Quantitative assessment of interfacial condition of cold joint using surface wave group velocity profile

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Abstract. Improperly constructed cold joints lead to poor water tightness. Water, chloride ions, and other harmful substances can therefore enter through the joint, causing the accelerated corrosion of steel bars. In this study, the surface wave group velocity profile, which can identify velocity at variant depths beneath concrete surfaces, was used to determine the interfacial condition of a cold joint. The proposed test method performed a single test with one impacting source and one receiver placed on a concrete surface across the joint. The short-time Fourier transform (STFT) and the reassignment technique were used to process the received signal and obtain the image of the group velocity spectrogram. The surface wave group velocity profile was then extracted from the spectrogram. A 0.4 m-thick reinforced concrete wall containing a cold joint was constructed for the experimental studies. The experimental results revealed a sudden decrease in wave speed for wavelengths larger than 0.2 m: the Rayleigh wave speed dropped from 2,000 m/s for normal concrete to 1,300 m/s for concrete including a cold joint. These results suggest that the rebars near both sides of the wall surface constrained the joint from separating up to the depth of 0.1 m; however, a poor interfacial condition was found near the center of the wall.

1. Introduction

Cold joints form on the interface of two concrete batches when the previous batch of concrete has begun to set before the subsequent batch is added. The poor water tightness of cold joints leads to the invasion of water, chloride ions, and other harmful substances and thus causes the accelerated corrosion of steel bars [1]. In addition, literature confirms that the presence of cold joints can produce a significant decrease in the flexural strength, tensile strength, and compression strength of the concrete [2–7].

Can a pour line of uneven color found on the surface of a wall or beam be considered a harmful cold joint? Sometimes the formation of the casting line can cause narrow spacing between the steel reinforcement and the wall of the formwork, even when the concrete is well mixed inside. In that case, although the surface appears to have a clear casting line or honeycombs, the core drilling results along the casting line indicate no reduction in strength, which means that only surface waterproof treatment is needed [8].

How can one distinguish cold joints from non-cold seams? Experienced engineers in the United States use one of three methods [8]: The first requires obtaining a core sample with a pouring line and performing a careful visual inspection on it. A seam will not be considered a cold joint if the layered interface line does not extend deep into the seam, or the distinguishing stratified layers continue to the
entire core but no crack has formed in the interface, or thick aggregates exceed the casting surface. The second method involves cutting the core sample into thin slices and observing them under a microscope for carbonization, drying, or changes in the pore structure of the mortar at the interface. The third method includes first adjusting the coring position to relocate the casting line to the center of the core and then conducting the splitting test on the core test; the split surface will therefore coincide with the pouring interface. The interface is considered a cold joint if the tensile strength is less than the splitting strength of the intact concrete core test.

This study used the dispersive characteristics of the group velocity of surface waves to design a new method of identifying cold joints based on the dispersion of surface waves. Tests were performed with one receiver positioned away from the impacting source. The short-time Fourier transform (STFT) was used to calculate the spectrogram of the group velocity obtained by the receiver, while the time-frequency reassignment technique was used to enhance the resolution of the spectrogram [9, 10]. This method has the advantage of being able to investigate a large area quickly, as it requires conducting only a single test to obtain multiple lamb wave modal dispersive characteristics.

2. Theoretical backgrounds

This study recommends the new method that involves only one test with a single impacting source and a single receiver, where the STFT and the reassignment technique are used to process the received signal and obtain the spectrogram of the group slowness. The dispersive characteristics of the group slowness of the test signal can be obtained by first performing the STFT on the test signal to construct the preliminary spectrogram and then using the time-frequency reassignment technique to enhance the images of the dispersion characteristics in the spectrogram. For the STFT, the signal \( s(t) \) is separated into a series of overlapping sections; each section is subsequently multiplied by a given window function \( h(t) \) and transferred into the frequency domain via Fast Fourier Transformation (FFT). The STFT, denoted as \( S_h(\omega, t) \), is defined in equation (1).

\[
S_h(\omega, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{-i\omega \tau} s(\tau) h(\tau - t) d\tau
\]  

(1)

The spectrogram of \( S_h(\omega, t) \) is the energy density spectrum of a STFT, which can be calculated with equation (2).

\[
E_h(\omega, t) = |S_h(\omega, t)|^2
\]  

(2)

For the reassignment technique, high-energy corresponding to the dispersive character of a plate can be moved from its original location \((\omega, t)\) to a newly reassigned coordinate \((\hat{\omega}, \hat{t})\), which is usually at the center of gravity of the high energy band. The reassigned coordinates are presented in equation (3) and Equation (4) [9], where \( S_h, S_{Dh}, \) and \( S_{Th} \) are the STFT of the signal \( x \) using a normalized window function \( h(t) \) and \( t^*h(t) \).

\[
\hat{t} = t - \text{Re}(\frac{S_{Th}(x, t, \omega) \cdot S_h(x, t, \omega)}{S_h(x, t, \omega)})
\]  

(3)

\[
\hat{\omega} = \omega + \text{Im}(\frac{S_{Th}(x, t, \omega) \cdot S_h(x, t, \omega)}{S_h(x, t, \omega)})
\]  

(4)

The MATLAB coding for the reassignment technique can be found in [11].

3. Experimental designs

3.1. Specimen preparation

A wall-like specimen measuring 3 m in width, 2.5 m in height, and 0.4 m in depth was built to establish the practicality of using the aforementioned method to detect voids inside the tendon ducts of a
prestressed structure. As figure 1(a) demonstrates, five galvanized tendon ducts with 0.1 m diameters, completely filled or partially filled with various amounts of non-shrinkage mortar, were thus placed inside the specimen. Eight #6 horizontal rebars with a cover thickness of 0.05 m were also placed near both wall surfaces at the lower part of the specimen, spaced 0.15 m apart. The cold joint formed due to an accident: When the self-filling high performance concrete was cast to about half full, one joint close to the foot of the wooden formwork separated, and the concrete slurry flowed out of the form until the remaining concrete was only about 30 cm high. The wooden mold was repaired, and one week later, concrete was cast to the full height, although the casting surface of the existing concrete had not been treated. A cast line of uneven color can therefore easily be seen on the surface, as indicated by the arrows in figure 1(b). Self-filling concrete (SCC) with a water to binder ratio of 0.38, was used for this study. Furthermore, cement was substituted with 15% fly ash and 35% water-blasted slag powder, based on weight. The weight ratio between fine and coarse aggregates is 1 and the maximum size of coarse aggregates is 20 mm.

![Figure 1. Preparation of (a) the specimen’s interior design and (b) position of the cold joint.](image)

3.2. Test method

As figures 2(a) and 2(b) illustrate, the test lines were organized in a grid-like configuration, allowing a horizontal and vertical space of 0.3 m at both wall surfaces. The grid lines were numbered as depicted, and the test lines at direct opposite positions on the other side of the wall were numbered the same. The positions of the vertical test lines do not coincide with the positions of the tendon ducts to simulate a situation in which the interior condition has not been determined. When a special impact hammer was applied to one intersection of the test grid, the displacement receiver at another intersection 0.6 m from the impactor recorded the produced stress waves. The impact source, pictured in figure 3(a), was made from a steel half sphere 5 mm in diameter that was embedded with a piezoelectric element to record the initial impact time.

Figure 2(a) also demonstrates the dots that indicate two of several test positions for the impactor and receiver across the cold joint as an example. Eight horizontal grid lines and 10 vertical grid lines were used. In this study, only results from tests conducted at vertical test lines were disclosed; tests were thus performed on the ordered pairs—such as (X1,Y1)-(X1,Y3), (X1,Y2)-(X1,Y4), (X1,Y3)-(X1,Y5), and so on—for vertical test line X1. Notice that the vertical test lines pass through the cold joint when the impactor and receiver are placed at Y6 and Y8. The test was conducted on 8,192 points recorded every 0.4 μs. Figure 3(b) presents the test setup.
Figure 2. Gridded test line configuration for two side surfaces and an example of two positions for the impactor and receiver.

Figure 3. Photos of (a) the impactor embedded with a piezoelectric element and (b) the experimental setup.

4. Experimental results

Figure 4 illustrates a test line that does not pass through the cold joint, while figure 5 illustrates one that does. Moreover, figure 4(a) describes the vertical displacement waveform obtained with the impactor placed at (X05,Y01) and the receiver placed at (X05,Y03). This test line does not traverse a tendon duct or the cold joint. The waveform signals were damped for slowness larger than 0.8 ms/m—which in this case affected signals above 0.48 ms—to enhance the surface wave response in the spectrogram. The slowness is time dividing the impactor-receiver distance (0.6 m). The group velocity profile of surface waves was obtained first by using equation (1) to perform the STFT to procure the slowness spectrogram with a Hanning window length of 0.4 ms and a window overlap of 96% and then by using the reassignment technique demonstrated in equation (2) to find the center of gravity of the high energy band in the spectrogram. Figure 5(b) provides the result of the response above −40 dB of the maximum amplitude. In the spectrogram, the dominant response below 30 kHz has a constant lowest slowness of about 0.5 ms/m, which corresponds to the Rayleigh wave depicted in figure 4(a) that begins at about 0.3 ms. As the concrete is solid under this test line, the Rayleigh wave exposes nondispersive characteristics in the spectrogram. The slowness spectrogram was transferred to the velocity-wavelength diagram displayed in figure 4(c), where the light-blue dots denote the largest amplitude. The surface wave velocity profile was obtained by finding the response with the continuous largest amplitude in the velocity-wavelength diagram as revealed in figure 4(d). An even wavelength-spaced linear interpolation between dots was then performed as depicted in figure 4(e) to be used for future construction of a 3-D velocity contour. The velocity profile verifies that the group velocity of the Rayleigh wave is around 2,000 m/s for wavelengths between 0.08 m and 0.75 m.

The response for a test line that traverses the cold joint is quite different from the response for one that does not. Figures 5(a)–(e) demonstrate the displacement waveform, slowness spectrogram, velocity-
wavelength diagram, scattering dotted velocity profile, and evenly spaced velocity profile for test lines that begin at (X4,Y6) and end at (X4,Y8), respectively. A distinct low-frequency wave between 0.4 and 0.5 ms was found in figure 5(a); the phenomenon is consequently represented by the high slowness (low velocity) dominant response below 10 kHz in the slowness spectrogram displayed in figure 5(b). The velocity profile in figure 5(d) reveals that the velocity remains around 2,000 m/s for wavelengths shorter than about 0.2 m and reduces to about 1,350 m/s for longer wavelengths. Previous studies confirm that a defect is usually located at the depth of about one half of the wavelength of the velocity turning point [12] and that the velocity profile is meaningful at the range of wavelength equal to or shorter than the impact-receiver distance [13]. The velocity profile presented in figure 5(d) thus implies that the interface of old and new concrete did not separate up to the depth of about 0.1 m; the cold joint was formed for a deeper region. The effective depth of measurement is up to 0.3 m from the wall surface. Since the wall depth is 0.4 m, the interfacial condition near the opposite wall surface must be determined by conducting a test on that surface. It is possible that the reinforcement with a diameter of 19 mm and a cover thickness of 50 mm confined the concrete shrinkage close to the reinforcement layer. The separation of the interface was due to the shrinkage of the top of the wall after a large volume of concrete was cast one week later.

Figure 4. Test line (X5,Y1)-(X5,Y3): (a) displacement waveform, (b) slowness spectrogram, (c) velocity-wavelength diagram, (d) scattering dotted velocity profile, and (e) evenly spaced velocity profile.
The evenly spaced group velocity profiles for all the vertical lines were incorporated to produce an image of the 3-D velocity contour. This process was accomplished by setting all the positions of grid interceptions that pass the test line to the same velocity defined by the corresponding group velocity profile. For instance, test line (X1,Y1)-(X1,Y3) passes through intersections (X1,Y1), (X1,Y2), and (X1,Y3). For interceptions with two test lines traversing them, the average of the velocities obtained from the two tests was the resulting velocity at that position. Finally, the velocity contour for all the velocity profiles for all the grid interceptions at each wavelength were assembled to form the velocity contour corresponding to the geometric position of the test points.

Figure 6 illustrates the velocity contour of wavelengths measuring 0.15 m, 0.2 m, 0.3 m, and 0.5 m for the two wall surfaces. The images on the left correspond to tests on the surface, closer to the tendon ducts, while the ones on the right correspond to tests on the other wall for the same wavelength. Focus on the variation of group velocity for the region between 6 and 8 on the Y-axis. For wavelengths equal to 0.15 m, no significant change in velocity occurred in the corresponding region; however, when the wavelength reached 0.2 m, the images from both wall surfaces revealed the beginning of lower velocity for some test lines that traversed the joint. This trend became clearer in the images of wavelengths longer than or equal to 0.3 m. The low velocity is caused by the waves traveling through the porous cold joint and leads to the reduction in wave speed from 2,000 m/s to as low as 1,300 m/s for vertical test lines X1, X2, X3, X4, X8, X9, and X10 at the surface, closer to the tendon ducts, and X2, X3, X4, X5, and X10 for the other side of the wall. This result suggests that up to the depth of 0.1 m, the front and back reinforcing steel bars constrained the later cast concrete from shrinking. A cold joint with serious interfacial defects still exists near the center of the interface. It can also be observed from the contour images in Figure 6 that in the region with vertical lines X2, X3, X4, and X10, cold joints formed near the center 0.2 m of the interfacial region as a similar pattern of velocity profiles were obtained from the direct opposite test lines. Both sides demonstrate little or no defect for the test lines X5, X6, and X7, and only the side with shallower ducts can be used to find cold joint responses for lines X8 and X9.
Figure 6. Group velocity contour plot for various wavelengths. Left: duct depth 0.06 m. Right: duct depth 0.24 m.
5. Conclusions and future works
In this study, the cold joint formed after an accident that caused concrete to leak from the damaged formwork. New concrete was cast one week later, with no treatment having first been applied to the casting surface. Using the impactor and receiver across the joint and performing the STFT and the reassignment method on the recorded waveform allowed the researchers to obtain the group slowness (or velocity) spectrogram and the corresponding velocity-wavelength diagram. The group velocity profile of the surface wave was then obtained from the velocity-wavelength diagram by extracting the strongest response, which is usually the Rayleigh wave response, from the diagram.

Several conclusions can be made regarding using the proposed method to assess cold joints: First, the velocity profiles’ w.r.t. wavelength can assess the interfacial condition of a joint w.r.t. depth. Second, in this case, the cold joint can reduce the Rayleigh wave speed by up to 35%; the large decrease in wavelength means that this method can easily assess the cold joint. Third, the steel reinforcement near the wall surfaces can constrain the pouring surface from becoming the cold joint but only around rebars.

Since this study is only a preliminary study and the wall-like specimen was made specifically for assessing voids inside its tendon ducts, more fundamental experiments must be designed for evaluating cold joints with different degrees of porosity by using the proposed method.

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