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Crack Depth Estimation in Concrete Using Energy Transmission of Surface Waves

by Sung Woo Shin, Jinying Zhu, Jiyoung Min, and John S. Popovics

The self-calibrating surface wave transmission method is a promising nondestructive technique for surface-breaking crack depth inspection of concrete. Determination of crack depth using the cut-off frequency in the transmission function (TRF) is difficult, however, in part due to the variability of the measurement data. In this paper, the spectral wave-energy transmission method, which employs the self-calibrating configuration, is proposed for crack-depth estimation in concrete structures. Results from an experimental study carried out on a concrete slab with varying crack (notch) depths are reported. The effectiveness of the proposed method is validated by comparing the conventional time-of-flight and cut-off frequency-based methods. The results show that spectral energy transmission has excellent potential as a practical and reliable in-place nondestructive method for in-place crack depth estimation in concrete structures.

Keywords: crack depth, nondestructive testing, spectral energy transmission, stress waves

INTRODUCTION

Cracks in concrete are common defects that may enable rapid deterioration and promote early failure of structures. Therefore, the assessment of the cracks in concrete is important for the condition evaluation of concrete structures.[1-3] Over the last decade, several studies on nondestructive techniques to characterize the surface-opening crack depth in concrete have been reported.[4-16] These methods can be classified into two major categories: 1) time-of-flight-based (time domain) approach; and 2) wave transmission-based (frequency domain) approach.

In the time-of-flight-based methods, the surface-opening crack depth is estimated by measuring the time required for a longitudinal wave generated by an impact event on one side of a surface-opening crack to diffract at the tip of the crack and be captured by a surface-mounted receiver at the opposite side of the crack. Lin and Su[5] assumed that the first measured wave arrival at the receiver on the same side of the crack is the surface wave, whereas Sansalone et al.[6] assumed the arrival of the longitudinal wave. In both cases, this first wave arrival is used to trigger the monitoring system. A stress wave pulse from a pulse-velocity meter may also be used, instead of an impact event, for crack depth estimation using the time-of-flight approach. Other techniques based on a time-of-flight approach also have been reported.[7,8] Song et al.,[9] however, have shown that the existing time-of-flight method does not always give reasonable estimates of the depth of surface-opening cracks and notches in concrete. They found that the estimation of the crack depth depends not only on the sharpness of definition of the crack tip as a diffractor of stress waves, but also on the accuracy of the determination of the arrival time of incident and diffracted wave pulses detected by receivers. Variation of signal shape may be caused by the characteristics of test setup and near-tip crack features.

On the other hand, wave transmission or attenuation (signal energy loss) measurements, performed under laboratory conditions, are very sensitive to the presence of cracking damage in concrete.[10] Especially the self-calibrating surface wave transmission method seems to be a promising nondestructive technique for crack-depth assessment of in-place surface opening cracks in concrete structures. Numerical studies and surface wave transmission measurements performed on concrete demonstrate superior sensitivity to the presence of cracking along the wave path in concrete over time-of-flight-based methods.[9,11-13] Accurate crack depth estimation from surface transmission, however, remains a challenge. Studies on crack-depth estimation based on the analysis of the transmission function (TRF) have been reported.[11,14-16] Those include the cut-off frequency method,[11] interceptor-frequency method,[14] inversion approach,[15] and wavelet-based method.[16] Among them, the cut-off frequency method is a commonly accepted method for estimating the depth of the crack. In this method, the crack depth is estimated by determining the depth-corresponding frequency (the cut-off frequency) in TRF. The experimental determination of the cut-off frequency for the crack depth assessment, however, may not be straight forward because of the significant variations of the experimentally measured TRF so the depth evaluation may be erroneous.[17] Moreover, because the Rayleigh wave velocity of the test structure should be known in the cut-off frequency method to quantify the depth of the crack, an additional test to measure the Rayleigh wave velocity is needed.[11,13]

In this study, a wave energy-based approach that employs the self-calibrating technique is proposed for crack depth estimation in concrete slabs. The surface wave transmission using the self-calibration technique is measured along the surface of concrete slabs, and then it is used to calculate the spectral wave-transmission energy for a specific crack depth. The calculated wave-transmission energy is normalized and related with a crack depth by regression analysis. Finally, the effectiveness of the proposed method is validated by comparing the conventional time-of-flight- and cut-off frequency-based methods.

RESEARCH SIGNIFICANCE

Concrete structures suffer damage from environmental deterioration or repeated service loads, where the damage

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most often takes the form of cracking. A distinct single surface-opening crack in concrete is a common defect that may promote significant deterioration and failure of concrete structures. Therefore, early detection, characterization, and repair of cracks in concrete structures are very important for maintaining the health of concrete structures.[1-3]

TECHNICAL BASES

Self-calibrating wave transmission measurements

The underlying principle of the wave transmission-based method is that a part of the incident wave energy will be reflected (that is, not transmitted) by the vertical crack, so the frequency content of the TRF across the crack changes. Practical one-sided surface wave TRF measurements in concrete have been obtained through a self-calibrating testing scheme to eliminate the disrupting effects of the source and receiver characteristics and the coupling condition.[12,13,18] In this section, the self-calibrating scheme is reviewed.

Referring to Fig. 1, a frequency domain signal that is generated by an impact source at Location A and detected by a receiver at Location B can be represented as

$$Y_{AB}(f) = S_A(f)T_{AB}(f)R_B(f) \tag{1}$$

where $Y_{AB}(f)$ is the Fourier transform of the acceleration time signal detected by the receiver at B, $S_A(f)$ is the impact source function at Location A, $R_B(f)$ is the frequency response function of Receiver B, and $T_{AB}(f)$ is the TRF from Location A to Location B.[7] Similarly, the stress waves generated by $S_A(f)$ and detected by the receiver at Location C can be expressed as

$$Y_{AC}(f) = S_A(f)T_{AB}(f)T_{BC}(f)R_C(f) \tag{2}$$

where T_{BC} and R_C are defined similarly to T_{AB} and R_B, respectively. In Eq. (1) and (2), the S_i and R_j terms include the effect of the variability in the impact source and receiver coupling.

The desired stress wave TRF (T_{BC}) across the crack region can be obtained in terms of the measured signals from Receivers B and C by incorporating a complimentary set of signals due to an impact source at Location D as

$$|T_{BC}(f)| = \left|\sqrt{\frac{Y_{AC}(f)Y_{DB}(f)}{Y_{AB}(f)Y_{DC}(f)}}\right| \tag{3}$$

where Y_{DB} and Y_{DC} are defined similarly to Y_{AB} and Y_{AC} in Eq. (1) and (2). It is assumed that the material is grossly homogeneous and isotropic and the receivers have no effect on the passing stress waves. Concrete can be regarded as homogenous if the wavelength is notably larger than the coarse aggregate size. The frequency range used in this study is 0 to 32.5 kHz. Assuming a surface wave velocity of 2250 m/s (7380 ft/s), the resulting minimum wavelength is approximately 70 mm (2.76 in.), which is larger than the maximum size of coarse aggregates of 10 mm (0.394 in.). Therefore, it is reasonable to consider the concrete in this study to be grossly homogeneous and isotropic.[12,13] The TRF T_{BC} is a function of frequency and indicates the ratio of the amplitudes of the surface waves at B and C. Thus, a $|T_{BC}(f)|$ of 1 means complete transmission (no attenuation) of stress waves between two locations, whereas 0 means no transmission (complete attenuation). Therefore, the $|T_{BC}(f)|$ values should theoretically be between 0 and 1. Further detail on the approach, including required signal processing, is given in References 12 and 13.

Spectral wave-energy transmission method

To estimate the crack depth based on the measured TRF, the most important step is to characterize the relation between a physical quantity (or a damage-sensitive feature) to the corresponding crack depth. In this part, the spectral wave-energy is introduced as a depth-sensitive feature, and then the spectral wave-energy transmission ratio is proposed to relate the calculated spectral wave-energy with the depth. Details of the spectral wave-energy scheme are presented in this section.

It has been discussed in previous studies that the signal transmission of plane surface waves is reduced significantly by scattering from a surface-breaking crack.[9,11] Therefore, it may be proper to assume that the total energy in a signal transmission function at a specific crack depth is distinct from that at another depth. In this assumption, the crack depth can be estimated from measured surface wave TRF.

The spectral energy E of the measured surface wave TRF T_{BC} at crack depth d_1 is defined as

$$E(d_1) = \int_{f_L}^{f_U} T_{BC}(f;d_1)df \tag{4a}$$

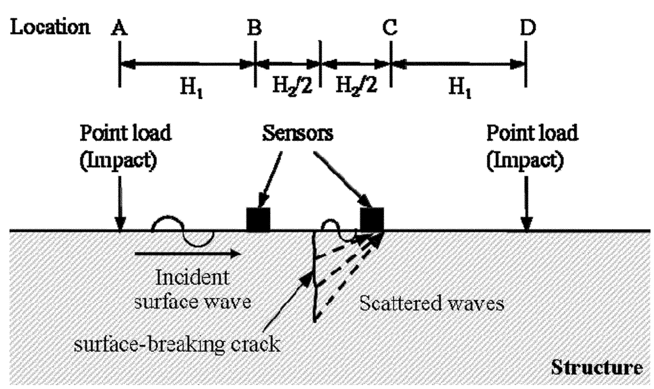

Fig. 1—Experimental setup for self-calibrating wave transmission measurements. Illustration of the interaction of an incident surface wave with a surface-breaking crack is represented.

or in discrete form

$$E(d_1) = \sum_{i=N_L}^{N_U} T_{BC}(f_i;d_1)\Delta_f \quad (4b)$$

where f_U is the upper frequency limit for integration corresponding to N_U and f_L is the lower limit corresponding to N_L, both in crack-free condition. These parameters are very important for a reliable and consistent calculation of the spectral energy. They are determined based on the acceptable value of signal measurement consistency, which is shown in the experimental study section.

A calculated spectral energy for a specific crack depth cannot be used for crack depth estimation directly. Because there is no rigorous relation between the amplitude of spectral energy and the crack depth, a relative relation between them must be sought. This can be achieved by the following normalization process

$$R(d) = \frac{E(d)}{E(d_0)} = \frac{\int_{f_L}^{f_U} T_{BC}(f;d)df}{\int_{f_L}^{f_U} T_{BC}(f;d_0)df} \quad (5)$$

where $R(d)$ is the spectral energy transmission ratio of the crack depth of d; d_0 is the depth index for the baseline case, that is, crack-free depth; and f_U and f_L are the integration parameters implemented in Eq. (4a). Theoretically, the range of the spectral energy transmission ratio is 0 (no transmission) to 1 (complete transmission) similar to the wave transmission coefficient $T_{BC}(f)$. Therefore, $R(d)$ should, in principle, decrease as the depth of the surface-breaking crack increases; for example, the value of 1 means no crack in the wave path. Once the crack-free spectral energy is obtained, the spectral energy transmission ratio for a specific crack depth can be calculated using Eq. (5). Then, the crack depth can be estimated by using a predetermined relation between the spectral energy transmission ratios and the crack depths.

One advantage of this method over the conventional cut-off frequency or time-of-flight methods is that the wave velocity is not needed in the estimation process. Therefore, an additional test for wave velocity measurement is not needed, which also reduces errors caused by inaccuracy in velocity measurement. Moreover, the spectral energy transmission method is characterized by simplicity and straight-forwardness in crack depth determination. Compared with the cut-off frequency method, the energy ratio method does not depend on frequency, thus the estimation of crack depth is straightforwardly determined from the spectral wave-energy transmission ratio.

EXPERIMENTAL INVESTIGATION

Concrete slab and test setup

A series of experimental tests was carried out to validate the proposed method. A reinforced concrete (RC) slab specimen, used in the experiments, was prepared by the research team in the Department of Civil and Environmental Engineering of the University of Illinois at Urbana-Champaign (UIUC). The specimen has been used for various studies of the nondestructive techniques for concrete structures.[19,20] The slab was nominally 0.25 m (9.8 in.) thick with lateral dimensions 1.5 x 2.0 m (5 x 6.5 ft). The 28-day compressive strength of the concrete was 42.3 MPa (6130 psi) that was determined from the standard compression test on companion cylinder specimens. The P-wave velocity of the concrete, determined by ultrasonic pulse velocity measurement, was 4100 m/s (13,500 ft/s), and the Rayleigh wave velocity was 2250 m/s (7380 ft/s). The slab contained a single artificial crack (notch) that had a linearly increasing depth, with a designed depth varying from 10 to 160 mm (0.4 to 6.3 in.) across the width of the slab. The notch was generated by inserting two greased metal sheets before casting concrete and removing the sheets after initial setting. The width of the generated notch was 0.6 mm (0.024 in.). Results from previous studies show that notches and real cracks in concrete have equivalent effects on TRF, so the width of the discontinuity does not affect the response; in the case of cracks, the crack closure and face contact condition has only a minor effect on the transmission response across the crack.[12,13] Thus, the results obtained herein with notches can be extended with confidence to real cracks in concrete.

The experimental setup for surface wave transmission measurements consisted of two wave sources, two wave sensors, a digital oscilloscope for signal digitizing and acquisition, and a fieldwork laptop computer that collected the data from the oscilloscope using a general purpose interface bus (GPIB) interface system. A set of different size of hardened steel balls, which are commonly used in impact-echo tests, was used to generate transient waves in concrete. Diameters of the balls ranged from 5 to 15 mm (0.2 to 0.6 in.). In this study, the sizes of 8 and 12 mm (0.3 and 0.5 in.) steel balls were used to generate waves and the mass of the balls were 15 and 20 g (0.033 and 0.044 lb), respectively. The ball was freely dropped on the concrete surface. Generally known, smaller balls generate shorter forcing function on the surface and are effective to excite high frequency waves. It is known from the preliminary examinations, however, that the sizes of the balls in this study do not cause much difference in wave transmission measurement. Miniaturized accelerometers having good low frequency response are used as contact-type wave sensors. Nominally, the spacing between the sensors (H_2 in Fig. 1) is 30 cm (12 in.) and between each wave source and the nearest sensor (H_1) is 150 mm (6 in.). The artificial crack (notch) is located midway between two sensors. When the impact source is applied to Location A, the propagating waves are detected by the two accelerometers (Locations B and C, successively) and are sent to separate channels of the oscilloscope. Each signal is collected and saved for further process. Next, the impact source is applied at Location D, and the entire data collection procedure is repeated.

Surface wave transmission results

Self-calibrating surface wave transmission measurements were performed on the concrete slab with various cracking conditions including crack-free and depth-varying cases. Measured transmission functions for various cases are shown in Fig. 2. The trend is observed that the signal transmission values decrease as the crack depth increases in frequency range of 0 to 50 kHz. The nature between the signal transmission and crack depth is shown in Fig. 3 for selected frequencies. Although the overall trend is similar to the relation between the TRFs and crack depths that the transmission decreases as crack depth increases, it seems difficult to estimate the crack depth using the conventional cut-off frequency method due to the frequency dependence of the signal transmission on the crack depth. That is, the signal transmission and crack depth relation at a specific frequency is distinct from that at another frequency.[12] For example, signal transmission for 35.89 kHz does not change much as the crack depth increases, whereas that for 10.01 kHz changes significantly. The estimated errors (root mean square error [RMSE]) in crack depth determination using the conventional cut-off frequency method[11] with the Rayleigh wave velocity of 2250 m/s (7380 ft/s) is shown in Fig. 4. It is identified that the estimated values are excessively deviating from the exact values. This result motivated to develop the proposed method.

Spectral energy transmission ratio results

As noticed in the previous section, the integration limits in Eq. (4), f_U and f_L, are important both for a consistent calculation of the spectral energy and for a reliable estimation of the crack depth. Because the surface wave TRF is not obtained from analytical solution but from an experimental measurement, the magnitude of the spectral energy is dependent on the integration frequency range. Moreover, incoherent noise content may reduce the signal-to-noise ratio and lead to unreliable results. Thus, a consistent procedure should be established to determine the frequency range within which the signal transmission measurement is acceptable and reliable. In this study, the signal consistency index[12,13] is employed for the determination of the frequency range.

The signal consistency index $S_C(f)$ is defined by five repeated self-calibrating wave transmission measurements on a crack-free (d_0) concrete surface

$$SC(f) = \frac{\sqrt[5]{T_{BC1}^{d_0} T_{BC2}^{d_0} T_{BC3}^{d_0} T_{BC4}^{d_0} T_{BC5}^{d_0}}}{(T_{BC1}^{d_0} + T_{BC2}^{d_0} + T_{BC3}^{d_0} + T_{BC4}^{d_0} + T_{BC5}^{d_0})/5} \qquad (6)$$

$S_C(f)$ has been shown to be a useful index for defining usable frequency ranges in signals that contain a broad range of frequencies with signal-to-signal variation and incoherent noise, regardless of the expected operating frequency range of the sensors. The value of $S_C(f)$ may range from 0 (no consistency among signals) to 1 (perfect consistency) at each frequency. Popovics et al.[12] suggested that $S_C(f)$ below 0.99 may contain noise content at a given frequency in wave transmission coefficients. An averaged wave TRF datum for the calculation of the spectral energy is accepted in the frequency range only if $S_C(f)$ is greater than certain specified value (for example, 0.99) at that given frequency. Using this criterion, f_U and f_L can be determined from the $S_C(f)$ curve. Figure 5(a) illustrates the acceptable frequency range in this study. Figure 5(b) gives the averaged wave TRF that was obtained by taking arithmetic average of the five TRF measurements.

It can be inferred from Fig. 5(a) that the criterion value of $S_C(f)$ has a significant effect on the determination of f_U and f_L, and the calculation of energy transmission ratio. A very high (strict) $S_C(f)$ criterion value may lead to a small and unstable integration range. On the other hand, a too low $S_C(f)$ criterion value may cause a very wide frequency range and introduce too much noise in the calculation. Therefore, the effect of $S_C(f)$ on the calculation of the spectral wave-energy transmission ratio was investigated to determine the

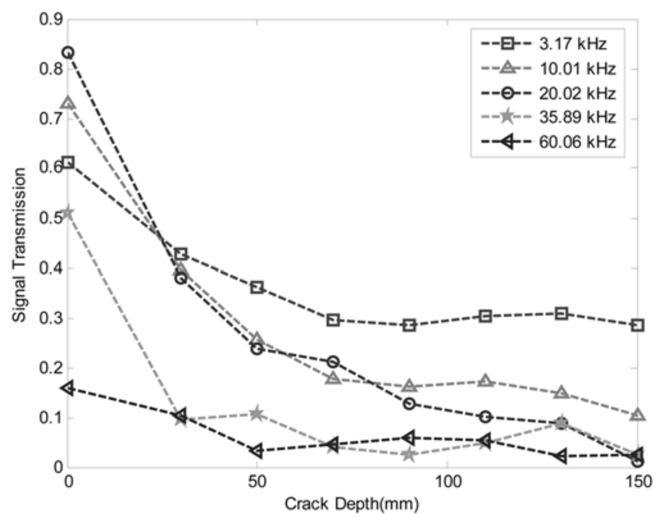

Fig. 3—Signal transmission as function of crack depth at selected frequencies. (Note: 1 in. = 25.4 mm.)

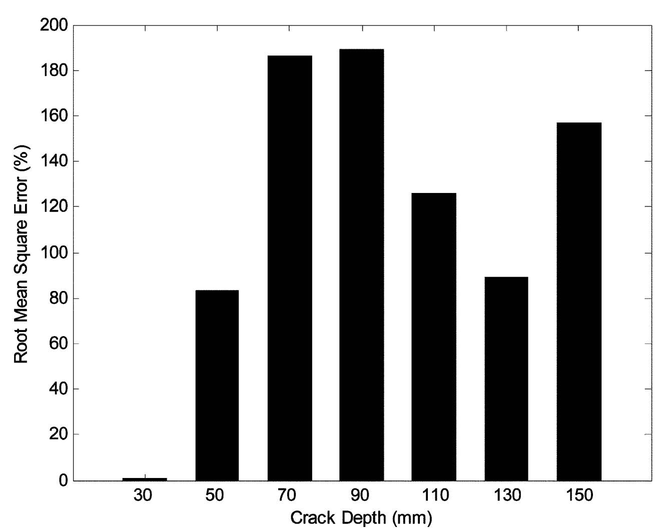

Fig. 4—The errors in estimated crack depth evaluation using conventional cut-off frequency method. (Note: 1 in. = 25.4 mm.)

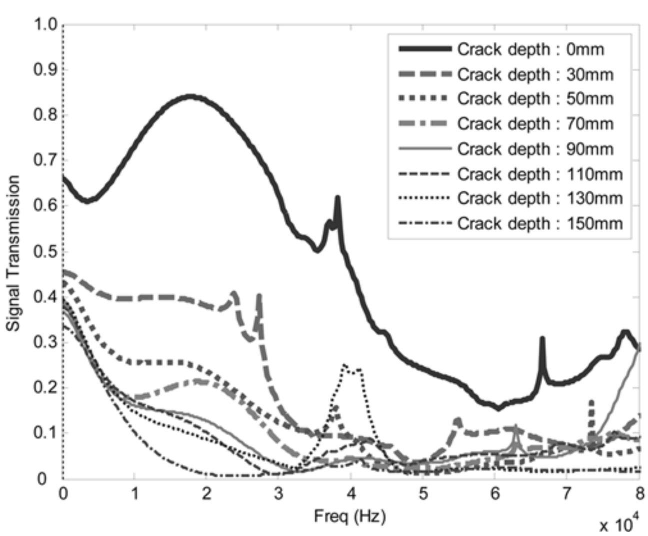

Fig. 2—Measured surface wave transmission functions for various crack depths in slab.

optimum value of f_U and f_L. It is noted that the parameters are determined in the baseline (crack free) TRF for consistency. Once these parameters are determined in crack-free wave path in the concrete structure, they are subsequently used in the calculation of the spectral wave-energy and spectral wave-energy transmission ratio.

Figure 6 shows the variation of spectral energy transmission ratios with corresponding crack depths for $S_C(f)$ criterion values ranging from 0.8 to 0.99. The spectral energy transmission ratio data show a clear trend between the ratio and the crack depth. It is also identified that $S_C(f)$ has little effect on the energy transmission ratio versus crack depth curve when $S_C(f)$ ranges from 0.85 to 0.95, whereas the curve for $S_C(f) = 0.99$ solely shows discrepancy. The transmission ratio decreases dramatically when crack depth is less than 100 mm (4 in.), and then the sensitivity of the ratio decreases as the depth increases. Therefore, it may be concluded that the spectral transmission energy ratio is a sensitive index for crack depth estimation up to 100 mm (4 in.). It is suggested to choose an $S_C(f)$ criterion value between 0.85 to 0.95 to determine f_U and f_L for the calculation of the spectral energy transmission ratio. Moreover, compared with the results in Fig. 3, the proposed spectral energy scheme is easier to apply in the crack depth estimation because the energy ratio method does not depend on frequency and is a function of crack depth only. Therefore, the proposed method will be used in practice more effectively.

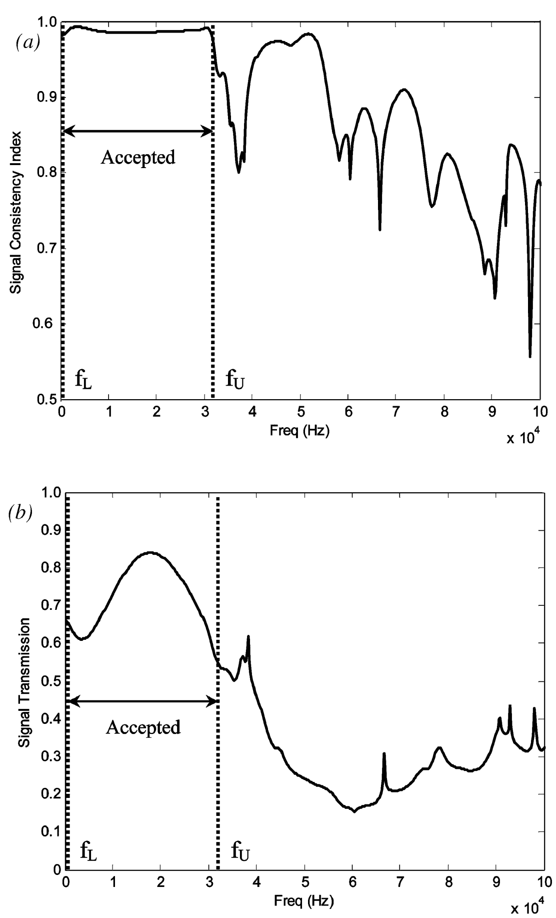

Fig. 5—The determination of frequency range for calculation of spectral energy (for the case of $S_C(f) > 0.95$*): (a) signal consistency index; and (b) averaged signal transmission function. Acceptable frequency bounds are indicated.*

Relationship between spectral energy transmission ratio and crack depth

The observed relation between the spectral energy transmission ratio (R) and crack depth suggests a possible approach for the measurement of in-place crack depth. A calibration curve or formula between R and crack depth d (mm) can be established based on the measured data. For any energy transmission ratio R determined from the self-calibrating measurement, crack depth d can be solved from the preestablished formula. In Fig. 5(a), it was found that the signal consistency above 0.85 was generally acceptable for the frequency range in the calculation of the spectral energy transmission ratio. The data for $S_C(f)$ above 0.95 were chosen for regression analysis, thus the integration parameters were determined to be 0 for f_L and 32.5 kHz for f_U.

A four-parameter power model is used to obtain a unique best-fit curve for R as

$$R(d) = a_1 e^{a_2 d} + a_3 e^{a_4 d} \tag{7}$$

where the constants a_1, a_2, a_3, and a_4 are empirical parameters to be determined by least-squares regression. For the experimental data shown in Fig. 7, the parameters were determined to be 0.7 for a_1, –0.0364 for a_2, 0.3 for a_3, and

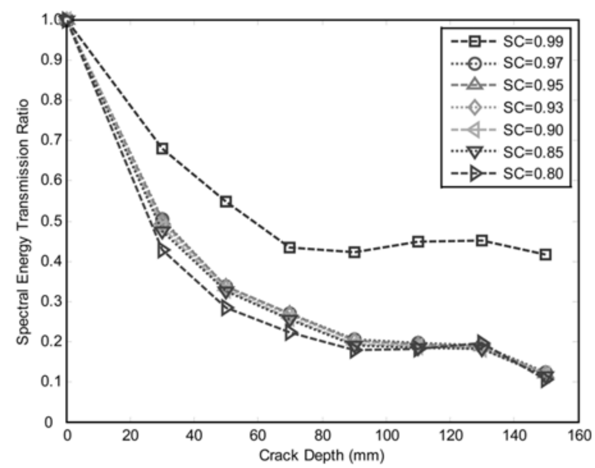

Fig. 6—Calculated spectral energy transmission ratios versus corresponding crack depths.

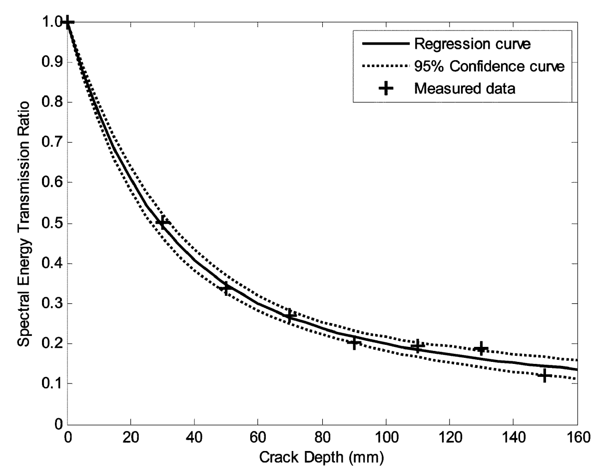

Fig. 7—Proposed relationship between spectral energy transmission ratio and crack depth. (Note: 1 in. = 25.4 mm.)

–0.005 for a_4, giving a fairly high 0.9968 squared correlation coefficient value. As clearly shown in the figure, the experimental data fit very well to the formula. The two dashed lines in Fig. 7 indicate 99% confidence bounds of the formulation.

Comparison with conventional nondestructive testing methods

To compare the results from the proposed method with the conventional methods, an additional experiment was carried out. The data were obtained from different crack depths of the same test slab, which were not used in the regression analysis. The data (wave TRFs) are shown in Fig. 8. Two conventional crack-depth estimation methods were applied to compare the results. Those were the cut-off frequency (CF) method[11] and the time-of-flight of diffracted (TOFD) wave method.[16] To accurately detect the first arrival time of diffracted P-wave, a strong and sharp impact source was used in the TOFD measurement. The results shown in Fig. 9 indicate that the surface wave energy transmission method and TOFD method give close results. However, the estimation errors of the CF method are unacceptably high. Among these methods, the energy transmission ratio method gives most reliable results. It validates the effectiveness of the proposed spectral wave-energy method for crack depth estimation.

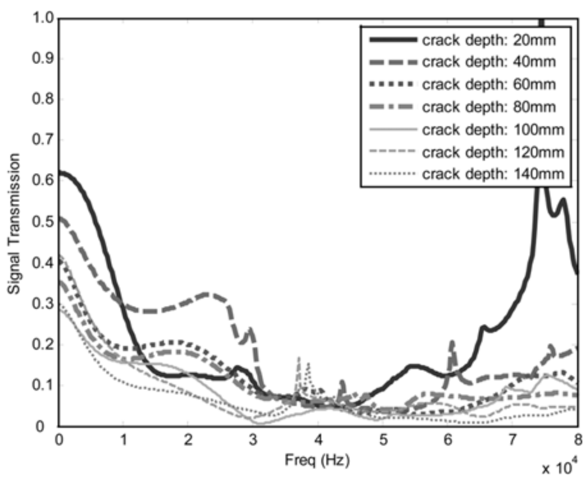

Fig. 8—Measured surface wave transmission functions for various crack depths in slab. (Note: 1 in. = 25.4 mm.)

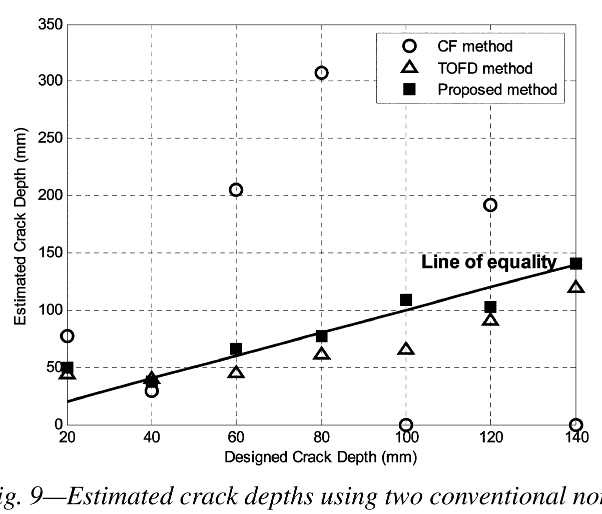

Fig. 9—Estimated crack depths using two conventional nondestructive test methods and proposed relationship. (Note: 1 in. = 25.4 mm.)

CONCLUSIONS

A nondestructive testing method is proposed for crack-depth evaluation in concrete based on self-calibrating surface wave transmission data. A frequency-independent parameter of spectral energy is introduced. The spectral energy transmission ratio is applied for crack-depth estimation. Experiments were performed on a concrete slab that contains a surface-breaking crack with depth linearly varying from 10 to 160 mm (0.4 to 6.3 in.). The obtained results demonstrate that the spectral energy transmission ratio depends only on the depth of the crack and is very sensitive to changes in depth. The spectral energy transmission ratio decreases with an increasing crack depth (d) up to 150 mm (5.9 in.): a sharp decrease is seen for $d \leq 100$ mm (4 in.) and a gradual decrease for 100 mm (4 in.) $\leq d \leq$ 150 mm (4 in. $\leq d \leq$ 5.9 in.). In addition, it is found that the spectral energy transmission ratios calculated from different $S_C(f)$ criterion values (from 0.85 to 0.95) do not vary significantly, and thus any $S_C(f)$ value within this region can be used for consistent depth estimation.

The relationship between the spectral energy transmission ratio and crack depth has been determined using results from the experiment. The spectral wave energy transmission approach compares favorably with two conventional NDT methods and shows excellent potential as a practical and reliable nondestructive method for detection and depth estimation of in-place surface-opening cracks (notches) in concrete structures.

Finally, it is worth noting that the effectiveness of the proposed method is verified using a concrete slab that is large enough in a real extent to prevent wave reflection from the edges of the slab. If the reflection components are included (due to the geometry of the structure) in the measurements, the results may be distorted. This on-going study investigates the effects of various factors including geometry, material composition, and material moisture content on the wave transmission response.

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