Experimental investigation on the dynamic properties of RC structures affected by reinforcement corrosion

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SUMMARY:
RC structures in service may be suffered from environment attack, especially the rebar corrosion, which may lead to the deterioration of both static and dynamic properties of concrete, and therefore jeopardize their performance in earthquake events. For studying the dynamic properties of RC structures affected by reinforcement corrosion, an electro-chemical accelerated corrosion process was introduced to beams and frames. Then, damping properties of RC beams with different corrosion degree were obtained by the method of 3-point bending beam damping measurement and cantilever beam free vibration. Furthermore, the dynamic tests were carried out to study the fundamental frequency and damping ratio of control frame and frames which designed degree of corrosion damage is 10%, 30% respectively. The experiment results show that the influence of corrosion damage on fundamental frequency and damping ratio is significant. This investigation provides further insight on the use of fundamental frequency and damping ratio to detect damage in RC structures.

Keywords: RC structures; rebar corrosion; damping ratio; fundamental frequency

1. INSTRUCTIONS

The safety and serviceability of RC structures are time-dependent due to degradation phenomena. It becomes increasing important for the durability of structures. Both European and Italian standards have recently renewed their attention to the durability of RC constructions. According to the investigation of NBS in 1975, the cost induced by kinds of corrosion was over 70 billion dollar in America and 40 % of the cost was induced by reinforcement corrosion. It is significant therefore to evaluate the influence of reinforcement corrosion on the dynamic properties of RC structures.

Among the most frequent environment attacks affecting RC structures, reinforcement corrosion is manifested by affecting the reinforcing steel, surrounding concrete and the mutual interaction between two materials. Two environment attacks may lead to reinforcement corrosion. One is the penetration of chloride ions, producing the so called "pitting corrosion". Otherwise, the carbonation process of concrete cover causes a more uniform corrosion pattern. The major available documents of reinforcement corrosion are focusing on mechanism of corrosion, assessment of strength, ductility and failure behaviour of structures affected by reinforcement corrosion. There are few research works considering the damping ratio, frequency of RC structures affected by reinforced corrosion. However, natural frequency is a good overview of the global structural condition. It was found to be a good indicator of damage. In this paper, for evaluating the influence of reinforcement corrosion on the damping ratio and frequency of RC beams and frames, the dynamic experiments were carried out.

2. DYNAMIC TESTS FOR RC BEAMS

2.1. Raw Materials and Specimens

In the test, Portland cement (strength grade was 32.5), medium sand, coarse aggregate (continuous grading, nominal dimension was 5~10mm) were used. The dimension of specimen was 60x60x900mm. Four identically-reinforced concrete beams were fabricated for this study and the reinforcement arrangement was shown in Fig. 2.1.

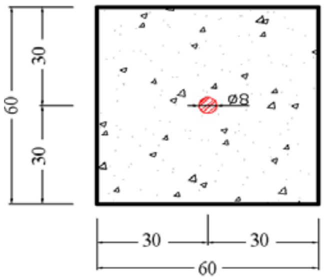


Figure 2.1. Reinforcement arrangement of beams

2.2. Cantilever Beam Free Vibration Test

The experimental instrument was shown in Fig. 2.2. The free vibration tests were performed by subjecting the beams to hammer impacts imposed near their free ends. As illustrated in Fig. 2.2, an accelerometer was mounted on the surface of beam end. After the hard impact, the cantilever beam was in free vibration. A time history curve of acceleration was got by accelerometer, then the damping ratio was calculated by formula (2.1),

$$\xi = (1/2n\pi)\ln(a_k / a_{k+n}) \tag{2.1}$$

Where ξ is the damping ratio; α is the amplitude of accelerometer; k, n is the number of different accelerometers.

Figure 2.2 Cantilever device for damping test

Figure 2.3. Three-point dynamic bending testing device

2.3. Three-point Dynamic Bending Test

The experimental investigation was carried out by the method of 3-point bending beam damping measurement (China Patent No: 200620020081.2) in room temperature. The test device was introduced in paper. The loss tangent and storage modulus of the reinforced concrete beam were calculated by the formula (2.2) and formula (2.3). The measuring apparatus for damping was as shown in Fig. 2.3.

$$\gamma = \frac{E''}{E'} = \frac{1}{1+\frac{Y_0}{P_0\cos\delta}\cdot\frac{\omega^2 ml}{2}} tg\delta \tag{2.2}$$

$$E' = \left[k\cos\delta + 2\pi^2 f^2 m\right]\frac{24l^3}{bh^3\pi^4} \tag{2.3}$$

Where P_0 is the amplitude of the excitation force; Y_0 is the vibration amplitude of the point located at the centre of the beam; δ is the phase shift between the excitation force and the displacement; I is the moment of magnitude of the surface area of the cross-section; m is the line density; f is the excitation frequency

2.4. Accelerated Corrosion

Galvan static method was used in order to accelerate the corrosion of steel-bar, the steel-bar was taken as anode, copper sheet as cathode and concrete as mediator. According to Faraday's law, the current intensity and time would be controlled to ensure the degree of corrosion. The specimen size was 60x60x900mm. The degree of corrosion damage can be expressed as formula (2.4),

$$it = 13441D(1-\sqrt{1-\rho_s}) \tag{2.4}$$

Where ρ_s is the reinforcement corrosion ratio; D is the initial dimension; i is the current intensity; t is the time to be controlled. The electro-chemical accelerated corrosion process was shown in Fig. 2.4. Four degrees of corrosion damage (0.2%, 0.4%, 0.8% and 1.6%) were obtained. The appearance of corroded beams was shown in Fig. 2.5.

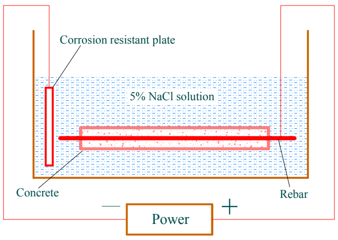


Figure 2.4. Electro-chemical accelerated corrosion device

Figure 2.5. The appearance of RC members after corrosion

2.5. Results and Discussion

Fig. 2.6. shows the influence of steel-bar corrosion on damping ratio and loss tangent. The damping ratio and loss tangent are fist decreased by steel corrosion, and then was increased when further corrosion occurs. In addition, the variation of damping ratio and loss tangent is consistent. In the corroded beams, the formation of rust products on the reinforcement contributed a significantly higher bond compared with the uncorroded or undamaged frame due to the surface roughness at the steel-concrete interface. For this dynamic test, the excitation energy induced by hard impact is low, so it is insufficient to disrupt the bond and it remained intact, preventing energy dissipation and thus giving more energy for vibratory motion compared with the undamaged frame. However, if the corrosion induced damage keeps on expanding, more cracks contributed to energy dissipation. The damping ratio and loss tangent was increased. Fig. 2.7 shows influence of steel-bar corrosion on loss modulus. The variation is opposite with the damping ratio and loss tangent

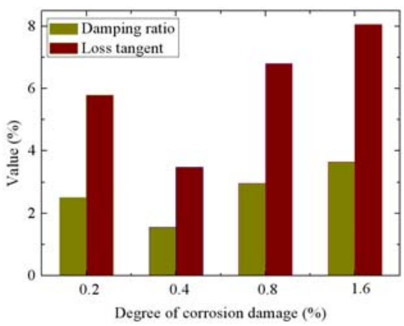


Figure 2.6. Influence of steel-bar corrosion on damping ratio and loss tangent

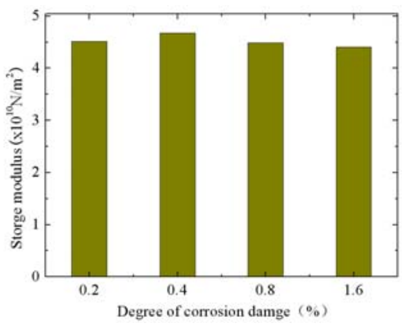


Figure 2.7. Influence of steel-bar corrosion on storage modulus

3. DYNAMIC TESTS FOR RC FRAMES

The experimental program was designed to investigate the effect of reinforcement corrosion on the frequency response and damping ration of frames. The dimension and reinforcements are shown in Fig. 3.1 and Fig. 3.2. The frames were fixed on a table. The four simulated stages of frames' service lives are: (a) healthy-control frame (denoted as H), (b) designed degree of corrosion damage being 10% (denoted as SC10) (c) designed degree of corrosion damage 30% (denoted as SC30). At the end of each stage, each frame was subjected to dynamic load tests to estimate its fundamental frequency and damping ratio.

3.1. Raw Materials and Specimens

According to the concrete used in civil engineering, a characteristic compressive strength of 30.0MPa was designed to use in the experimental study. The water-cement ratio was 0.51. The materials used were Portland cement of type 32.5, natural sand, coarse aggregate with maximal diameter 15mm and tape water. The concrete frames and two columns were cast in ligneous mode and then compacted by a vibrating table. Specimens were cured in a fog room for 28days. The 100-mm^3 cubic specimens were also cast to evaluate the cubic compressive strength of concrete.

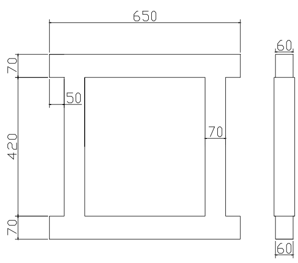


Figure 3.1. Dimension of the frame

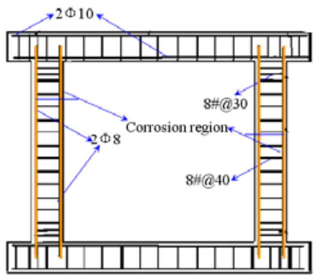


Figure 3.2 Reinforcement arrangement and corrosion region

3.2. Dynamic Load Tests

Dynamic load tests were performed on the frames by subjecting the frames to hammer impacts. As illustrated in Fig. 3.3, two accelerometers were mounted on the end of the beam. After the hard impact, the frame was in free vibration. A time history curve of acceleration was got by accelerometer. The fundamental frequency was obtained form the dynamic load test response using the Fast Fourier transform and the damping ratio was obtained using random decrement technique and Ibrahim Time Domain Technique.

Figure 3.3. Experimental instruments for dynamic test of frame

3.3. Accelerated Corrosion

An electro-chemical accelerated corrosion process was introduced to all frames but one control frame. Two columns were also accelerated corrosion at the same time which were used to evaluate the real steel loss induced by electro-chemical accelerated corrosion. An epoxy coating was applied on the surfaces of each beam and steel bars in beam to restrict corrosion to longitudinal steel bars in columns. As shown in Fig. 3.4, no sign of spalling was observed for all corroded frames. However, visual examination revealed that both columns of frames subjected to corrosion had cracks running longitudinally along the sides. Maximum longitudinal crack widths recorded were 1.0mm, 2.0mm for frames SC10 and SC30, respectively. The practical steel losses for designed degree of corrosion damage 10% and 30% were 14% and 35%, respectively.

a) Frame with steel loss 14%-SC10

b) Frame with steel loss 35%-SC30

c) Corroded column

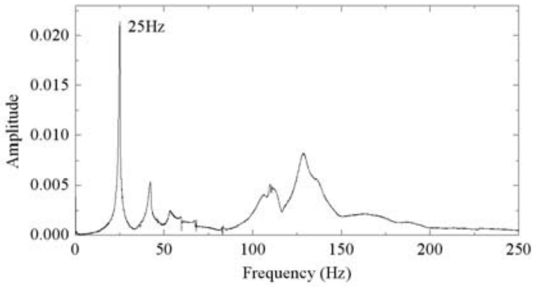
d) Cracks induced by corrosion damage

Figure 3.4. Appearance of corroded column and frame

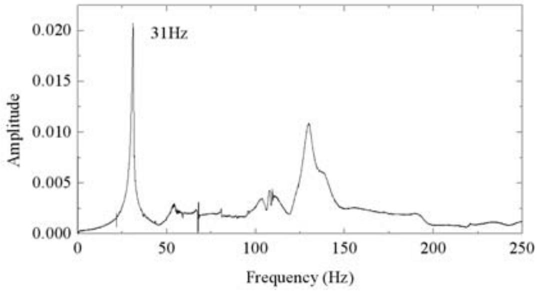
3.4. Results and Discussion

Fig. 3.5 shows the Fourier spectrum of the accelerometer. The highest peak shown in each spectrum corresponds to fundamental frequency of frames, at 25, 31 and 29Hz for stages H, SC10 and SC30. It is shown that substantial increases were observed in fundamental frequency after the accelerated corrosion process. This increase may be attributed to the enhanced bonding between the bars and concrete due to the formations of corrosion products. According to Maaddawy and Soudki's report, they suggested that rust increased the roughness of the bars and improved the bonding between the bars and concrete. Hence, at the initial stages of steel loss, corrosion improved the bond strength and stiffness. However, at advanced stages of steel loss, excessive corrosion produces accumulated around the bars resulting in reductions in both strength and stiffness.

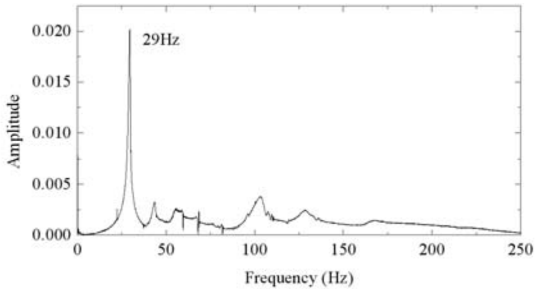
Fig. 3.6 shows the influence of steel corrosion on damping ratio. The damping ratios for the H, SC10 and SC30 frames are 1.6%, 2.5% and 1.1%, respectively. It indicated that the proper steel corrosion can increase the energy dissipation of the frame and there is a critical corrosion point which makes structural system has the maximal energy dissipation capacity. At the proper corrosion induced damage, the excitation energy makes the bond disrupted and the steel-concrete interface becomes detached, allowing much more energy dissipation compared with the undamaged frame. However, when the corrosion induced damage is in at advanced stage, the cracks are too large loosing the ability of energy dissipation.



a) Control frame



b) Frame with steel loss 14%



c) Frame with steel loss 35%

Figure 3.5. Fourier spectrum of accelerometer

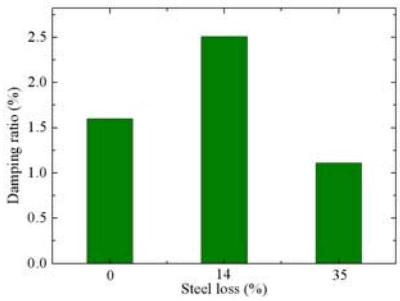


Figure 3.6. The influence of steel corrosion on damping ratio of frame

4. CONCLUSIONS

The influence of reinforcement corrosion on the frequency and damping response of beams and frames were reported in this paper. Several conclusions derived based on experimental results obtained in this paper may be summarized as follows:

(a) For RC beams, at four different stages of corrosion damage (0.2%, 0.4%, 0.8% and 1.6%), significant changes in damping ratio and loss tangent were detected. The damping ratio and loss tangent are fist decreased by steel corrosion, and then was increased when further corrosion occurs. The turning point is around 0.4%. In addition, the variations of damping ratio and loss tangent are consistent

(b) For RC frames, at three different stages of corrosion damage (0, 14% and 35%), substantial increases are observed in fundamental frequency after the accelerated corrosion process even the maximum longitudinal crack widths recorded were 1.0mm and 2.0mm. The proper steel corrosion can increase the energy dissipation of the frame and there is a critical corrosion point among 14%~35% which makes structural system has the maximal energy dissipation capacity. In addition, the variations of fundamental frequency and damping ratio are inconsistent.

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