The effect of different location of steel bar corrosion on RC beams' dynamic performances

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ABSTRACT: This paper presents a dynamic test of three corroded RC beams (with different damage zones). One beam with bending cracks at center part and an intact beam with the same dimension are also involved in this study. The effects of corrosion expanded cracks and the changes of natural frequencies of these RC beams, with different local steel bar corrosion damage, are correlated to the amount of corrosion and damage parameter of the beams' section. In addition, by modifying flexural rigidity of the beams with damage parameter of the beams' section, the results of finite element analysis, including model shapes and natural frequencies, agree well with testing results. The investigation provides that natural frequencies of RC beams are sensitive to steel bar corrosion and the residual bending capacity of RC beams correlate to the location of bar corrosion damage significantly. So it would be reasonable to evaluate the bar corrosion damage in RC beams by vibration measurement.

1 INTRODUCTION

1.1 *Problem statement*

Dynamic tests represent an inexpensive way to achieve abundant information on the mechanical behavior of a structure without a need for dismantling the structure. And this kind of technique makes it possible to determine structures' safety, reliability and operational life of which the structural health-monitoring problem consists. So for many years, experimental modal testing has become a significant topic in the field of structural assessment in RC engineering. From the changes of model characteristics of a construction building, such as natural frequencies, model shapes, and strain energy, one could obtain information about the damages existence, location and then estimate the extent of damages in the structures. But a lot of works should be done after these identification steps, such as: we need to know what kind damages them would be in order to find out an effective way to control or recover the damages.

This paper presents a summary of laboratory investigations carried out at the Civil Engineering Department in Hunan University, as part of a large study on the *corrosion damage consequences on reinforced concrete structures*, which include static, dynamic and fatigue testing of corroded reinforced concrete (RC) beams. In particularly, this paper discusses the relationship between corrosion rate, damage location and natural frequencies, model shapes obtained from experiments using simply supported RC beams subjected to accelerated corrosion.

1.2 *Aims of the investigation*

The corrosion of steel bar in concrete represents one of the leading causes of durability problems in RC structures, especially in aggressive environments. The basic problems associated with the deterioration of RC structures due to corrosion include: reducing mechanical strength of steel bar itself (Abdullah, 2001), weakening of the bond between concrete and steel bar (Cabrera, 1996) and expanding destroy of the covered concrete around the corroded bar (Roberto, 1995). Since the corrosion of ordinary steel is inevitable, even if they are embedded in concrete, it is necessary to detect and monitoring this kind of damage. Many corrosion engineers have employed a variety of electrochemical tools in order to determine the corrosion status of steel bars embedded in concrete (Nicholas, 1999). Although all these methods are sensitive to the corrosion damage, they not always efficient and facile in practice since many manual works are needed. In some cases, many places in construction buildings are not as easily to reach as we expected. So it is also important to improve knowledge on the relationship between rate of corrosion and dynamic parameters of constructions (Razak, 2001). Focusing on the testing results in this paper, we think that it is possible to identify corrosion damage in RC structure through analysis of their vibration characters.

2 EXPERIMENTAL DATA

2.1 *Experimental program*

The experimental data, which was used to verify the possibility to identify steel corrosion in RC structure, is obtained from experiments with five simple supported RC beams. Three of them were subjected to different location of steel bar corrosion, and one was cast with two artificial bending cracks, while the other one was intact beam, which acted as the control and contrast. The details of the test beams and the technique adopted to induce corrosion in the steel bar are described below. Longitudinal crack widths on the side of the beam were measured using a crack microscope.

2.2 *Geometry of the test beam*

All the five beams are 2.7m in length and have a same dimension of the cross section, which is shown in Figure 1. The cross section is a rectangle block along the testing members. The bar sizes in these beams are also presented in Table 1.

Table 1. Properties of steel bars

Bar No	Type	Diameter mm	Yield stress MPa	Ultimate stress MPa
1	Deformed	16	370	550
2	Deformed	12	370	550
3	Plain	6	260	350

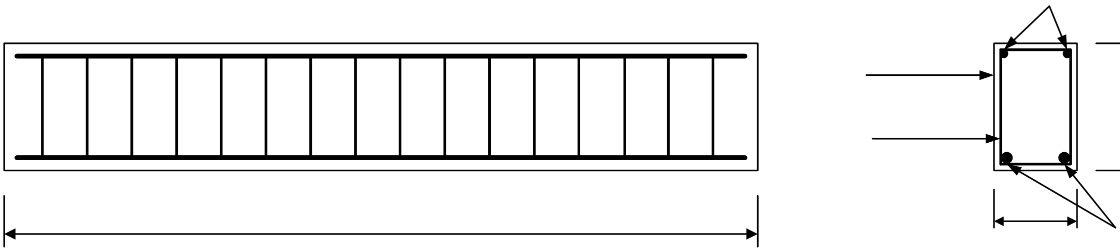


Figure 1. Geometry and reinforcement of the beams

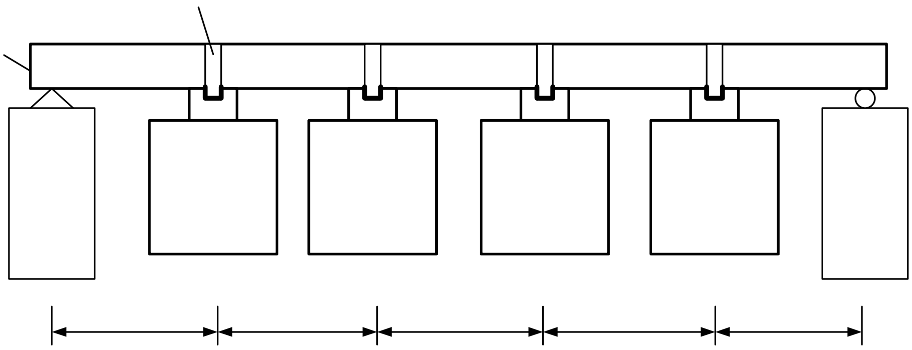


Figure 2. The schematic of the beams with 4 lumped masses

2.3 *Material properties*

The cement used in this investigation was normal 42.5# Portland cement conforming to JGJ 55—2000 in China. The concrete mixtures consisted of 1:2.27:3.17 cement, sand and gravel, respectively (proportion by weight). The cement content was 330kg/m^3 and the water cement ratio was 0.6.During casting of the beams, control specimens were taken in order to determine the mechanical properties at different ages. At each ages, compression test had been performed on three cubes (150mm), to obtain the actual compressive strength (listed in Table 2). And the properties of the steel bars (without corrosion) were determined by testing 3 specimens. The average value of tensile tentative results listed in Table 1.

Table 2 Average compressive strength of cubes

Age	14d	28d	3m
f_{ccube} (MPa)	19.1	26	30.2

2.4 *Lumped mass*

The schematic of the beams under study is shown in Figure 2. The beams are considered to be uniform of constant length l (2500mm). Each beam carries 4 lumped masses M , which were assumed attaching to the beam firmly, along the beam span. And the beam is separated into five parts (part A, B, C, D, E) by the lumped masses along the span, shown in Finger 2. The thickness of the beam is assumed to be small compared with the beam length, e.g., the ratio of the beam length to width is nearly to be 14, so that the effects of rotary inertia and shearing deformation can be ignored. Provided that the lumped masses M are placed symmetrically with respect to the beam length and the beam transverse motion can be considered to be purely planar as a slender member.

2.5 *Damage control*

There are two kinds of damages included in this study. One is local bending cracks, the other is local steel bar corrosion. And an intact beam without any damage is also included. The details of the testing beams are shown in Table 3.

Table 3. Test matrix

Specimen	Damage		
	Type	Location	Predicted degree
Corr_A	Corrosion damage	Part A	5% mass loss
Corr_B	Corrosion damage	Part B	5% mass loss
Corr_C	Corrosion damage	Part C	5% mass loss
BC_C	Bending cracks	Part C	Two cracks with 60mm high and 0.2mm width
Int	Without damage		

2.5.1 *Artificial bending cracks*

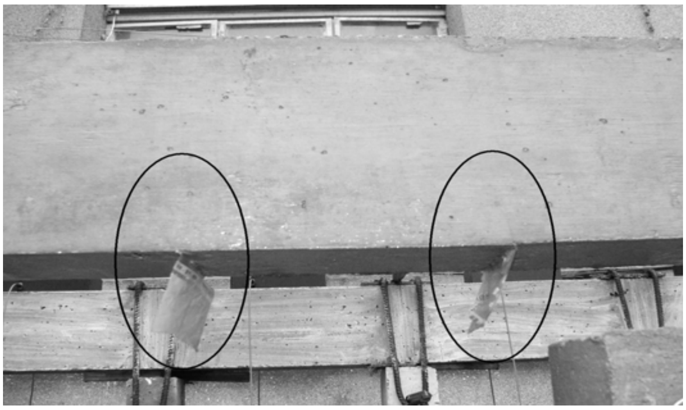


Figure 3. The artificial bending cracks in beam BC_C (two cracks and the remnant plastic patches circled by marks)

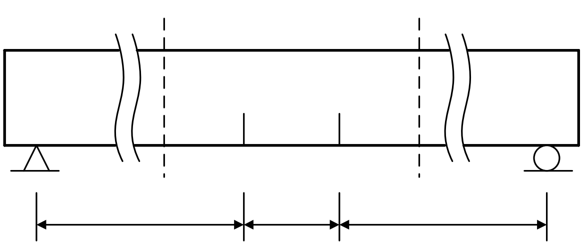


Figure 4. The schematic artificial bending cracks in BC_C

In order to simulate bending cracks, one beam (BC_C) was cast with two weak sections. At each of these sections, a piece of plastic (60mm high, 0.2mm wide) was put across the half below section. So the beam was segmented and became incompletely connected at this section. Figure 3 is the record photo of the two artificial bending cracks in beam BC_C, at Part C. Two of them were all placed in Part C in beam BC_C. One was located a distance 1150mm from left end of this beam, and the other located a distance 1450mm from left end of this beam (see Figure 4).

2.5.2 *Corrosion damage*

In order to complete the tests within a reasonable amount of time, two techniques were employed to accelerate corrosion. Firstly, to depassivate the steel bar in concrete, 3% NaCl by weight of cement was added to the concrete mix. Secondly, an impressed current technique (Maaddawy, 2003) is used. After 35 days maintenance, the beams(Corr_A, Corr_B, Corr_C) were put on the ground, and covered the expected corroded parts with sands, which constantly soaked with 3% NaCl solution. Figure 5 is the record photo of the beam covered by sand. So corrosion was induced by applying an electrochemical potential between the steel bar (anode) and an external copper plate (cathode). The potential applied was varied, in order to achieve a constant applied current density. The applied current was limited within 170mA to 200mA. With respect to Faraday's law, time for induced corrosion was calculated (nearly 90 days). Until the three beams reached the expected corrosion degree, they were put on bearings, and dynamic testing was processed.

Figure 5. Corr_B corroded part covered with sands

2.6 *Dynamic measurements*

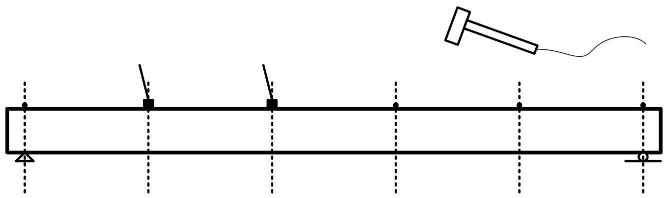


Figure 6. Location of accelerometers

Modal tests were performed on all testing beams. The accelerations were measured by means of piezoelectric sensor (see Figure 6), which had the sensitive to acceleration of maximum 100*g* within a frequency range of 5000Hz. Their weight can be neglected. In order to get a detailed measurement of the mode shapes, two sensors at point B and point C were used (see Figure 6). For the sensor a sampling rate of 2000Hz was used. And a hammer, with a force sensor at the top of it, was used to excitated vibration of these beams.

During the dynamic test, we hammered the beam from point A to point F (see Figure 6), and considered it is a pulse-excitation as each hammer. At the same time, record the input pulse force at the top of hammer, and the response singles (acceleration singles at point B and C). All of these digital singles recorded by the signal acquiring system DASP (made in China).

Followed these digital signals, the Me’scope system (Version3.0.0.25) was used to obtain modal parameters. In order to obtain the modal parameters, the transfer function method (Maia, 1997) of modal testing was adopted. This method is based on the use of digital processing techniques and the fast Fourier transform (FFT) algorithm to measure the transfer function between each input force record and signal response records on the test beams.

3 EXPERIMENTAL RESULTS AND DISCUSSIOONS

3.1 *State of corrosion*

After 90 days electrolyze, the beams subjected to corrosion (Corr_A, Corr_B, Corr_C) had cracks running both longitudinally along the soffit and transverse along the sides. The degree of corrosion damage was determined by the width of cover crack that results from such corrosion (Vidal, 2004). Cracking maps were drawn with the widths of the corrosion cracks (see Figure 7). The width of every transversal cracks generated by stirrups corrosion was recorded only at the side faces, since the value of them at different location are similar.

From Figure 7 we can see that each part was badly cracked. According to the results from other studies (Alonso, 1998), the most significant parameter influencing cracking initiation is the cover/diameter ratio. There are three kinds ratio in one beam (see Table 4), with the initial diameter of the steel bar and the exposed cover thickness. These values are used to verity the average corrosion degrees, which are calculate with Faraday’s law (Uhlig, 1971).

Table 4 Average ranges of cover/diameter ratios

Specimen	Stirrups	Longitudinal steel bar	
		Top bars	Bottom bars
Corr_A	1.2～1.5	1.1～1.3	0.9～1.1
Corr_B	1～2	1～1.2	1～1.2
Corr_C	1～2	1～1.5	0.7～1

3.2 *Modal test results*

A finite element beam model is constructed using five beam elements to simulate the simply supported beams in this study, as shown in Figure 8. Since there are four lumped massed on each beam, it is reasonable to built the mass matrix of this dynamic

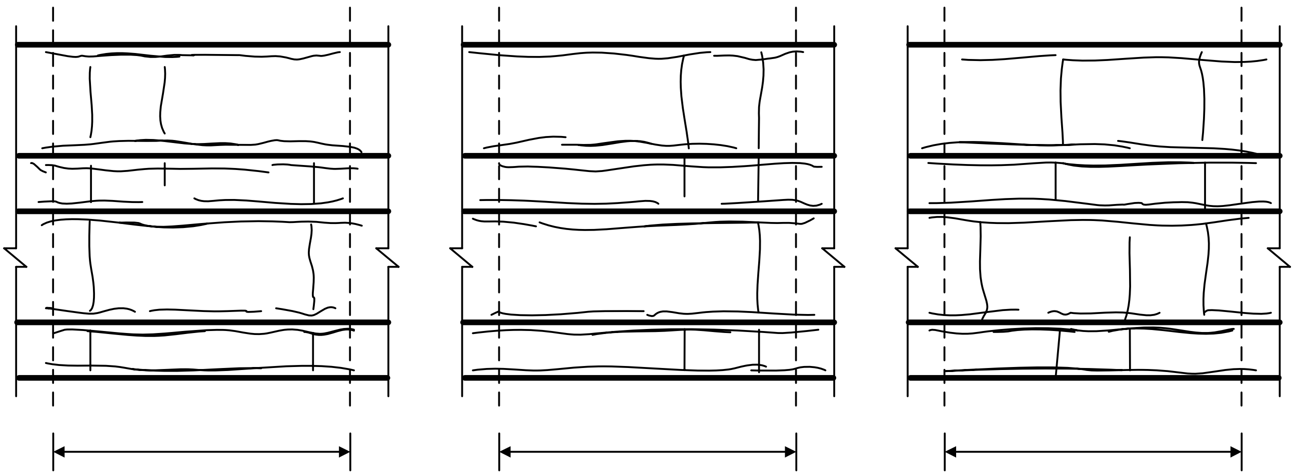


Figure 7. Cracking map of beam Corr_A, Corr_B, Corr_C

system as placing point(concentrated)masses m at node points of every beam element. The stiffness of the bearing springs, K_1 and K_2, were considered to be rigid enough, so the effect of boundary condition was neglect when our testing analysis was limited in the first four modes.

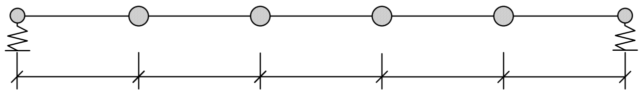


Figure 8. Simply supported beam with four lumped masses

3.2.1 *Natural frequency*

Obviously, corrosion crack is a kind of damage which would lead to a reduction in stiffness of these beams. Consequently, a reduction in stiffness leads to changes in the dynamic parameters, namely natural frequency and modal shapes (Clough, 1995). The magnitude of the changes is also an indicator of the severity or state of change experience. This is apparent in the changes in the natural frequencies of the damaged beams as compared to the control beam, for the first four modes, as shown in Table 5.

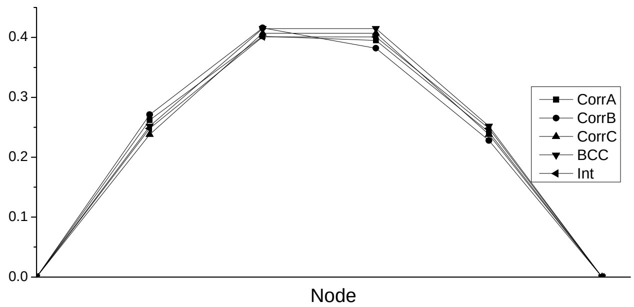
Table 5. The first for natural frequencies of testing beams (Hz)

Specimen	Mode			
	1	2	3	4
Corr_A	16	59.3	126.9	201.8
Corr_B	15.8	58	128.1	198.5
Corr_C	15.1	62.8	126.9	192.9
BC_C	15.6	64.5	127.3	206.4
Int	17.1	65.2	131.8	217.5

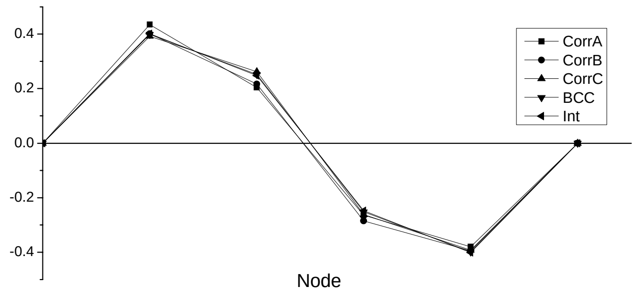
Table 5 shows, for various beams, natural frequency droping values of each mode depend on the corrosion locations and the damage degree. As the effect of corrosion was more severe in beam Corr_C, it experienced a greater reduces in natural frequencies. In general, it can also be observed that the trend of the magnitude of the change in natural frequencies increase with higher modes. The drop for beam Corr_C ranges from 3.7% to about 11.5%, while the range for beam BC_C is between 1.1% and 8.8%, and the drop trends of every mode of the two beams are similar. However, the relationship between damages and first few frequencies in a complex system is always very weak, because different damage location may cause similar change in natural frequencies in the same system. For example, beam Corr_A and beam Corr_B, with different corroded location, have similar frequency drop in the first four modes. The results indicate the presence of damage in a global sense but cannot localize it without further analysis. For a better localization of damage other dynamic parameters are needed (Maia, 2003).

3.2.2 *Mode shapes*

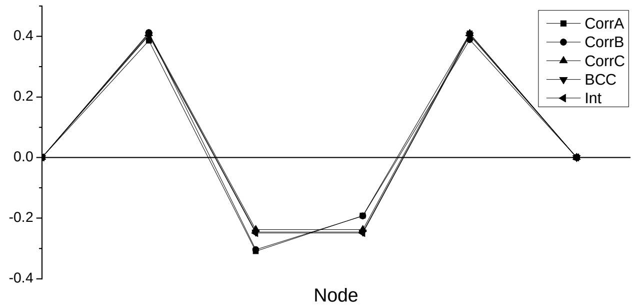
The main difficulty in locates and magnitude damages from the experimental data lies in fact that the measured mode shapes can never be perfectly smooth. Figure 8 summarizes the mode shapes of the first four modes of the beams.



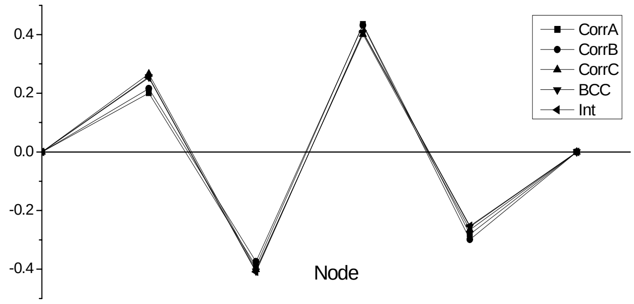
a) Mode 1



b) Mode 2



c) Mode 3



d) Mode4

Figure 8 Mode shapes of testing beams

By analyzing the mode shapes (see Figure 8), we can identify the zone of local damage of every beam with the help of many methods. To beam Corr_A and Corr_B, corrosion damage zone are unsymmetrical along the beams. So the symmetrical mode shapes of them, such as mode 1 and mode 3, changed significantly. While beam Corr_C and BC_C are all have damage at the center part along the beams. So the unsymmetrical mode shapes of them, such as mode 2 and mode 4, changed significantly. Since mode shapes are calculated by unit-normalized of mass, it is difficult to identify the damage magnitude. Moreover, from the figure above we can see corrosion damage in the beam Corr_C leads the similar change in the first four mode shapes, compared to beam BC_C, which has two bending cracks at the same part. These results correspond to the similar trends of frequency changes.

As we assumed that a beam with bending cracks could be represented by a decrease in stiffness of a small beam element, whether it would work with the damage is corrosion cracks. In order to prove the feasibility of this issue, a simply supported finite element beam model with lumped mass was constructed using 5 elements as show in Figure 8. The damp in this system was neglected. For the intact beam Int, a constant stiffness EI was assumed for all elements, while the damage beams (Corr_A, Corr_B, Corr_C) were modeled by reducing EI of the element at the corrosion zones of them. Then the stiffness matrix of corroded beam element can be found as

$$\left[k^{(n)}\right]_{\text{damage}} = \alpha_n \left[k^{(n)}\right]_{\text{intact}} \tag{1}$$

Where $\left[k^{(n)}\right]_{\text{intact}}$ =stiffness matrix of intact beam element; $\left[k^{(n)}\right]_{\text{damage}}$ =stiffness matrix of corroded beam element; $\alpha_n \in (0,1)$; n =element number

And construct the object function as follows (Yi, 2001):

$$F = \sum_{i=1}^{4}\left[\frac{f_i^{test} - f_i^{cal}}{f_i^{test}}\right] + \sum_{i=1}^{4}\sum_{i=1}^{6}(\phi_{ij}^{test} - \phi_{ij}^{cal})^2 \tag{2}$$

Where $f_i^{test} = i$ th test frequency; $f_i^{test} = i$ th calculate frequency; $\phi_{ij}^{test} = i$ th test modal at point j ; $\phi_{ij}^{cal} = i$ th calculate modal at point j .

Then, the post-damage modal parameters of FE model were generated numerically using the commercial ANSYS. Adjusting coefficient α between 0 and 1, we can find the minimum F . Table 6 shows the numerical analysis results of these beams. The numerical analysis can fit well with the testing results.

Table 6 Numerical analysis results

Specimen	α_n	$F_{\min}$
Corr_A	α_1=0.6	0.37
Corr_B	α_2=0.54	0.41
Corr_C	α_3=0.5	0.29
BC_C	α_3=0.82	0.27

4 CONCLUSION

Three corroded beams (with different damage zone), one beam with bending crack at the center part and an intact beam were included in this study. First four mode parameters of these beams were obtained through dynamic test. And a FE model was used to simulate the effect of using EI reducing as local corrosion damage on the calculation of modal parameters. It was found that corrosion damage could reduce natural frequency of these beams rapidly. Moreover, mode shapes of the corroded beams also have specific changes, corresponding to the different corrosion zone. Therefore, it could be concluded that modal parameters are sensitive to corrosion damages. And further investigations are needed to locate and quantify the corrosion damage with the degradation of modal parameters in RC structure.

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