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Experimental Damage Identification in Concrete Structure Using Stack Migration Imaging Technology

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Abstract

Stack migration imaging technology (SMIT), an advanced data processing technique typically used in geophysical exploration, was employed for the detection of small cracks inside concrete structures. Ultrasonic transducers were utilized as both actuator and sensor to generate and receive stress waves in the concrete. The wave field reflected from the damage was synthesized at a common reflective point to highlight the effective signals by using multiple transducers. Two concrete specimens with embedded damage were examined using horizontal stacking technology and diffracting scan pre-stack migration technology, respectively. The dimensions and locations of the damage were successfully imaged. Compared with traditional ultrasonic detection, the experimental results show that SMIT offers better damage visualization and allows damage detection from one side of the specimen.

1. Introduction

To prevent engineering accidents such as building collapses and airplane crashes, a lot of attention has been focused on the quality of construction. In most cases, the load bearing capacity, security and durability of engineering structures can deteriorate over time due to environmental factors and mismanagement. The damage and collapse of a structure begin with invisible cracks. To some extent, the growth of these cracks determines the reliability, functionality and durability of a structure. It is therefore crucial to have appropriate non-destructive evaluation (NDE) methods to assess the locations of cracks and their damage potential.

Different NDE methods have different capabilities and limitations for detecting engineering defects. Normal NDE methods including the ultrasonic wave method (Ramamoorthy et al. 2004; Masserey and Mazza 2007), surface wave method (Popovices et al. 2000; Klysz et al. 2004), rebound method (Hobbs and Kebir 2004) and infrared imaging method (Büyüköztürk 1998) are often used to detect cracks inside concrete. While all these methods have shown to be useful in detecting wider cracks, especially opening cracks, they are limited in detecting small cracks due to the complexity of concrete material and the high energy loss of high frequency ultrasonic waves. Conventional ultrasonic detecting methods are not applicable for the detection of small cracks because of the high frequency attenuation of ultrasonic waves owing to the fact that wave propagation scatters strongly in concrete. Alternatively, Yuan et al. studied the use of stack migration imaging technology (SMIT) for damage identification in an aluminum board and suggested that the geophysical array method could be used to measure and process weak signals (Wang and Yuan 2005, 2007). SMIT, the transducer-array method, can effectively locate defects. Yuan et al. showed that SMIT can detect not only the existence of damage but also the precise location and the degree of the damage. However, the technique was only applied in damage identification of a simple isotropic material. Some relevant preliminary studies have shown that cracks in concrete structures are analogous to stratigraphic faults detected by the common reflection point (CRP) stacking method (Chang and Wang 2001; Luo and Li 2010; Liu et al. 1996). Therefore, it may be possible to detect small cracks in concrete structures.

In this study, SMIT was adopted as a feasible alternative NDE method for interpreting the recorded wave field data and producing a damage section image of the concrete samples. The horizontal stacking method and diffracting scan pre-stack migration method belonging to SMIT were used to detect horizontal and inclined cracks, respectively. Some data processing procedures related to migration were also demonstrated. The traditional ultrasonic testing method was also used on the same samples for comparison purposes.

2. Detection principle and method of SMIT

As shown in Fig. 1, is the actuating source and is the
the receiving source. Point \( A \) is the CRP. The time-distance curve equation of CRP can be expressed as

\[
t = \frac{1}{v} \sqrt{x_i^2 + 4h_0^2} \quad (i = 1, 2, \ldots n)
\]

where \( h_0 \) is the vertical distance between CRP and the concrete surface. Equation 1 represents the relationship between trigger-receive distance \( x_i \) and the travel time \( t \) of elastic waves. By taking the self-excited, self-received time as the base time \( t_0 \), the normal time difference \( \Delta t \) of all channels is expressed as \( t - t_0 \).

\[
\Delta t = t - t_0 = \left( \frac{x_i^2}{v^2} + t_0^2 \right)^{1/2} - t_0 = t_0 \left[ \left( \frac{x_i^2}{t_0v^2} + 1 \right)^{1/2} - 1 \right]
\]

(2)

where \( v \) is the ultrasonic velocity. When \( \frac{x_i}{t_0v} \), as in the case of deep damage, performing a series expansion of Eq. 2 gives the first two terms \( \Delta t \approx \frac{x_i^2}{2t_0v^2} \). Dynamic correction is used to correct the corresponding time-distance curves. Thus, the residual time difference after dynamic correction is zero. Signals from the same reflection point stack after dynamic correction and the reflection waves are enhanced.

For the inclined interface, the precise dynamic correction time difference \( \Delta t_\phi \) is given as follows:

\[
\Delta t_\phi = t_{out} \left( \frac{x^2 \cos^2 \phi}{t_{out}v^2} + 1 - 1 \right)
\]

(3)

where \( t_{out} \) is the travel time from the source to the CRP and \( \phi \) is the inclined angle. Similarly, a residual time difference exists when dynamic correction of the horizontal interface is applied to correct the inclined interface and the different phases affect the stacking results. Therefore, diffracting scan pre-stack migration technology is fit for detecting inclined cracks.

**Figure 2** shows the principle of diffracting scan pre-stack migration. Points (\( S_s, S_s, \ldots S_s \)) receive signals from the excited points (\( O_1, O_2, \ldots O_n \)). For any point \( M \), a channel records the reflection information if it is a reflecting point (Fig. 2a). For the same point \( M \), there are \( P \) channels with waves intersecting at point \( M \) as CRP while the voltage is covered by \( P \) times (Fig. 2b). The total stacked amplitude \( P \times N \) obtained is given by

\[
A(M) = \sum_{j=1}^{N} \sum_{i=1}^{P} f_j(M)
\]

(4)

where \( f_j(M) \) is the instantaneous amplitude of the \( j \)th channel of the \( i \)th exciting point and \( N \) represents the number of receiving channel. By calculating \( f_j(M) \) of every point in the grid, the amplitude \( A(M) \) of every point \( M \) is obtained and all calculated migration stacking amplitudes are displayed in a way. **Figure 3** shows that the section below the survey line of the concrete is divided into square grids with width \( \Delta x \) and height \( \Delta h \), with their magnitudes chosen between 0.1 and 3mm. Because all the reflective amplitudes near the tangent point are taken away and are almost stacked by the same phase, the stacking amplitudes become more enhanced and the reflective energy becomes more outstanding. The record quality of post-stacking increases greatly. If the ordinate \( H \) is changed to vertical time \( \frac{T_i}{2} \), in other words \( H = \frac{V}{2} T_i \). The relation between the location and the recorded time of reflective geophones on the concrete surface is a diffracting wave double curve diffracted by scan point \( M \)

\[
t_s = \sqrt{\frac{x_{s}}{v^2} + \frac{T_i}{2}^2} + \sqrt{(x-x_{s})^2 + \frac{T_i}{2}^2}
\]

(5)

Using the same method mentioned above to scan stacking, the pre-stack migration time section is obtained.
As shown in Fig. 4(a), the measurement and scanning proceed along the survey lines on the top of the specimen. Eleven PZT transducers are set to detect damages. When the actuator is excited at the location of point A1, all other ten sensors (from point S1 to S10) on the survey line simultaneously record the reflected echoes from the structure. Next, the actuator and sensor groups move forward by a unit distance \( d \) for the second measurement, the actuator is triggered at the location of A2 and the ten sensors (from point S2 to S11) record the reflected echoes, and so forth. As shown in Fig. 4(b), \( \Delta x \) (5 mm) is the channel interval and \( x_i \) (50 mm) is the minimal actuator-sensor distance. \( x_{\text{max}} \) (95 mm) is the distance between the actuator and the last sensor, and \( d \) (5 mm) is the actuator interval.

3. Experimental processing and analysis

3.1 Experiment preparation

Two plain concrete specimens (S-1 and S-2) with different types of simulated cracks were prepared for the study. The characteristic strength of the concrete was 30 MPa with the static modulus of elasticity at 28 days tested to be 31 MPa. All of the specimens had length of 1000 mm, width of 240 mm, and height of 240 mm. The aggregate had a maximum size of 31.5 mm. The velocities of the concrete for the compressional waves and Rayleigh waves were 3730 m/s and 1846 m/s.

A piece of artificial wood panel (60 × 8 mm) was embedded horizontally in the center of specimen S-1, and specimen S-2 was embedded with the same size panel to form a defect in the concrete at a dip angle of 15°. The dry density of the artificial wood panel was 780 kg/m³.

The equipment used in the experiment is shown in Fig. 5. A pulse wave was emitted by a waveform generator at 150 kHz along the survey line, as shown in Fig. 6. The sensor in one end received the reflective signals, which were amplified by a power amplifier and recorded by an oscillograph. The diameters of the transducers were 15 mm with a frequency of 150 kHz. The sampling rate for measurement was 2.5 MSa/s. The same setting was applied to two beams.

3.2 Experimental results

The channel set is a side-by-side display of time histories recorded by the 10 receivers in a spread for every excitation. Figure 7 gives the typical traces of the scattering waves excited with the horizontal crack damage and inclined crack damage. The reflecting amplitude in Fig. 7(a) is greater than that in Fig. 7(b) as the distance increases. The position of the crack cannot be identified after a single excitation. Thus, more single actuators are needed to stack the signals reflected from CRP. In order to reduce the effects of the attenuation characteristics of ultrasonic waves, the weaker echo reflected from the damage should be amplified by a data processing method before stacking.

Specimen S-1 was scanned first in this study. It was
necessary to rearrange the data in pretreatment after scanning. The reflective energy among the shallow, middle and deep layers differs greatly, as well as the energy among different channels. As a result, decorative procession and multi-channel digital filtering were needed to improve stacking effects. During the process, the band filter range was chosen from 120 to 180 kHz based on the collected data. Labview software was used to make the band-pass filter. After the signal was recorded, the data was imported into the band-pass filter and the post processing data was used as effective information. Signals inside and among the channels should be balanced. The reflective signals strengthen noticeably following elimination of the effects of the strong Rayleigh wave amplitude. A gray-scale image of the horizontal stacking section is shown in Fig. 8. The length of the crack from the experiment was 65 mm, which differs only by 5 mm compared with the actual length of 60 mm. This indicated the feasibility of imaging of the horizontal crack on plain concrete.

Specimen S-2 with an inclined crack at a 15° dip angle was evaluated using the same acquisition parameters. Figure 9 shows the image of a concrete structure with an inclined crack migrated from the data recorded in the experiment. The length and the depth of the crack are 65 mm and 45 mm, respectively, which corresponds very closely to the position of the actual crack. While the major part of the damage is imaged, there are some scattered blocks around the damage. These errors are mainly due to the coarse approximation of arrival time introduced in the process of reconstructing the scattered...
wave field through interpolation. This could be corrected by using more sensors and thus omitting the interpolation process.

### 3.3 Traditional ultrasonic detection comparison

In order to validate the advantage of SMIT, the traditional ultrasonic testing method was performed as a comparison. The principle of damage detection includes penetration testing and slop testing (Colombo and Felicetti 2007; Prassianakis and Prassianakis 2004). The possible area of damage can be detected by the change of velocity and amplitude from both sides of the specimen. The amplitude and travel time decline as the signals propagate across the crack. Therefore, the crack areas of S-1 and S-2 are detected as shown in Figs. 10 (a), (b).

The results showed good agreement between the SMIT and traditional ultrasonic detection method. However, traditional ultrasonic detection can merely distinguish the possible area of damage, but cannot readily identify the specific position. Compared to the ultrasonic test, SMIT has significant advantages: lower subjective factors influence, more intuitive results and abundant information. Imaging of the damage within the concrete cross section can be produced from one side of the specimen.

### 4. Conclusions

In this study, SMIT has been demonstrated to be an advanced technique that could be adopted for failure detection in structures. The results showed that SMIT has obvious advantages for engineering structures over the traditional ultrasonic detection method. SMIT can detect not only the existence of small cracks, but also produce imaging of the damage within the cross section of the specimen from one side. The migration technology has potential for identifying different failure modes, such as matrix cracks and delamination in anisotropic structures. The resolution and the location of the damage depend greatly on more advanced filtering and sensing technology. Current studies on the application of SMIT on damage identification of concrete structure are still at the preliminary stage and further research is needed to develop a reliable SMIT monitoring system.

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