The influence of surface opening cracks on the ultrasonic waves near the surface in concrete members

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Abstract. Based on the velocities of waves near the surface in concrete, the propagation path and travel time of different waves were calculated, and the influence of crack on these waves was analyzed. Some theoretical conclusions were verified by FEM. The ultrasonic waves were received by array transducers and the velocities of different waves were calculated and distinguished according to wave velocity in the simulation. Simulation results show that when sound wave propagates through the crack, longitudinal waves will arrive at the receiving arrays, and the crack will diffract transverse wave to generate new longitudinal wave and transverse wave by mode conversion, and Rayleigh wave will propagate along the surface (including the crack side wall). Finally, it is found that the relationship between crack depth and amplitude and energy is approximately linearly monotone decreasing by studying the waves near surface with different crack depths.

1 Introduction

With the development of modern society, many engineering like motorway, bridges and dams demand lots of concrete whose bulk is huge. Affected by the leap of temperature, evaporation of water, undesirable construction method, however, it's easy to form surface opening cracks on the surface of concrete, which damage structure. Therefore it's necessary to detect these cracks, and get hold of its depth and width to estimate the damage to the structure and the life of structure. There are many methods used in detecting surface opening cracks in concrete, such as: (1) single ultrasonic flat-measured method; (2) perforating method; (3) Rayleigh wave methods. The perforating method breaks workpiece, and much costs ; the single ultrasonic flat-measured method detect cracks less than 500mm; however, the Rayleigh wave method has these advantages: (1) large energy; (2) not affected by fluid; (3) flexible detection for its propagation character.

Large numbers of researchers all around the world have done research on the detection of surface cracks of concrete. Based on the MFCE(Matched Filtering of Center of Energy), Foo Wei Lee, Kok Sing Lim[1] determine the arriving time of Rayleigh wave. G Hevin[2] have found that the variation of spectral ratios between the transmitted and incident wave were studied as a function of the crack depth. Yangyang[3] has combine time reserval and the Rayleigh wave method, and found that enlarging the cracks depth resulted in an increase in the level of distortion in the reconstructed wave signals, and a higher damage index was obtained. Zhang Zaidong[4]

obtained the relationship between slot depth and the absorption frequency on the basis of spectral analysis.

Ultrasonic method has its advantages in detecting surface opening cracks, it's necessary to analyze the influence of the surface opening cracks on the waves near surface including Rayleigh wave. Based on the sound velocity of different wave modes near the concrete surface, this paper will analyz the influence of cracks on the waves near surface, and distinguishes the waves near surface by utilizing receiving array . Simulation results show that longitudinal waves arrived at the receiving array at twice, and the crack diffracted transverse wave to generate new longitudinal wave and transverse wave by mode conversion, and Rayleigh wave propagated along the surface (including the crack side wall), when sound waves near the surface propagated through the crack.

2 Influence on the waves near surface

The waves propagate along the surface are: longitudinal wave, transverse wave and Rayleigh wave. The velocity of longitudinal c_P is fastest , and the velocity of transverse c_R and Rayleigh wave c_S is almost half of that of longitudinal wave. The ratio between c_R and c_S is dependent on the Poisson ratio. Here, the Poisson ratio of concrete is 0.33, and the ratio of concrete is 0.93.

Fig. 1 model geometric structure

On the basis of Fermat theorem, the Snell law near the crack walls and the Huyghens principle near the crack tips, this section analyzes the reflection and diffraction of waves caused by opening cracks, and computes the propagation path and time, and distinguishes the waves finally by velocity. Fig. 1 shows the geometry of the structure, E is excitation source; R is receiving array; A, B are the right and left tips of cracks respectively; C, D are two edges of cracks respectively; N, M is the mode conversion point. According theories and geometry, we can obtain:

(1) The longitudinal wave propagated fastest, and the original longitudinal was diffracted near the crack tips, then the diffracted wave propagated to the receiving array at the velocity of longitudinal wave. This phenomenon is used in single ultrasonic flat-measured method[6]. This wave is denoted by 1 longitudinal wave.

(2) According to (1), the original longitudinal was diffracted by crack tips; the velocity of transverse caused by diffraction is slower, so the transverse wave will converse into longitudinal wave by mode conversion when the wave propagated near the surface. This longitudinal wave is denoted by 2 longitudinal wave.

Table. 1 The traveling time and propagation path of different waves.

Wave mode	Propagation time	Propagation path
1 P-wave	$\frac{EA+AB+BR}{c_p}$	
2 P-wave	$\frac{EA}{c_p} + \frac{AB}{c_r} + \frac{BM}{c_s} + \frac{MR}{c_p}$	
3 P-wave	$\frac{EA}{c_s} + \frac{AB}{c_r} + \frac{BN}{c_s} + \frac{NR}{c_p}$	
1 S-wave	$\frac{EA}{c_s} + \frac{AB}{c_r} + \frac{BN}{c_s} + \frac{NR}{c_s}$	
R-wave	$\frac{EC+CA+CB+BD+DR}{c_r}$	

(3) The original transverse wave was diffracted near the crack tips. The transverse wave caused by diffraction propagates into surface, and mode conversion occurs at N point with the introduction of longitudinal wave and transverse wave. Among them, the longitudinal wave propagates at the soonest and is received by receiving array. The corresponding longitudinal is denoted by 3 longitudinal wave.

(4) On the basis of (3), mode conversion at N point introduced transverse wave and Rayleigh wave. Their velocity difference is small for the short propagation path, and received by receiving array. This transverse

wave is denoted by 1 longitudinal wave.

(5) As we know, Rayleigh wave propagate along the solid surface., the propagation path of Rayleigh wave was from exciting source to the receiving array including crack walls.

The propagation time and propagation path of different waves mentioned above are presented in Fig1.

3 Numerical model and results

3.1 Numerical model

FEM method was introduced to simulate wave propagation near surface of two-dimension concrete, which is isotropous. Fig.2 shows simulation geometry.

Fig.2 model geometric

The geometry size is 600mm×200mm; filled with concrete; the parameters of material are listed in table 2. Correspondingly, $c_p=4013\text{m/s}$, $c_s=2021\text{m/s}$, $c_r=1886\text{m/s}$.

Table. 2 Medium parameter in the simulation.

Solid acoustic constant	Young modulus	Poisson ratio	Density
value	$2.5 \times 10^9 [\text{Pa}]$	0.33	$2300 [\text{kg/m}^3]$

In the simulation, biggest size of mesh is 1.67mm; time step is $4.16 \times 10^{-8}\text{s}$; sampling frequency is 50MHz. Receiving array is adopted in the simulation which are at 400, 420, 440, 460, 480, 500mm denoted as R₁, R₂, R₃, R₄, R₅, R₆ respectively. Contacting surface between concrete and air is almost free boundary, and in order to avoid the disturbance of waves reflected by boundaries, absorbing boundary is adopted. For the sake of near field effect, Rayleigh wave and transverse

wave are mixed, thus the distance between transmit-receive probes couldn't be less than 150mm according to document [5]. The distance selected in this paper is 200mm.

There are two simulation models for two simulation purposes, one of which is to study the influence of crack on the waves, and the other is to study the relationship between crack depth and waves near surface, 20, 30, 40, 50, 60, 70, 80mm respectively.

3.2 The influence of crack on the near surface wave

Based on the parameters listed in table1, sound fields simulated by FEM are seen in figure 3 and 4. By means of observing wave propagation and mode conversion in the sound field, the waves are distinguished received by R1. Figure 5 shows the waves received by R1, and we can find the preceding three waves are longitudinal wave, and the next is slower transverse wave, and the final is Rayleigh wave.

Fig.3 Sound field in 50μs

Fig.4 Sound field in 80μs

To distinguish the received wave modes, the method of one transmitting and multi-receiving mode was adopted in the simulation. Figure 6 shows the wave signals received by R₁ to R₆.

In Fig. 6, line segments were adopted to link the arriving time of different waves for different receivers., the the first three line segments indicate the velocities of longitudinal wave; the last two show transverse wave and Rayleigh wave respectively. Furthermore the relationship between the distance of between receivers and the arriving peak time of different waves was drawn in Fig. 7.

From Figure 7, the velocities of every wave were simulated that are: $c_P=4013\text{m/s}$, $c_S=2061\text{m/s}$, $c_R=1886\text{m/s}$. the velocity of transverse wave is bit faster than the Rayleigh wave. In the sound field, the propagation times of different wave mode were simulated based on the propagation paths and velocities of different wave mode.

Obtained from Figs 8 and 9, the original longitudinal wave was diffracted to introduce the new longitudinal wave and the new transverse wave. According to the Fermat theorem, the traveling time of the new longitudinal wave received by R₁ is:

$$t_{p1} = \frac{(EA + AB + BR)}{c_P} = 52.3\mu\text{s} \quad (1)$$

Fig.5 Waves near the surface received by R1 at 400mm

Fig.6 Waves near the surface received by R1, R2, R3, R4, R5, R6

Fig.7 sound velocity of different wave modes in the wave near surface

Fig.8 model geometric

Fig.9 model geometric

The subscript p is on behalf of the longitudinal wave. Obtained from figure 9, the new transverse wave introduced by the original longitudinal wave propagated to the concrete surface at a certain angle, and the mode conversion was introduced. The point of mode conversion is approximately at M (375mm, 200mm) referred to the sound field. Therefore the traveling time of the second longitudinal wave (2 L-wave) received by R_1 is:

$$t_{p2} = \frac{EA}{c_p} + \frac{AB}{c_R} + \frac{BM}{c_s} + \frac{MR}{c_p} = 76\mu s \quad (2)$$

Fig.10 Sound field in 90μs

Fig.11 Sound field in 97μs

Obtained from figure 10 and 11, the original transverse wave was diffracted near the cracks tips, and the diffracted transverse wave which is dominating in the waves introduced by diffraction propagated to the concrete surface, with mode conversion similarly. The point of mode conversion is approximately at N (356mm, 200mm) refer to the sound field. Therefore the traveling time of the third longitudinal wave (3 L-wave) and the transverse wave received by R_1 is:

$$t_{p3} = \frac{EA}{c_s} + \frac{AB}{c_R} + \frac{BN}{c_s} + \frac{NR}{c_p} = 96\mu s \quad (3)$$

$$t_{s1} = \frac{EA}{c_s} + \frac{AB}{c_R} + \frac{BN}{c_s} + \frac{NR}{c_s} = 106\mu s \quad (4)$$

Finally the slowest Rayleigh wave propagates along the surface including that of cracks only, therefore the traveling time of Rayleigh wave received by R_1 is:

$$t_r = \frac{EC + CA + CB + BD + DR}{c_R} = 137.9\mu s \quad (5)$$

The subscript s indicate the transverse wave and the subscript r implies the Rayleigh wave.

The simulation results show that longitudinal waves will arrive at the receiving array at twice, and the crack will diffract transverse wave to generate new longitudinal wave and new transverse wave by mode conversion, and Rayleigh wave will propagate along

the surface (including the crack side wall), when sound waves near the surface propagate through the crack.

4 Conclusion

Based on the velocity of waves near surface, Fermat theorem, Snell law near the crack side wall; Huygens principle near the crack tips, ray-tracing algorithm was adopted to analyze the influence of opening cracks in concrete on the waves near surface using finite element simulation. Simulation results show that longitudinal waves will arrive at the receiving array at twice, and the crack will diffract transverse wave to generate new longitudinal wave and new transverse wave by mode conversion, and Rayleigh wave will propagate along the surface (including the crack side wall), when sound waves near the surface propagate through the crack. Simulation results show that with the increase of crack depth, the amplitude of 1 L-wave and the energy of the 1 L-wave and the 2 L-wave decrease approximately monotonously.

References

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