

# Evaluation of Distributed Surface-breaking Cracks in Concrete Using Surface Wave Transmission Method

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## Abstract

Previous research has indicated that the surface wave transmission (*SWT*) method can be used to measure the depth of a single surface-breaking crack in concrete. In this paper, the authors extend the *SWT* method to evaluation of distributed cracks in concrete. First, scattering field of surface waves caused by distributed cracks in concrete was investigated using numerical simulation. Second, effects of crack spacing and the number of cracks on transmission coefficient were investigated numerically. These preliminary results provide necessary background for applying the *SWT* method to distributed crack evaluation.

## Résumé

Plusieurs recherches antérieures ont indiqué que la méthode de transmission d'ondes superficielles (*SWT*) peut être utilisée pour mesurer la profondeur d'une fissure unique qui débouche en surface. Les auteurs étendent la méthode *SWT* à l'évaluation de fissures distribuées dans le béton. En premier lieu, le domaine d'éparpillement des ondes créées par les fissures distribuées a été investigué à l'aide de simulations numériques. En second lieu, les effets de l'espacement des fissures et le nombre de fissures, sur le coefficient de transmission ont été investigués numériquement. Ces résultats préliminaires fournissent la base pour l'application de la méthode *SWT* dans le contexte de fissures distribuées.

## Keywords

Distributed surface-breaking cracks, *NDT*, surface waves, transmission.

## 1 Introduction

Distributed surface-breaking cracks are common damage patterns in reinforced concrete structures. The cracks not only affect concrete durability and appearance, but also reduce the strength, stiffness, impermeability of concrete, and finally lead to premature failure of concrete structures. From the sustainability viewpoint of civil infrastructures, reliable evaluation of distributed surface-breaking cracks in concrete structures is necessary for practices associated with repair and rehabilitation.

Using non-destructive testing (*NDT*) methods to estimate the depth of a surface-breaking crack has been extensively investigated in recent decades. Previous studies showed that the surface wave transmission coefficient  $Tr$  across a surface-breaking crack can be used to estimate the crack depth. Using ultrasonic transducers, Viktorov<sup>[1]</sup> experimentally developed the relationship between the surface (Rayleigh) wave transmission coefficient and the normalized crack depth  $h/\lambda$ , i.e., the ratio of crack depth to the wavelength, for a surface-breaking crack in a solid. Achenbach and his colleagues<sup>[2-3]</sup> analytically derived the  $Tr$  and  $h/\lambda$  relation based on diffraction and scattering of harmonic incident Rayleigh waves by a surface-breaking crack. Masserey and Mazza<sup>[4]</sup> extended the analytical solutions by prior researchers<sup>[2]</sup> to an arbitrary transient excitation function using the finite difference method, and verified that the established  $Tr$  and  $h/\lambda$  relation is also valid for transient incident waves. For concrete, a heterogeneous but globally isotropic material, the Surface Wave Transmission

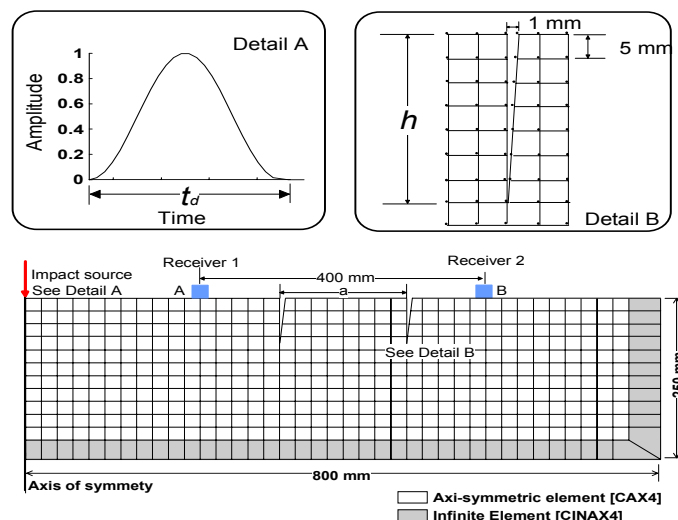
(*SWT*) method has been proved sensitive to depth variation of surface-breaking cracks, even for tightly closed and ill-defined cracks [5-7]. Hevin *et al.* [5] obtained the transmission ratio of a surface wave in the frequency domain using boundary element analysis, and proposed the cut-off frequency ( $h/\lambda = 0.3$ ) method to estimate a crack depth. Popovics *et al.* [6] and Song *et al.* [7] obtained the  $Tr$  and  $h/\lambda$  relation using experimental test data in laboratory. They found that the relationship was not affected by the width of the crack opening and the shape of crack tips. In addition, Jian *et al.* [8] investigated near-scattering of surface wave by a surface breaking crack using finite element model, where depth of crack is very large compared with the wavelength of incident surface wave. More recently, Kee and Zhu [9] further investigated near field effects caused by crack tip scattering through the wide range of  $h/\lambda$ , and improved the accuracy of surface wave transmission calculations using finite element model.

Deterioration mechanisms for concrete, such as alkali-silica reaction, freeze-thaw *et al.*, typically cause distributed cracks instead of a single surface crack. However, the scattering of surface waves caused by distributed surface-breaking cracks has not been systematically investigated. The objective of this paper is to extend the *SWT* method to assessment of distributed cracks in concrete. In this study, we used numerical simulations to investigate the effects of crack spacing and crack number on surface wave transmission measurement.

## 2 Model description

Finite element method (FEM) was used to investigate surface wave transmission across a surface-breaking crack in a solid. The solid was modeled by 4-node axi-symmetry elements (CAX4) in the commercial program ABAQUS 6.7-1, with mesh size of 5 mm. The finite element model is shown in figure 1. To reduce wave reflections from boundaries, absorption boundary (CINAX4) elements were applied.

For the investigated wavelength ( $>40$  mm) in this study, concrete can be regarded as a homogeneous material. The material properties are: Young's modulus of 33630 MPa, Poisson's ratio of 0.222, and mass density of 2400 kg/m<sup>3</sup>. The corresponding velocities of P-, S-, and surface waves are 4050, 2420, and 2215 m/s, respectively. The force function of the transient impact point source is  $f(t) = \sin^2(\pi/T)$ , where  $T$  is the duration time 60  $\mu$ s. The location of impact source is illustrated in figure 1. Responses from two receiver locations are used to calculate surface wave transmission ratios.



**Figure 1.** A finite element model containing two surface breaking cracks. The receiver spacing is 400 mm, and the receivers are symmetric about the center line of cracks.

### 3 Scattering field caused by two cracks

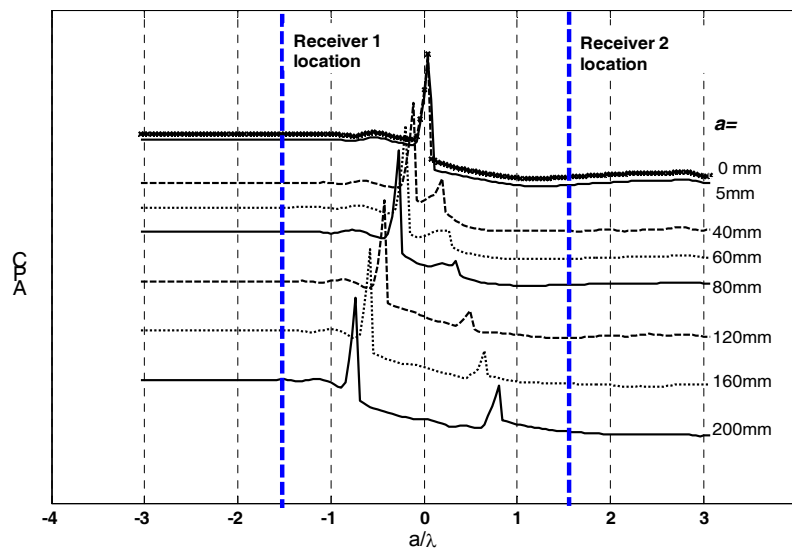
To study the near field effect caused by the crack tip scattering, particle velocity responses at all surface nodes between A and B were obtained from various finite element models. All models contain two cracks of 50 mm deep, and the crack spacing varies from 0 mm (single crack) to 200 mm. The duration time of impact point source was  $T=60 \mu\text{s}$ . To eliminate geometric attenuation effect, the vertical component of velocities obtained on the cracked model ( $V_{zi}$ ) is normalized by that obtained from the crack free model ( $V_{z0}$ ). Amplification coefficient (APC) is defined as the peak amplitude ratio between  $V_{zi}$  and  $V_{z0}$  at corresponding locations, as shown below

$$APC(x/\lambda) = \frac{V_{zi}(x/\lambda)}{V_{z0}(x/\lambda)}, \quad (1)$$

where  $x$  is the distance from center line of the two cracks, and  $\lambda$  is the center frequency wavelength of incident surface waves. For  $T=60 \mu\text{s}$ ,  $\lambda$  is about 131 mm. The near field size  $a_n$  suggested by Kee and Zhu<sup>[9]</sup> is about 90 mm.

Figure 2 shows the amplification coefficient curves versus the normalized distance  $x/\lambda$ . Analysis shows that the APC curve is strongly affected by the cracking spacing  $a$ , even if the crack depths are the same. When  $a=5$  mm, which is much smaller than the near field size  $a_n$ , the APC curve is similar to that on a single crack model ( $a=0$  mm). APC oscillates in the near crack region (near field), and then converges to a constant value in the far field for large  $x/\lambda$ . When the cracking spacing  $a$  increases but less than  $2a_n$ , the forward scattering field from the first crack tip interferes with the backward scattering field from the second crack tip. Consequently, complex near scattering field forms in the region between the cracks, as shown in figure 2 for  $a = 40 \sim 160$  mm. When  $a$  is greater than  $2a_n$ , the two cracks are far separated. Previous researchers suggested that near-field size,  $a_n$ , is dependant on crack depth  $h$ , and wavelength of incident wave  $\lambda$  (or duration of impact  $T$ ). Therefore, the condition that cracks can be individually considered is also dependant on  $h$ , and  $\lambda$ . In this case, the previous surface wave transmission theories and methods<sup>[2,3,9]</sup> are still valid for each single crack.

If the surface wave transmission ratio after the first crack is  $Tr$ , then the transmission after the second crack will be  $Tr^2$ .



**Figure 2.** APC curves vary with the distance from the crack center  $x/\lambda$ , for different crack spacing ( $a=5\text{mm}\sim 200\text{mm}$ ). The crack depth is 50 mm.

## 4 Surface Wave transmission coefficient

### 4.1 Effect of crack spacing

To investigate the effects of crack spacing on surface wave transmission coefficients, various finite element models were built and analyzed. The models contain two cracks with five different crack depths (10 ~ 50mm in intervals of 10mm), and the crack spacing ranges from 0 to 200 mm in step of 20 mm. In this study, the surface wave transmission coefficient  $Tr$  is defined as the frequency response ratio between the cracked model and the crack free model, as follows

$$Tr(f, h, a, N) = \frac{V_b(f, h, a, N)}{V_b(f, 0, a, N)}, \quad (2)$$

where  $Tr$  is the surface wave transmission coefficient in function of frequency  $f$ , crack depth  $h$ , crack spacing  $a$ , and the number of cracks  $N$ .  $V_b$  is Fourier transforms of the time domain signals measured at location B in figure 1. The receiver at B is located 200 mm from the centerline of the cracks. From figure 2, it can be seen that the APC curves reach constant values at the receiver location for all models except for  $a = 200$ mm. That means the receiver is located in the far scattering field.

Among the parameters that affect surface wave transmission, analysis indicates that the normalized crack spacing  $a/h$  has the largest influence. Figure 3 shows the relationship between  $Tr(f_c)$  and  $a/h$  for different crack depths, where  $Tr(f_c)$  is calculated at the center frequency  $f_c$  of the incident surface waves. For all crack depths concerned in this study,  $Tr$  first decreases with increasing  $a/h$ , and reaches a minimum value when  $a/h$  is between 2 and 3. Then  $Tr$  increases and converges to a constant value for large  $a/h$ . As mentioned before, the transmission coefficient converged to  $Tr^2$  for very large crack spacing.

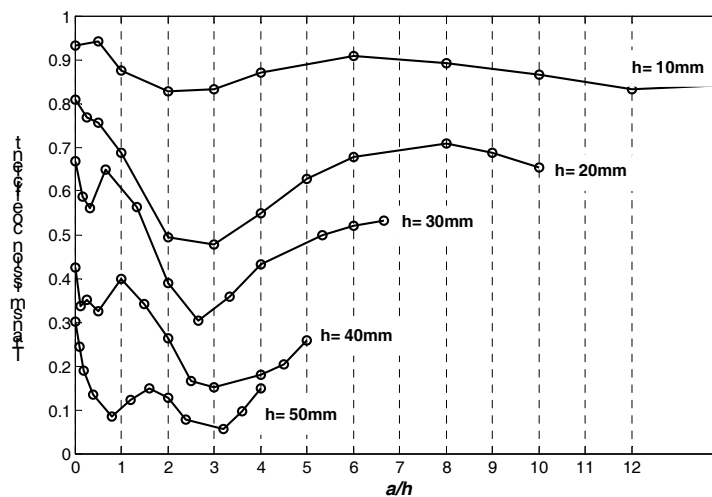


Figure 3. Effects of crack spacing  $a/h$  on surface wave transmission coefficient.

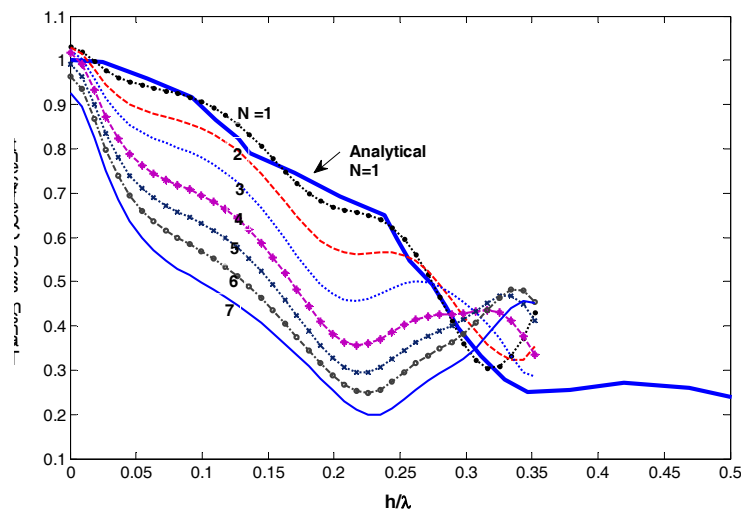
### 4.2 Effect of the number of cracks

To investigate how the number of cracks affect surface wave transmission, seven finite element models with crack number  $N=1$  to 7 were analyzed. The crack depth was fixed to

$h=10$  mm, and the crack spacing  $a/h=1$ . For an impact force duration  $T=60$   $\mu$ s,  $\lambda = 131$  mm, so we have  $h/\lambda = 0.076$ .

Figure 4 shows the transmission coefficients  $Tr$  versus normalized crack depth  $h/\lambda$  for seven crack models. For comparison purposes, the analytic solution given by Angel and Achenbach<sup>[3]</sup> for a single crack is also shown. For crack depth estimation, the usable frequency range is the range of  $h/\lambda$  in which  $Tr$  monotonically decreases. In figure 4, the usable range for multiple cracks is about  $h/\lambda < 0.22$ . Within this range, the transmission coefficient  $Tr$  decreases with the increasing number of cracks  $N$ .

To further investigate the effects of crack spacing  $a$  and the number of cracks on surface wave transmission, a normalized transmission  $Tr_n$  is defined as the ratio between  $Tr(f_c, h, a, N)$  and  $Tr(f_c, h, a, 1)$ , measured at the center frequency  $f_c$ . Figure 5 shows  $Tr_n$  vs.  $N$  curves for five crack spacing  $a/h=1, 2, 3, 4$  and  $8$ . The  $a/h=3$  curve shows the lowest transmission, which agrees with the conclusion in section 4.1.  $Tr_n$  increases for  $a/h=4$  and  $8$ . For large crack spacing such as  $a/h=8$  in the figure 5, the  $Tr_n$ - $N$  curve converges to the dash line  $Tr^N$ , which is defined as  $Tr(f, h, a, 1)^N / Tr(f, h, a, 1)$ .



**Figure 4.** Transmission coefficient versus normalized crack depth relationship for different number of cracks. The crack spacing is  $a/h=1$ .

## 5 Conclusions

This research is the first attempt to apply the surface wave transmission method to evaluate distributed surface breaking cracks in solid. The findings from this study are summarized as follows:

- (1) Amplification coefficient oscillates in the near crack region (near field), while it converges to a constant value in far field for large  $x/\lambda$ . When the crack spacing is less than two times of the near field size, the forward scattering field caused by the first crack interferes with the backward scattering field caused by the second crack, which causes very complex scattering field between the cracks.
- (2) Crack spacing affects the surface wave transmission measurement.  $Tr$  shows the lowest value when  $a/h$  is between 2 and 3. For large crack spacing, each crack can be treated as a single surface breaking crack, and previous surface wave transmission theories apply.
- (3) The surface wave transmission decreases with increasing crack number  $N$ . For large crack spacing  $a$ , the surface wave transmission ratio over  $N$  cracks will be  $(Tr_1)^N$ , where  $Tr_1$  is the transmission over a single crack.
- (4) The numerical simulation results provide a guideline for evaluating concrete structures with distributed surface-breaking cracks using the surface transmission method.

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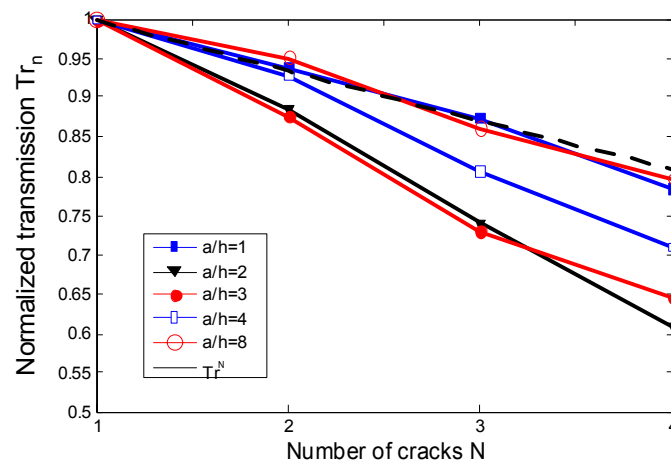


Figure 5. Effect of crack number  $N$  on the normalized transmission coefficient

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