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GUIDED WAVE BASED METHODS FOR DAMAGE DETECTION: EXPERIMENTAL STUDY ON CONCRETE JOINT

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Abstract: Since Guided wave (GW) is sensitive to small damage and can propagate a relatively longer distance with relatively less attenuation, GW-based method has been found as an effective and efficient way to detect incipient damages. In this study, a full-scale concrete joint was constructed to further verify the effectiveness of GW-based method on real civil structures. GW tests were conducted in three stages, including baseline, serviceability and damage conditions. The waves are excited by one actuator and received by several sensors, which are made up of independent piezoelectric elements. Experimental results show that the method is promising for damage identification in practices.

Keywords: Guided wave, damage detection, concrete structure, crack

1 INTRODUCTION

Structural health monitoring (SHM) has become a research hotspot for over two decades. Hundreds of damage detection methods have been proposed, most of which can be found from an early review by Sohn et al. (2003), while its recent progress in mainland China has been summarised by Ou and Li (2010). Generally, these techniques can be classified as either global or local. The global vibration-based SHM techniques are based on relatively low-frequency structural vibration measurements. The first few modes are used to identify the locations and the severities of damages. However, a small number of the global modes are usually insufficient to reliably detect minor damage in a structure. Further, these techniques often require a high-fidelity numerical model of the intact structure to be compared with experimental results, which is usually not available. Therefore using the global approaches alone is sometimes insufficient to detect a relatively small damage. The conventional local methods, i.e., non-destructive techniques (NDT), could be very sensitive to small damage but their detection range is usually very small and they require that the vicinity of the damage is known as a priori and that the portion of the structure being inspected is readily accessible. Therefore it is usually time consuming and costly to use these methods to assess conditions of a large-scale civil infrastructure.

Recently, Guided Wave (GW)-based method has been found as an effective and efficient way to detect incipient damages (Raghavan and Cesnik, 2007). GW is sensitive to small damage and can propagate a relatively longer distance with relatively less attenuation. Therefore, this method may provide a detection range between those of the conventional local non-destructive techniques (NDT) and the vibration-based global SHM techniques.

Though it is in essence a particular kind of ultrasonic methods, several characteristics make GW-based methods stand out of other local methods (Wang 2009).

1. Conventional SHM only “listens” to the structure but does not interact with it, so it can be called as passive SHM. In contrast, GW-based methods use active actuators and sensors that interrogate the structure to detect the presence of damage, and to estimate its extent and intensity (Giurgiutiu and Cuc, 2005). This often leads to active SHM, which can increase the reliability of SHM system (Boller et al., 1999).

2. GW-based methods apply a fairly high frequency pulse (usually from tens to hundreds of kHz range) to the structure. Because of the short wavelength of GW, it is very sensitive to small changes in the structure. This makes minor damage detection become possible (Croxford et
3. Last but not least advantage of using GW is its sensing range, which is between those of the conventional local methods and the global SHM methods (Raghavan and Cesnik, 2007).

Based on the test approach, GW-based methods can be divided into two categories, including pitch-catch and pulse-echo (Raghavan and Cesnik 2007). The pitch-catch approach is based on the fact that after a pulse signal is sent across the specimen under interrogation, a sensor at the other end of the specimen receives the signal. From various characteristics of the received signal, such as delay in time of flight (defined as the time that it takes for a particle, object or stream to reach a detector while travelling over a known distance), amplitude, frequency distribution, etc., information about the damage can be obtained. As for pulse-echo method, after exciting the structure with a narrow bandwidth pulse, a sensor collocated with the actuator is used to “listen” for echoes of the pulse coming from discontinuities. Because the boundaries and the wave speed for a given centre actuation frequency of the pulse are known, the signals from the boundaries can be filtered out (or alternatively the test signal can be subtracted from the baseline signal). Then, signals from the defects are left (if present). From these signals, defects can be located using the wave speed. In this study, pitch-catch method is adopted due to its easy realisation.

GW-based methods have been applied to damage identification of reinforced concrete (RC) structures. Na et al. (2003) fabricated four sets of RC specimens with different lengths of delamination. Theoretical studies were conducted for Lamb mode selection. GW tests were carried out to obtain a function of the relationship between the received signal amplitude and its frequency. Song et al. (2007) applied GW-based method to detect possible internal cracks inside the RC bent-cap. The experimental results on such a large-scale structure showed that the transmission energy between the actuator and sensor will drop dramatically when a crack exists inside, which demonstrated the sensitivity of piezos in detecting cracks. In a series of papers, GW-based methods are used for identification of various damage in civil structures, including debonding damage in RC structures (Wang et al., 2009), crack on steel beam (Wang et al., 2010; Wang et al., 2011) and multiple damages on concrete beam (Wang and Hao, 2011; Wang and Hao, 2012).

In order to further verify the effectiveness of GW-based method on real civil structures, a full-scale concrete joint was built in the laboratory. GW tests were conducted, including serviceability and damage tests as well as baseline tests. This paper will focus on the experimental setup and the test results.

2 EXPERIMENTAL SETUP

2.1 Specimen and Sensor Location

By simulating beam column concrete joints that may be typically found as an external column in a building, the following concrete joint was constructed. As shown in Figure 1, the concrete joint measured 1.2 metres long and 1.2 metres high with a width of 400 mm. The beams were composed of 6N12 grade 450 MPa deformed reinforced bars and five N6 stirrups spaced at 220 mm. Similarly, the concrete columns were line with four reinforced bars and stirrups at 220mm spacing.

![Concrete Joint and Sensor Locations](image)

The model was composed of Grade 40 MPa concrete with 80mm aggregates. Based on compression tests of the concrete sample, the average compressive strength of the concrete was 35.1 MPa.

2.2 Guided Wave Test Equipment (Wang 2009)

The experimental system for wave propagation tests, shown in Figure 2, includes two parts: a) the actuating part to provide the excitation or input of the system. It includes the actuator based on piezoelectric strips and the power amplifier that provided the power supply of the actuator; b) the piezo sensing element to
measure the response. This part includes the piezo film element and its charge amplifier.

The strip actuators from APC International, Ltd. were selected as actuators in this study. The DT1 series piezo film elements from Measurement Specialties, Inc. were selected as the sensors. The actuators and sensors were glued to the surface of concrete joint with Araldite Kit K138. The detailed locations are shown in Figure 1.

![Scaled Model](image)

Figure 2: Guided wave test system (Wang 2009)

NI USB-6251 was used to generate the short-time Morlet wavelet for actuating the structure by a linear power amplifier. Signals from actuators and sensors were collected by a data acquisition system made with NI PCI-6133. The sampling frequency of the system was up to 2 MHz. An in-house Labview-based program was used during the GW test. It is a data acquisition program that works in conjunction with the NI USB-6251 and NI 6133 to generate and record wave signals. The program records both the response signal from the sensors and the transmitting signal that was sent from the actuators. Parameters, such as sampling rate, window width, input range, trigger threshold and pre-triggering range, can be set based on the test conditions. The program allows linear de-trending which linearises the response signals, and allows for easier processing of the results. In addition, an inbuilt filtering function allows filtering out of potential noise within the response signals.

2.3 Loading Apparatus and Test Procedure

2.3.1 Loading apparatus

As shown in Figure 3, the concrete joint was placed upright, standing on the column face and bolted down by the support frames (labelled as B). They were used to resist any rotating moments caused by loading on the lever arm of the concrete joint. Two load bearing frames (labelled as A) together with two hydraulic jacks were placed on each side of the beams and bolted to the floor to resist the loads that would be applied there to crack the joint. Each frame had a maximum capacity of 160 kN and thus the total capacity was 320 kN support load for the concrete joint.

![Figure 3. Front and Side Views of Concrete Loading Apparatus (Nguyen, 2008)](image)

2.3.2 Three-stage test

The load arrangements were such that the force on the beam arms act downward towards the ground on both sides. The load was applied at 50 mm from the edge of the beam by using hydraulic jacks. Based on theoretical results, the ultimate failure force for the joint is 165 kN, however, due to safety reasons, the force was limited to a maximum of 150 kN. Load cells with 200 kN capacity were used to measure the applied force in realtime. A monitoring device was also set up to pick up the displacement of the beam arms under the load.

Three-stage tests were performed on the beam arms. First, GW tests were conducted under intact condition as baseline tests. Second, 40 kN forces were added on both beam arms and then GW tests were performed as serviceability tests. The third stage was damage test. The loadings on the arms were increased gradually until concrete cracks. Four actuators were used to generate the pulse in sequence. Sensors 1-4 were used to record the propagated waves for tests using column actuator 1 or 2. Sensors 5-8 were used to record the propagated waves for tests using beam actuator 3 or 4. It should be noted that for safety reasons, the load was removed before GW testing was commenced.

3 EXPERIMENTAL RESULTS

3.1 Loading Procedure
Based on visual inspection, under the serviceability loads (40 kN), no obvious crack occurred on the concrete surface. Concrete started cracking at the top upper corners, where the beam and column intersects, when the load reached 108 kN. The loading was increased until 112 kN to incur more damages to the cracks.

Figure 4 illustrates both cracks, labelled as 1 and 2, respectively. Table 1 shows the details of their location, width, length and the load. The width of the crack was measured by using a magnifying glass with internal scales.

![Concrete joint cracks](image)

Figure 4. Concrete joint cracks (Nguyen, 2008)

Table 1 Loading induced cracks

<table>
<thead>
<tr>
<th>Crack Location</th>
<th>Crack Width (mm)</th>
<th>Crack Length (cm)</th>
<th>Load at cracking (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Right Corner (1)</td>
<td>0.10</td>
<td>31.3</td>
<td>108</td>
</tr>
<tr>
<td>Upper Left Corner (2)</td>
<td>0.05</td>
<td>20.8</td>
<td>110</td>
</tr>
</tbody>
</table>

3.2 GW Tests

In GW tests, the frequencies of the generated waves were varied between 30 and 70 kHz with a 10 kHz increment and the number of the wave cycles was either 5 or 7. Figures 5-8 show results from the tests for the 50 kHz 5-cycle wave propagation generated by Actuators 1-4, respectively. Similar results, which are not shown here, were obtained by using other frequencies and/or other wave cycles.

Figure 5 shows both overall and detailed views on the time history of GW, while Figures 6-8 only show the detailed views. For Figures 5 and 6, the wave propagation results from Sensors 1-4 are shown as the 2nd-5th subplots in sequence. For Figures 7 and 8, the wave propagation results from Sensors 5-8 are shown as the 2nd-5th subplots in sequence.

![GW test results (Actuator 1)](image)

Figure 5. GW test results (Actuator 1)

As shown in Figures 5 and 6, the received waves generated by Actuators 1 and 2 are close to each other under different stages. Especially for far end sensors (Sensors 3 and 4 for Actuator 1 and Sensors 1 and 2 for Actuator 2), the recorded waves are almost identical. The reason is that there is no crack or micro crack on the path of propagating waves generated by Actuators 1 and 2. The first received wave is easily identified. Taking the waves generated by
Actuator 1 and recorded by Sensor 3 for example, the arrival time of this wave is 0.269ms. Based on the distance (0.608m), a wave speed of 2260 m/s can be determined, very close to the theoretical shear wave speed for M40 concrete, 2254 m/s. Based on these results, the received wave can be determined as a shear wave. In comparison, the received surface waves in Wang and Hao (2011) were longitudinal waves, with a velocity of 3379m/s. The results indicate the complexity of wave propagation on the surface of concrete materials, which may depend on the size, material properties, and many other factors. Further investigations are needed for better understanding, which will be done in the future studies.

For near end sensors (Sensors 1 and 2 for Actuator 1 and Sensors 3 and 4 for Actuator 2), the recorded waves seem irregular, though their amplitudes keep the same level under different stages. This may be caused by the sensor attachment method. As can be seen in Figure 1, the sensors are orientated in their longitudinal direction. Therefore, the waves propagating in this direction will be easily detected, i.e., waves received by far end sensors. However, for near end sensors, the first few received waves are from the minor direction, making them irregular.

As shown in Figures 7 and 8, the changes of the received waves generated by Actuators 3 and 4 under different stages are obvious. For far end sensors (Sensors 7 and 8 for Actuator 3 and Sensors 5 and 6 for Actuator 4), the amplitudes of the recorded waves showed slight changes under the serviceability load (only received data of Sensor 8 from Actuator 3 changed a lot), while they are largely reduced after concrete cracked. This may indicate that the existence of cracks on the wave propagation path can have large effects on the results. For Sensor 8 from Actuator 3, some invisible micro-cracks may exist on the path, so the amplitude of the recorded wave is largely reduced. As for the wave velocity, similar results (i.e., 2235 m/s for wave from Actuator 3 to Sensor 7) are yielded using the baseline data. For serviceability and damage results, the arrival times show a minor change. Since under serviceability load, concrete is still in its elastic stage, the reason may be accounted for the geometrical change, i.e., the displacement. However, further studies are needed to explain the results.

For near end sensors 5 and 6 for Actuator 3, the amplitudes of the recorded waves are obviously reduced under serviceability load as well as cracking load. In contrast, for Sensors 7 and 8 for Actuator 4, the recorded waves seem irregular but the amplitude keeps the same level. These results indicate that there are micro-cracks around Actuator 3 but not around Actuator 4 under serviceability load, which coincides with the results shown in Table 1, where a bigger crack occurred at the right corner of the joint (close to Actuator 3).

3.3 Discussions

Based on the test results, when there is no crack or micro crack on the wave propagation path, the recorded waves are regular and stable, especially in the longitudinal direction of the sensors. When crack or micro-crack exists, the recorded waves will be changed. This change can be a good qualitative indicator for concrete crack damage.

In order to further investigate the relationship between the damage and the changes, parametric studies based on refined numerical models will be necessary. The models can also be used for model updating based on the test results, which leads to quantitative damage identification. Therefore, construction of a refined numerical model is suggested as a future study.
4 CONCLUSIONS

In order to verify the applicability of GW-based method on real civil structures, a full-scale concrete joint was constructed in this study. GW tests were conducted in three stages, including baseline, serviceability and damage. Experimental results show that GW based method is very sensitive for concrete crack damage, and thus it will be a promising tool for damage identification in practices.

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