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Guided waves for damage detection in rebar-reinforced concrete beams

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HIGHLIGHTS

- Material property change due to cracking was assessed by guided waves.
- Principal component analysis (PCA) was used to classify corroded rebar.
- Statistical parameters from wave signals were extracted as damage indices for PCA.

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ABSTRACT

The propagation properties of ultrasonic waves in rebar-reinforced concrete beams were investigated for the purpose of damage detection. Two types of piezoelectric (PZT) elements were used in experiments in which PZT disks were attached on the surfaces of concrete beams to observe wave propagation in concrete before and after a four-point bending test, while rectangular PZT patches were attached at the exposed ends of the rebar to monitor wave transmission along the rebar with and without simulated corrosion in the form of partial material removal from the rebar. Experimental testing demonstrated that the surface-attached PZT disks were capable of detecting the change in material properties due to the existence of cracking. In consideration of the inevitable discrepancies in different concrete beams due to specimen preparation and sensor installation, principal component analysis based on statistical parameters extracted from wave signals was applied to highlight the difference between benchmark and damaged rebar. The results show the potential of the principal components as damage indices for quantifying integrity conditions of concrete structures.

1. Introduction

Rebar-reinforced concrete is currently widely used in civil infrastructure including buildings, dams, power plants, bridges and roads, because of its high load-carrying capacity and low maintenance. Although reinforced concrete is a relatively durable and robust constructional material, it can be severely weakened by poor manufacture or a hostile environment. Deterioration of reinforced concrete is generally attributable to either chemical degradation of the cementitious matrix, corrosion of the rebar, or physical damage (e.g. cracking due to impact, fire, and seismic loads) [1]. In the last decade or so there has been increasing awareness of the need for sustainable integrity surveillance for large reinforced concrete structures. Some novel damage identification techniques have emerged, based on acoustic emission [2], impedance [3], and optical fiber [4] techniques, etc. However, because these techniques offer only local measurement, dense populations of sensors must be used. More importantly, these approaches may lose their acuity with minute damage, for example, debonding between rebar and concrete, which is insensitive to static or low-frequency structural responses [5]. In this respect, an identification technique based on guided waves may be a promising solution, which has been validated for detecting diverse defects in various structures [6].

In consideration of different wave modes propagating in concrete and along embedded rebar, applications of guided waves for evaluation of the integrity of concrete structures have been reported recently to detect defects occurring in concrete and in reinforcement rebar [7–9]. Generally speaking, bulk and surface (Rayleigh) waves can propagate into the concrete when a surface-attached transducer is excited [8]. The bulk waves, which include longitudinal (L) and shear (S) waves, propagate through the interior of the concrete, whereas Rayleigh (R) waves propagate

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mainly along the surface of the concrete, decreasing rapidly in magnitude with depth below the surface. On the other hand, L and S edge waves that also propagate along the surface are very weak and barely recognizable, although they propagate more quickly than L and S waves that propagate through the interior of the concrete [10].

Frequencies lower than 100 kHz are generally employed for identifying damage occurring in concrete [11], to avoid possible wave interactions between wave modes of smaller wavelengths at higher frequencies and aggregates in the concrete. Aggregate-scattered waves can significantly complicate the acquired wave signals, together with interference of wave reflection from the free surfaces of the concrete. Song et al. numerically and experimentally investigated Rayleigh wave propagation in concrete structures using a surface-bonded piezoelectric actuator and sensor system [12]. Sun et al. investigated the effect of uniaxial compressive stress and the resulting internal cracking of the concrete on the amplitude of the waveforms captured by piezoceramic sensors [8]. Yang et al. numerically and experimentally evaluated the depth of surface-breaking cracks in concrete plates at low frequencies where surface waves evolve into Lamb waves with large wavelengths [9].

On the other hand, for the case of wave propagation through rebar that is surrounded by concrete, the system should be considered as a solid steel cylinder embedded in a solid medium with finite boundaries, showing more complex wave behaviors than in the case of bare rebar [13]. Substantial wave energy propagating in rebar may be lost or attenuated due to leakage into the surrounding concrete in the form of S and L bulk waves, separately or together [14]. As a result, the inspection region in the longitudinal direction of rebar is limited because of severe wave leakage. It is generally appreciated that, as the excitation frequency increases, the energy travelling in some wave modes becomes progressively more concentrated at the center of the rebar, with the velocity close to the velocity of L bulk waves in steel, indicating little interaction between rebar and surrounding concrete and therefore lower energy leakage [15].

On the basis of these observations, Beard et al. succeeded in detecting steel bar deformation and an angled cut in a steel bar surrounded by mortar using L(0,12) mode at frequencies above 2 MHz [15]. Ervin and Reis monitored the accelerated corrosion of rebar embedded in mortar using L(0,9) mode at a frequency of 5.08 MHz [13]. However, it was reported that wave modes at higher frequencies were particularly insensitive to surface defects and the medium surrounding the rebar [16], implying that they might be incapable of detecting damage such as delamination or debonding, which is generally simulated experimentally by resin/grease/PVC coating. For this reason, Wang et al. used a spectral element method for the simulation of wave propagation along a steel rebar in concrete at 50 kHz, and evaluated the effect of different damage scenarios of debonding on wave propagation [5]. Sharma and Mukherjee termed the different properties of longitudinal guided wave modes at low and high frequencies as ‘surface seeking mode’ and ‘core seeking mode’ respectively, and discussed their respective applications for detection of delamination and pitting caused by chloride corrosion [17].

In this study, the capability of ultrasonic waves for damage detection in rebar-reinforced concrete beams was investigated, with the ultimate aim to attach or embed slim and lightweight PZT elements into concrete structures to constitute ‘smart concrete’, in accordance with the concept of structural health monitoring [11,12,18,19]. Two series of experiments were conducted. PZT disks were first attached on the surfaces of rebar-reinforced beams to determine the change in dynamic properties of the concrete specimens after the occurrence of cracking damage, and rectangular PZT patches were attached at the exposed ends of the rebar to evaluate simulated corrosion in a form of partial removal of material from the rebar embedded in the concrete. Because of differences in the constitution of individual concrete beams and the installation of PZT elements, it was inappropriate for direct comparison between the captured wave signals from different rebar specimens with and without damage. Principal component analysis was thus proposed to highlight the exact difference in wave signals due to the existence of damage, facilitating the identification of different conditions of the rebar.

2. Detection of change in elastic properties of concrete beams

With the assumption of concrete as an isotropic elastic medium and the lateral dimensions of the concrete beam being not small relative to the wavelength of the activated waves, the relationship between the velocities of elastic waves and the mechanical properties of concrete can be given by the following equations [8,20]

$$c_L^2 = \frac{\lambda + 2\mu}{\rho} \tag{1}$$

$$c_S^2 = \frac{\mu}{\rho} \tag{2}$$

where

$$\mu = \frac{E}{2(1+\upsilon)}, \lambda = \frac{E\upsilon}{[(1-2\upsilon)(1+\upsilon)]}$$

are known as Lamé constants, and c_L and c_S are the velocities of L waves and S waves, respectively. E, ρ and υ are the Young’s modulus, material density and Poisson’s ratio, respectively. The velocity of R waves can be approximated as [20]

$$c_R = c_S\left(\frac{0.87 + 1.12\upsilon}{1+\upsilon}\right) \tag{3}$$

In this study, 6 PZT disks (PI® PIC151, 10 mm in diameter and 1 mm in thickness) were attached on the top and bottom surfaces of two rebar-reinforced concrete beams, respectively, with the dimensions detailed in Fig. 1a, in which two pieces of rebar with a diameter of 10 mm were cast. The averaged mechanical properties of the concrete tested from standard small and large cylinder samples are listed in Table 1. A 5-cycle Hanning-windowed tone-burst at different central frequencies was imposed on P1 with a peak-to-peak voltage of 60 V. Wave signals were acquired individually by sensors P2–P6 at a sampling frequency of 20.48 MHz to investigate the propagation properties of elastic waves in the concrete beam.

Processed with the assistance of a linear-phase bandpass signal filter [21], typical wave signals captured by P2 at a central frequency of 50 kHz and 200 kHz, respectively, are shown in Fig. 2a and b, where the signal at 50 kHz demonstrates a higher signal magnitude than that at 200 kHz. This finding may be attributable to the greater energy dissipation of elastic waves at relatively higher frequencies, induced by the complex interactions between the waves and the concrete aggregates. Typical wave signals captured by P3–P6 at a central frequency of 50 kHz are shown in Fig. 2c–f, respectively. Featuring the longest propagation distance, the wave signal captured by P6 still displays good waveforms although the magnitude is much lower than that captured by sensor P2 because of wave attenuation. The results of P6 at the frequency of 200 kHz are not shown here because of the poor signal-to-noise ratio.

After ignoring L and S edge waves which propagate along the surface of concrete because of their marginal magnitudes, two examples of propagating routes for L and S waves before they are captured by sensor P2 are shown in Fig. 1a, where the waves from actuator P1 to sensor P2 reflect from the bottom surface once (solid