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Preliminary investigation of changes in damping mechanism caused by corrosion in reinforced concrete beams.

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Abstract: Corrosion induced damages are one of the major durability issues that reinforced and pre-stressed concrete structures face, during their service life span. Vibration - based test methods have gained great attention in the structural health monitoring field during the last decades as, they are non-destructive and easy of conducting, compared to the other test methods. Dynamic characteristics of undamaged and damaged materials vary from each other and reflected through the modal parameters, like natural frequency, damping ratio and mode shapes, etc. In an RC member, along with the initiation of corrosion process, generation and propagation of corrosion products through the voids in concrete, initiate tensile cracks. Further to that, reinforcement will lose its effective diameter and at a later stage, the bond between reinforcement and concrete is reduced. These internal activities can cause changes in the damping mechanism of that member. Finally, failure will occurs due to loss of bearing capacity of the member. This study is focused on the vibration behaviour of reinforced concrete beam specimens, by performing modal tests under free vibration condition. The accelerated corrosion technique is used to induce artificial corrosion at different degrees. The damping ratio, evaluated by half-power bandwidth method and Eigen system Realization Algorithm was used to investigate changes expected in the damping mechanism.

Keywords: corrosion, non-destructive, vibration, damping mechanism

1. Introduction

Vibration based structural health monitoring (SHM) has been investigated in the field of non-destructive SHM in order to identify the premature deteriorations of Reinforced Concrete (RC) bridges or Pre-stressed Concrete (PC) bridges, among other available test methods. These deteriorations have been attributed mainly to corrosion of reinforcement during the service life of the structure due to various reasons [1]. Previous researches carried out in this area have shown that corrosion of reinforcement or tendons can cause a complete breakdown of the bond between concrete and reinforcements along with extensive cracks developed up to spalling of cover concrete. This phenomenon can cause catastrophic failures, resulting in injuries or severe fatal damages. Therefore, it is important to identify these types of damages in a structure at its early stage, so that necessary remedial actions can be taken to prevent or minimize the damages.

Physical properties of a structure like mass, stiffness and damping are related to modal parameters (natural frequencies, modal damping and mode shapes etc.) of the same. Damages of the structure alter the physical properties so that it will be reflected through changes in modal parameters. This phenomenon is the platform for the concept of vibration based SHM.

Corrosion of reinforcement bars or tendons in a reinforced concrete or pre-stressed concrete element is an electro-chemical process that causes ultimately loss of effective diameter and mass of rebar and induces internal cracks in concrete and finally spalling of cover and reduce the bond between reinforcement and concrete [2]. These deteriorations can directly alter the physical properties of that element and, consequently, the modal properties. The investigation of changes in modal parameters can be used to develop a structural health monitoring paradigm of structures, due to corrosion induced damages.

The natural frequency is a global property of a structure directly related to the stiffness properties. Maas et al [3] has shown that the natural frequency is a reliable indicator of structural damages in concrete structures, but mostly efficient after the

first crack has occurred. The damping ratio also shows significant response to damages or changes to the structural integrity [4]. Damping changes in an RC member along with the increase of corrosion induced damages, may be used as a tool to identify those damages, even if those are not visible to human inspections.
It can be hypothesized that there should be certain effect of structural damages on the mechanisms of damping. For example, when the crack width increases, damping could be affected due to friction between both faces of the crack. Further, if slippage of rebar takes place, again, there could be a significant change occur in damping due to variation of friction between rebar and concrete. These changes may be observed by investigating the changes in the modal damping values with the increase of corrosion level.

According to Maas et al. [3], linear and nonlinear dynamic properties can be used as damage indicators. A lot of researches have been done in this area by using linear dynamic damage indicators. They performed dynamic vibration test on 6 meters long concrete beams and damaged them with three point bending experiment, by increasing the cracking load. At each load step, those beams dynamically tested in a free-free setup under a swept sine excitation. According to them, damping is sensitive to the damage level and excitation force amplitude.

Razak, and Choi [5] conducted an experimental investigation to study the effect of corrosion on the modal parameters of reinforced concrete beams. Here an appreciable amount of steel corrosion damage was introduced by considering the crack width and spalling of cover concrete. The modal parameters were obtained by performing modal tests, both on damaged beams and control specimen. They concluded that both natural frequency and damping ratio are damage sensitive. But natural frequency is more damage sensitive and the variation of damping ratio is inconsistent with that of natural frequency.

Shahzad et al. [6] conducted laboratory tests to examine the possibility of using damping ratio to detect corrosion damages in RC beams. Uniform and local corrosion pattern were induced using accelerated corrosion technique and modal parameters were examined and compared with increasing in corrosion damage levels. According to the results obtained in this research, modal damping increased with damage level and more sensitive to corrosion damages when compared with natural frequency.
This paper describes a preliminary experiment in order to investigate changes in modal properties of RC beam due to corrosion of reinforcing bars. The experiment focuses on possible changes in damping mechanism along with development of corrosion of reinforcing bars and associated damages in concrete. The degree of corrosion was controlled by a series of accelerated corrosion tests (ACT). Impact testing was conducted at different corrosion levels to identify relevant modal parameters like damping ratio and natural frequency.

A better understanding in this area as a non-destructive test method, can be utilized to develop a SHM paradigm to investigate the health status of RC members in civil engineering structures effectively and efficiently.

2. Methods

2.1 Specimens

Three identical reinforced concrete beams, named Tr-1, 2 and 3 were cast for the following purposes.

a) Tr-1: to study a suitable experiment setup and instrumentation for ACT and impact testings.
b) Tr-2: to study the effect of corrosion, on natural frequency and damping ratio of an RC member under three stages of ACT
c) Tr-3: to conduct a series of ACTs and modal tests based on the understanding from Tr-1 and Tr-2 above.

The dimensions of the specimens were 100 x 70 x 880 mm and 10 mm diameter two reinforcing bars were embedded in each specimen that provided a reinforcement ratio of 4.4%. Two reinforcing bars were used in order to facilitate development of cracks. Cover to reinforcement was 30mm and grade of concrete was 40 MPa. See Figure 1 for more detail.

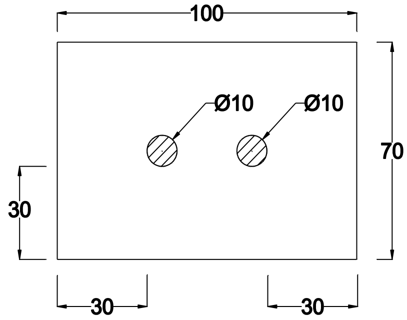

Figure 1: Dimensions of the specimens

2.2 Accelerated corrosion test

Localized corrosion pattern at the centre of the specimen of 100mm wide was subjected to ACT, since localized corrosion may be realistic when considering the actual structures. Specimens were subjected to an electro-chemical ACT with a constant current supply of 200mA equivalent to a current density of 3000 μA/cm^2. A constant power output unit was used to provide a constant current. The current was applied between the steel reinforcement and a copper sheet of 200 x 100 x 5 mm placed under a sponge sheet that was used to facilitate the electric flow between concrete and copper sheet as the specimen was not submerged in the solution (Figure 2). Here, the copper sheet acts as the cathode and the reinforcement acts as the anode. Sodium chloride solution of 3% by weight was used as the electrolyte to provide electrical contact between anode and cathode.

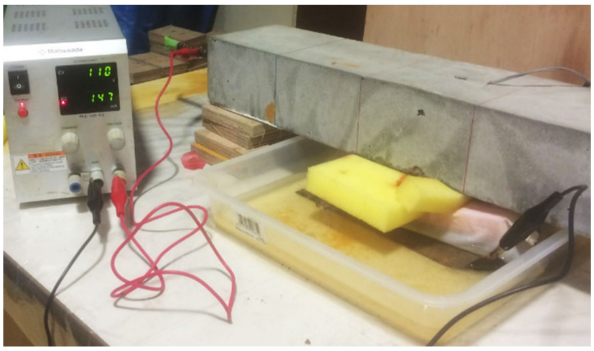

Figure 2: Accelerated corrosion Test

2.3 Impact testing

Impact testings were performed after each ACT by subjecting the specimens to hammer excitation under free-free support condition. Five piezoelectric accelerometers were mounted on the bottom surface of the specimen and strain gauges installed on top of the embedded reinforcing bars. The accelerometers were connected to charge amplifiers and strain gauges were connected to dynamic strain meters to obtain dynamic responses. Plastic hammer was used to give an impact to the top surface of the specimen from 270 mm away from one end, which can excite first three bending vibration modes (See Figure 3 & 4). First bending vibration mode was considered in this analysis hereafter.

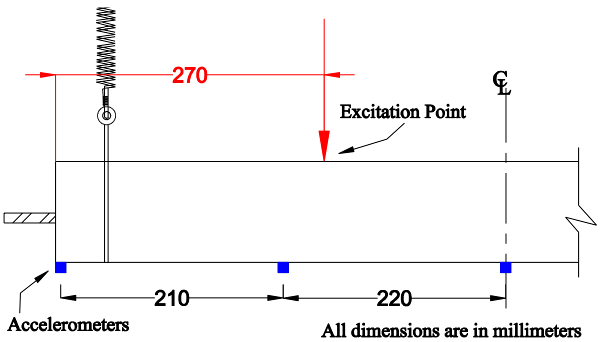

Figure 3: Accelerometer locations and point of hammer excitation in impact test

Modal properties were identified by both time and frequency domain methods: natural frequencies and damping ratios were identified from Fourier transform (FT) and half-power bandwidth method (HBW) and Eigensystem Realization Algorithm (ERA).

Figure 4: Impact testing

2.4 Static strain measurement

There will be an internal expansion due to pressure applied by the corrosion products which, finally exceed the tensile capacity of the concrete and initiate a crack [7]. This internal pressure can be reflected through the internal expansion of the concrete and can be identified by static strain measurement at the location of local corrosion during the ACT. For this purpose, strain gauges were embedded in concrete in the direction perpendicular to the longitudinal axis of the beam in the localized corrosion area and near to an end of the Tr-1 specimen.

3. Results and Discussions

3.1 Modal properties

According to the findings from the trial tests did on the Tr-1 specimen, for proper establishment of a constant current in the ACT, it was required to wet the local corrosion area of the specimen and maintain a sufficient level of electrolyte solution.

The time history responses were processed using both FT and ERA to estimate the natural frequency and damping ratios of the specimens at the end of each ACT. It was observed that, along with increases in the degree of corrosion, the natural frequency tended to decrease and the damping ratio tended to increase. Figure 5 shows examples of the acceleration time histories and the corresponding spectra before and after an ACT. As observed in the figure, relative spectrum amplitude at first natural frequency was reduced after the ACT.

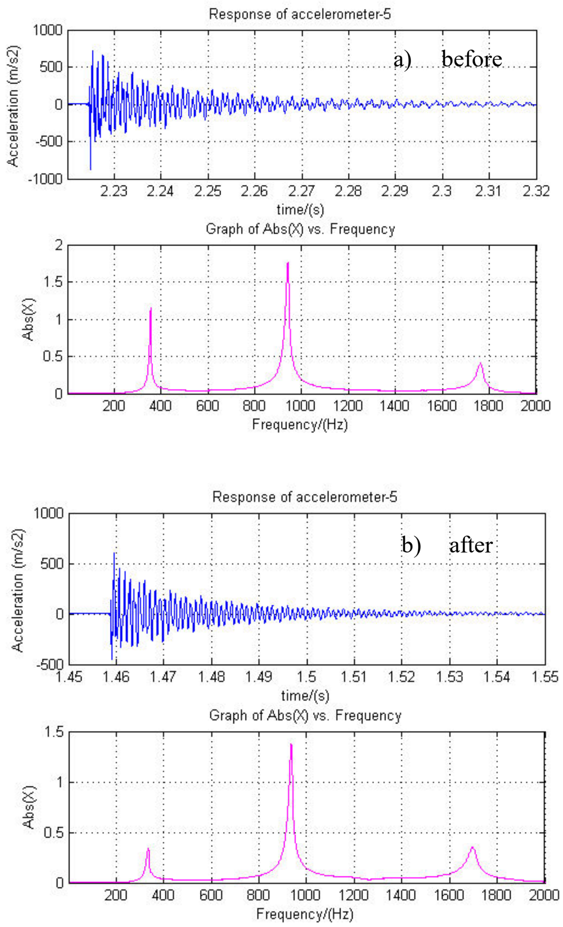

Figure 5: Responses before and after a corrosion process of Tr-3 specimen

Table 1 shows a summary of results obtained from impact testing for Tr-2 specimen. In addition to, the natural frequencies (f_1) and damping ratios (DR_1) obtained for the first mode, normalized values of both of those modal parameters (normalized by the corresponding healthy state at level-0) are also included in the table for comparison purpose. Accordingly, decreases in the normalized natural frequency (R_f) were observed when corrosion level increased, and increases in the normalized damping ratio (R_{DR}) can be observed after each level of the corrosion process.

Table 1: Natural frequencies and damping ratios obtained with increased of corrosion- Tr-2 specimen

Corrosion Level	f_1 /(Hz)	R_f	DR_1	R_{DR}
L-0	357.0	1.000	0.0104	1.000
L-1	289.5	0.811	0.0521	4.988
L-2	264.2	0.740	0.0626	5.987
L-3	238.6	0.668	0.0799	7.644

HBW method incorporated with FT and ERA were used to identify natural frequencies and damping ratios in Tr-3 specimen. The results of HBW method and ERA showed agreement at a certain degree, although some differences were observed in the damping ratio, in particular.

Table 2 shows a summary of results obtained from impact testing for Tr-3 specimen, as an example. The degree of corrosion here is expressed by multiplying the amount of current provided in milliamperes during the mentioned time in seconds for each ACT interval. Before starting the ACT, the specimen was subjected to a modal test to study the initial status of modal properties mentioned as "control" in Table 2. Figures 6 and 7 shows the natural frequencies (f_1) and damping ratios (DR_1), respectively, at different corrosion levels presented in Table 2.

Table 2: Natural frequency and damping ratio identified by ERA with increased level of corrosion- Tr-3 specimen

Modal test No.	Duration of ACT / (h)	Degree of corrosion / (A*s)	f_1 / (Hz)	DR_1
control	-	-	352.66	0.0068
1	0.5	360	353.46	0.0077
2	0.5	720	355.41	0.0068
3	0.5	1080	354.23	0.0075
4	1.0	1800	354.16	0.0068
5	1.0	2520	353.73	0.0070
6	1.0	3240	355.12	0.0063
7	1.0	3960	354.82	0.0066
8	2.0	5400	354.49	0.0067
9	2.0	6840	353.54	0.0072
10	*4.0*	*9720*	*340.79*	*0.0109*
11	2.0	11160	334.40	0.0123
12	4.0	14040	331.72	0.0161
13	0.0	14040	332.65	0.0123
14	15.0	24840	332.70	0.0151
15	4.0	27720	332.16	0.0148

The first sign of a longitudinal crack observed at the bottom of the specimen before the 10^{th} modal test. The crack propagated up to two sides before the 14^{th} modal test. It should be noted that for the understanding purpose of the continuation of corrosion process even with different current supply, the current supplying interval was reduced to two hours between 10^{th} and 11^{th} modal tests and four hours between 14^{th} and 15^{th} modal tests. Zero current passed between 12^{th} and 13^{th} modal tests for 24 hours.

According to Figures 6 and 7, at initial stages of corrosion both natural frequency and damping ratio show mild fluctuations. After the 9th modal test (the level of corrosion in between 7000-10,000 A*s), a significant change of modal parameters can be observed. This stage is directly related to the occurrence of the first crack. The crack was further developed through either side of the specimen due to increased level of corrosion.

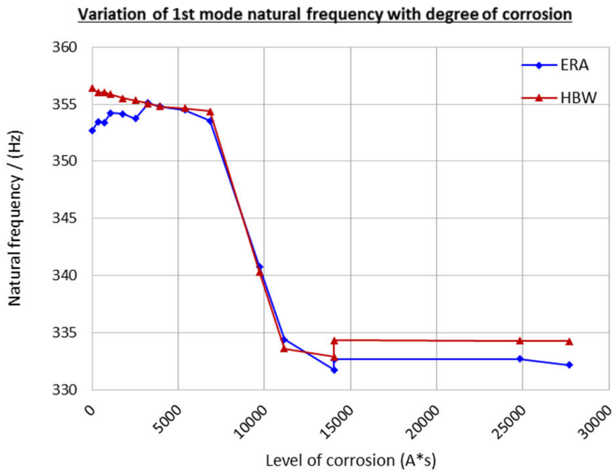

Figure 6: Variation of 1st mode natural frequency with level of corrosion

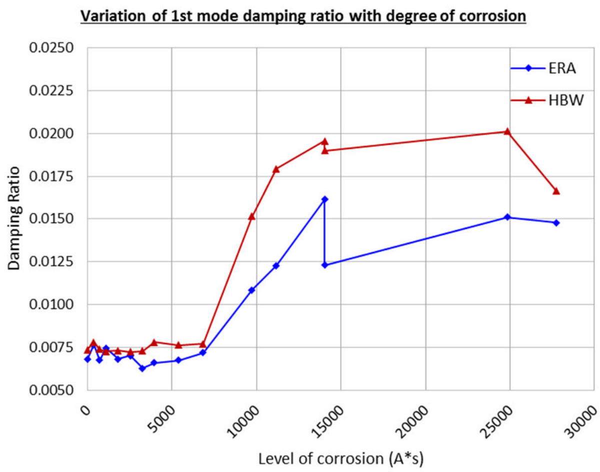

Figure 7: Variation of damping ratio obtained from 1st mode with level of corrosion

The sudden increase in natural frequency and drop in damping ratio values around the corrosion level of 14,000 A*s is due to stop of the current supply as mentioned above. Corrosion leaks were observed even in this state, but in very slow rate and later, those leaks were solidified, which may be the reason to increase the natural frequency around 0.3% and reduce the damping ratio by 24% in the immediate next modal test. At the end of the series of ACT, it was found that there was a 5.8% reduction of natural frequency and 117% increase of damping ratio with respect to the control stage of Tr-3 specimen.

3.2 interpretation of results of modal properties

These observations could be explained as follows. Before starting and up to a certain limit of continuation of the corrosion process, the stiffness of the specimen will not be changed significantly. Once the stress due to accumulation of corrosion products around the interface of reinforcement and concrete inside exceeded the tensile capacity of concrete, an internal crack will be developed. With further increase of corrosion level, these cracks develop over the cover depth and surface crack will appear [7]. At this stage, the damage can be clearly identified from outside of the specimen (corresponding to the 10th modal test). After appearing the crack, the stiffness of the specimen is reduced and the effective diameter of rebar also reduced further. Therefore, the natural frequency reduces with further increase of the corrosion level (See Figure 6).

In parallel, the damping mechanism may also be subjected to following changes. At the beginning, the damping mechanism is dominated by the material damping. After developing the cracks, friction damping due to the opening and widening of the cracks and due to abrasion of loose particles trapped inside the cracks (See Figure 8) can add additional friction damping component, while there is a contribution from material damping from the non-cracked areas in the same cross sections. Further, there can be a slippage or relative displacement in between reinforcement and concrete at the interface that contribute friction damping to the system. At this stage, the contribution from material damping reduces.

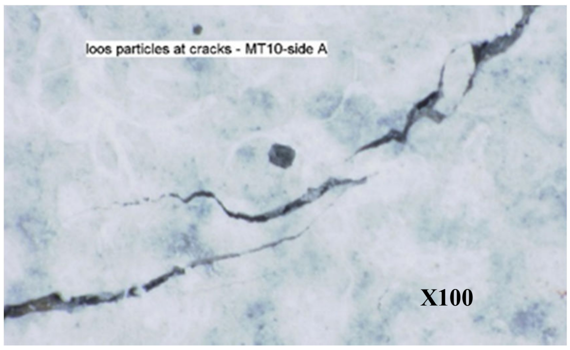

Figure 8: Loose particle trapped inside

In the later part of corrosion process due to more extension of the cracks cause to reduce the contribution from material damping further. Widening of the cracks and removing of the fine loose particles affect to abrasion of cracked surfaces and reduce the friction damping also at the later stages of corrosion.

3.3 Static strain measurement

From the static strain measurements obtained from Tr-1 specimen, it is understood that the results may be consistent with the phenomena that there is an internal stress due to corrosion products generated and internal strain around that area increases accordingly. Once the crack developed, the strain increases steeply as the crack is widened. (See "Detail -A" between 1500s – 2000s in Figure 9).

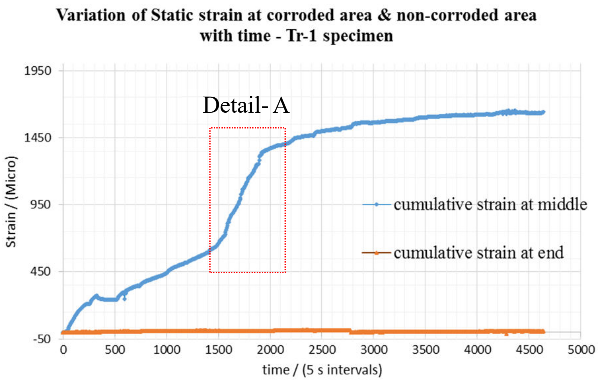

Figure 9: Variation of static strain with increase of corrosion of Tr-1 specimen

3.4 Accelerated corrosion test

The ACT on specimens took over around 20 hours, which continue over 3 days along with intermediate modal tests under stipulated conditions in Section 2.2 above. The examination of corroded reinforcing bars revealed significant loss of steel in the localized corrosion area. Out of two reinforcing bars, one showed higher loss of steel area compared to the other (See Figure 10). Possible reasons for this may be include inhomogeneous material properties of concrete, presence of aggregate around the reinforcing bars that acting as barriers to flow of corrosion products and development of crack across and deviations in cover to reinforcement.

Figure 10: Corrosion of reinforcement - specimen Tr-3

Crack development during ACT was monitored. At early stage, fine leaks of light yellow colour were observed from side walls and, then, a hair crack developed around that place. After that, due to increase in crack width, corrosion process accelerated and greenish and dark brownish colour corrosion products tended to leak from the cracks.

4. Conclusions

Findings obtained from this preliminary experimental study are summarized as follows:

(a) The damping ratio showed higher sensitivity to corrosion induced damage than the natural frequency in the results described in this paper. In order to ensure this result, further investigations are in progress.

(b) The results of this study may have shown an evidence of damping mechanism changes along with deteriorations due to corrosion of reinforcing bars in an RC beam. Further experiments are being conducted to investigate this.

References

[1]. Wallbank R.J., The performance of concrete in bridges- A survey of 200 highway bridges, Department of Transportation, London. (1989).

[2]. S.Ahmad, Reinforcement corrosion in concrete structures, its monitoring and service life prediction-a review, Elsevier-Cement & concrete composites 25, 2003, pp 459-471.

[3]. Stefan Maas, Arno Zürbesa, Danièle Waldmanna, Markus Walteringa, Volker Bungarda, and G. De Roeckb. Damage assessment of concrete structures through dynamic testing methods. Part 1 – Laboratory tests, Elsevier- Engineering Structures Vol. 34, 2012, pp 351–362.

[4]. R.O.Curadellia, J.D.Rierab, D. Abrosinia, M.G. Amania, Damage detection by means of structural damping identification, Elsevier -Engineering Structures 30, 2008, pp 3497-3504.

[5]. H.Abdul Razak, F.C Choi, The effect of corrosion on the natural frequency and modal damping of reinforced concrete beams , Elsevier -Engineering Structures 23, 2001, pp 1126-1133.

[6]. S.Shahzad, H.Yamaguchi, R.T.Takanami and S.Asamoto, Detection of corrosion induced damage in reinforced concrete beams based on structural damping identification, Proceeding - Hokkaido University Collection of Scholarly and Accademic Papers (HUSCAP),2013.

[7]. H.S.Wong, Y.X.Zhao, A.R.Karimi, N.R.Buenfeld and W.L.Jin, On the penetration of corrosion products from reinforcing steel in to concrete due to chloride-induced corrosion, Elsevier – Corrosion Science 52 ,2010, pp 2469-2480.