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Effect of cracking, corrosion and repair on the frequency response of RC beams

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ABSTRACT

This paper presents a laboratory investigation to study the effect of cracking, corrosion and repair on the frequency response of simply-supported reinforced concrete beams. The beams were subjected to four-point bending at 70% of their theoretical ultimate loads. Corrosion was then induced using an electro-chemical acceleration technique. The beams were then repaired to restore their load-carrying and deflection capacities. Based on response time histories, the fundamental frequency characteristics of the beams were deduced using Fourier transform (FT) and Hilbert-Huang transform (HHT). Experimental results revealed significant changes in the normalized frequency, R_f, with decrease in R_f associated with load-induced cracking, an increase in R_f associated with moderate reinforcement corrosion and a subsequent decrease in R_f associated with repair. The results of this study support the use of frequency response, obtained with an appropriate signal processing technique such as HHT, to infer the health of monitored structures, taking into account environmental conditions, likelihood of corrosion occurrence, properties of repair material and interfacial bonding.

1. Introduction

The problems of premature deterioration of reinforced concrete (RC) structures, and in extreme case structural failures, have been attributed to corrosion of the steel reinforcement during the service life of the structure as well as to overload. These problems motivated the interest in the use of various non-destructive system identification (SI) techniques to assess and monitor the health and performance of structures on a regular basis. The key object in structural health monitoring (SHM) is to detect damage in its early stage so that remedial actions can be taken to minimize or prevent premature and/or catastrophic failures which may lead to injuries, fatalities and losses of property.

Most popular SI techniques are based on examination of changes in vibration characteristics or responses of RC structures. The principle is based on the concept that system parameters (such as natural frequencies, mode shapes and modal damping) are functions of the physical properties of structures, namely, geometry and/or the material properties including mass, damping, stiffness, changes to the boundary conditions and system connectivity. Therefore, any change in the physical properties due to damage results in measurable change in the system parameters [1]. The simplest and cheapest method employed under this approach is to monitor frequency parameters which give a good overview of the global structural condition. Natural frequency is a global property of structures where any change signifies a change in the structural characteristics, such as the occurrence of damage or the stiffening of the structure. In some applications, this parameter has proven to be a sensitive and reliable indicator of structural integrity. It can be easily obtained from monitored time history responses [2].

Common damages in RC structures are usually in the form of cracking and corrosion. Casas and Aparicio [3] performed dynamic studies on concrete beams with cracks introduced by formwork at various locations along their length whereas Chowdhury and Ramirez [4] studied the case where anomalies were cast into RC and plain concrete beams to simulate delaminations and cracks. Another study conducted by Koh et al. [5] on one-way RC slabs subjected to progressive degree of load-induced flexural crack damages in a four-point bending configuration with simply-supported boundary conditions, showed a maximum reduction of 33% in fundamental frequency when the slabs were loaded from virgin to yield state. The frequency was found to be a good indicator of damage in the study.

The effect of corrosion on frequency response of RC beams had previously been studied [6,7]. Capozucca and Nilde Cerri [6] conducted a laboratory experiment where they have subjected the compression zones of two beams to accelerated corrosion while the third beam served as control specimen. The frequencies for the corroded beams showed small decreases in the first and third mode natural frequencies of 3.50% and 2.94%, respectively for one beam and 3.32% and 1.60% for the other. They postulated that the main effect of corrosion was decrease in strength of compressive concrete subjected to a biaxial state of stress due to the

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Nomenclature

A'_s	area of compression steel reinforcement
A_s	area of tension steel reinforcement
EI	beam's flexural rigidity
f_1	fundamental frequency
f_n	beam's natural vibration frequency
$\overline{m}$	beam's mass per unit length
n	vibration mode
R_f	normalized (by the corresponding healthy state value) fundamental frequency
$R_{\sqrt{EI}}$	normalized value of $\sqrt{EI}$

bending moment and pressure from rust in the compressive steel. This resulted in cracks, creating a compressive softening effect affecting the strength, ductility and bending stiffness.

Similarly, Abdul Razak and Choi [7] used two corroded beams with slight spalling and moderate cracking and showed a decrease in natural frequencies ranging from 4% to about 11% (for spalling) and from 1% to 4% (for cracking) for the first seven modes compared to a controlled healthy beam. Changes in modal damping ratio were inconsistent with the changes in frequencies and they attributed this inconsistency to the enhanced bond at the steel/concrete interface as a result of accumulation of the rust products and suggested that this phenomenon was probably a unique characteristic of corroded structural members.

Frequency response has also been used as a criterion to assess the success of repaired RC members. Salawu and Williams [8] conducted dynamic tests on a multi-span highway bridge structure before and after structural repairs (repair was needed due to inadequate longitudinal flexural capacity to resist the hogging moments in two spans). They concluded that the repair works caused a slight decrease in the frequencies (less than 3% for the first seven modes) although there were no large changes in the overall mass of the bridge after repair.

2. Research significance

It appears that the use of natural frequencies as a parameter for health assessment is simple and popular but needs to be further studied and improved. Most studies, either numerical or experimental, focused on one particular type of damage, such as severe damage at global structural level and crack at individual structural member level. However, throughout its service life, a structure or its components may encounter more than one type of damage, which may have a counteracting effect on and/or adversely affect its performance, safety and reliability. Thus, the research presented in this paper aims to highlight the effect of a series of tests involving two consecutive damages and the subsequent repair on the frequency response of simply-supported reinforced concrete beams. In addition, a recently developed signal processing technique—the Hilbert-Huang transform [9]—is employed to assess its capability in providing more information on the frequency content of the structure. The experimental results may provide engineers with better insight into the health assessment of RC structures.

3. Experimental program

The experimental program was designed to investigate the effect of cracking, corrosion and repair on the frequency response of RC beams. The beams were tested as simply-supported using pin and roller supports, with a span of 2000 mm and overhangs of 250 mm. The four simulated stages of the beams' service lives are: (a) healthy (denoted as H), (b) cracked (CR), (c) corroded (CO), or subjected to cyclic wetting and drying only (CO*) and (d) repaired (R). For the third Stage (CO), an electro-chemical accelerated corrosion process was introduced to all but two control beams that were subjected to cycles of wetting and drying (CO*). For the fourth Stage (R), an engineered cementitious composite (ECC) material and externally-bonded carbon fiber reinforced polymer (CFRP) laminates were used to repair the corrosion-damaged beams. At the end of each stage, each beam was subjected to static and dynamic load tests to estimate its stiffness and fundamental frequency, f_1. The latter was obtained from the dynamic load test response using both the Fast Fourier transform (FFT) and Hilbert-Huang transform (HHT).

3.1. Specimens

Two series of three identically-reinforced concrete beams measuring 324 × 235 × 2500 mm were fabricated for this study. The reinforcement comprised two No. 13 ($A'_s = 265$ mm^2) and three No. 16 ($A_s = 603$ mm^2) high strength steel reinforcing bars corresponding to compressive and tensile reinforcement ratios of 0.42% and 0.95%, respectively. Shear reinforcements made from 6 mm diameter mild steel plain bars were provided to prevent failure by shear. To restrict corrosion of the steel bars to within the span, each reinforcement cage was coated with epoxy over a length of 250 mm at both ends.

The first series, designated as Series O, consisted of three regular RC beams (Beams O1, O2 and O3) cast with ordinary Portland cement concrete (OPC) material. The second series were functionally-graded concrete (FGC) beams (Beams E1, E2 and E3), where each FGC beam had at the bottom one-third, a layer of engineered cementitious composite (ECC) material made of a hybrid fiber (0.5% steel fibers and 1.5% polyethylene fibers) reinforced cement. Compared to conventional RC beams, FGC beams possess better cracking behavior under service load conditions and have higher corrosion, spall and delamination resistances under aggressive environment [10]. The layout and details of beams are shown in Fig. 1. An epoxy coating was applied on the surfaces of each beam (prior to corrosion regime) to restrict corrosion to three test regions as highlighted in Fig. 1. A summary of the experimental program is presented in Table 1. The mix proportions of the concrete materials are summarized in Table 2. The OPC and ECC materials were designed to have cylinder compressive strengths of 40 MPa and 55 MPa, respectively.

3.2. Dynamic load tests

Dynamic load tests were performed at the end of each of the four stages by subjecting the beams to hammer impacts imposed at their mid-spans. As illustrated in Fig. 2, six accelerometers and two piezoelectric film sensors were mounted on the top surface of each beam. In addition, three electrical resistance strain (ERS) gauges were attached at the mid-span on the tensile bars. These sensors were connected to a 16-channel oscilloscope to capture and display in real-time signals in terms of acceleration-, voltage- and strain–time histories of the beams under impacts. Inputs to the beam were recorded by another accelerometer mounted on the head of the hammer. The impacts imposed by the hammer were controlled to have a peak force between 10 kN and 20 kN. A near-triangular waveform with a duration of approximately