resistance strain gauges and the strains calculated by the DIC technique.

3.3 Crack process of concrete tracked by DIC

The images of reinforced concrete with speckle pattern in the later corrosion stage have been captured. It’s difficult to intuitively show the cracking process of concrete with speckle pattern because the black and white binary images were photo by CCD camera. But, the DIC could offer the deformation and strain values on the surface of reinforced concrete, the cracking pattern and process of concrete under accelerated corrosion could

![Fig. 7 the strain field around reinforced bar tested by strain gauge](image)

![Fig. 8 Comparison between the strains measurements obtained by strain gauges and DIC](image)
be obtained. The original images and cracking process of reinforced concrete were shown in Fig. 9. The brittle crack of concrete under accelerated corrosion could be observed, and the crack width in upper zone of concrete would be kept stable and even be narrowed due to crack occurred on other areas around reinforced bar. According to the DIC profiles, the 10 hours deformation (before and after crack) of the concrete around reinforced bar was calculated and presented in Fig. 10. Additionally, the deformation of concrete from reinforced bar to the upper surface of concrete, and the surface of concrete in area No.5 was also calculated and shown in Fig. 11. As can be seen, the crack pattern and deformation could be reflected by DIC technique with image format directly and data format quantificationally.

4. Conclusions

The following conclusions can be drawn from the present experimental work using the DIC measurement technique and classical strain gauges:

1) The comparison between the classical measurement techniques such as strain gauges and the DIC technique suggests that the two techniques are suitable for the analysis of strain field of concrete induced by corrosion of reinforced bar. The good agreement about strain and stress field evolution between the two measurement methods indicates that the DIC technique is an efficient measuring tool for obtaining displacements and analyzing strain fields during corrosion of reinforced concrete.
2) Measurements of strains and crack process at or after failure of reinforced concrete are possible with DIC technique compared to the classical methods. However, the test accuracy of DIC is lower than that of strain gauges, and it’s difficult to track the micro-deformation of corroding reinforced concrete.

3) When reinforced concrete was attacked by accelerated seawater corrosion, the tension stress induced by the corrosion of reinforced bar was applied to concrete in upper zone of reinforced bar and the surface of concrete, and compressive stress was applied to concrete in bottom zone of reinforced bar. The brittle failure occurred on reinforced concrete under accelerated corrosion.

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