Structural Integrity Assessment of Concrete Using a New Nondestructive Method

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ABSTRACT*: A nondestructive testing (NDT) method to detect internal cracks in concrete structures is presented. The method is based on the dynamic response of flawed concrete structures subjected to impact loading. The present method uses non-contacting devices for both impact generation (a shock tube producing shock waves) and response monitoring (laser vibrometers measuring concrete surface velocity). Experimental and numerical (finite element) studies are carried out for concrete specimens containing artificial defects (penny-shaped cracks parallel to the free surface) with varying length and depth. It is seen that the present method enables an effective detection of defects, particularly in the range of shallow defects.*

INTRODUCTION

Numerous concrete structures such as bridge decks, slabs, tunnels, etc., require periodic inspections through nondestructive testing (NDT) methods to assess their structural integrity, that is, to detect the presence of defects such as: internal cracks, voids, shallow delamination, honeycombing, surface-opening cracks. There is a large number of well known NDT methods for concrete structures including: infrared thermography, ground-penetrating radar, acoustic impact method (sounding), ultrasonic pulse-velocity method, ultrasonic pulse-echo method, impact-echo method (e.g. see Ref. 1). Except for the first two methods, the other methods are based on the mechanical principle of stress wave propagation.

Stress wave propagation-based NDT methods require contacting devices for both mechanical impact and response measurement. In this paper, a new non-contacting NDT method using shock waves and laser vibrometers is presented [2,3]. The principle of the method is briefly explained and the adopted instrumentation (testing technique) is described. Then, some results of an experimental campaign along with a numerical simulation are presented and discussed.

THEORETICAL BACKGROUND

The proposed method is based on the dynamic response of flawed concrete structures subjected to impact loading. The impact loading is applied on the free surface, and normal-to-surface velocity against time is monitored by transducers located on the free surface itself at different locations. Typically, a single transducer is positioned near the central point of impact loading, but also configurations with multiple output reading points can be considered. The dynamic response of flawed concrete structures subjected to impact loading is governed by stress wave propagation. Two kinds of vibrations can be distincted: thickness vibration and, in the presence of shallow defects, plate-like flexural vibration. Both these vibrations determine characteristic velocity time histories on the free surface, which permit the detection of defects.

Let us consider an infinite plate subjected to a point impact (Fig. 1). The pulse travels along spherical wavefronts through concrete as P (dilatation or normal) and S (distortion or shear) body waves and R (Rayleigh) surface wave (e.g. see Refs 4,5). The dynamic problem is governed by the Theory of Elasticity, since, for the applied stress levels, concrete can be treated as a linear-elastic, isotropic and homogeneous medium. The velocity of P-waves is given by:

$$C_P = \sqrt{\frac{(1-n)E}{(1+n)(1-2n)r}} \tag{1}$$

where E = Young's modulus; n = Poisson raio; r = density. S-waves and R-waves have lower velocities, equal to about 0.61 C_p and $0.56C_p$, respectively, for n = 0.20. When body stress waves reach back-wall surface, reflection and mode conversion occur. 2P-wave is the reflected P-wave and PS-wave is the S-wave produced by P-wave (mode conversion). A thickness vibration due to a stress P-wave resonance, and characterised by a transient period (round-trip travel period of P-wave from point C to A, and backwards), occurs. Such a vibration is characterised by the following period T_d (and frequency f_d):

$$T_d = \frac{1}{f_d} = \frac{2d}{C_P} \tag{2}$$

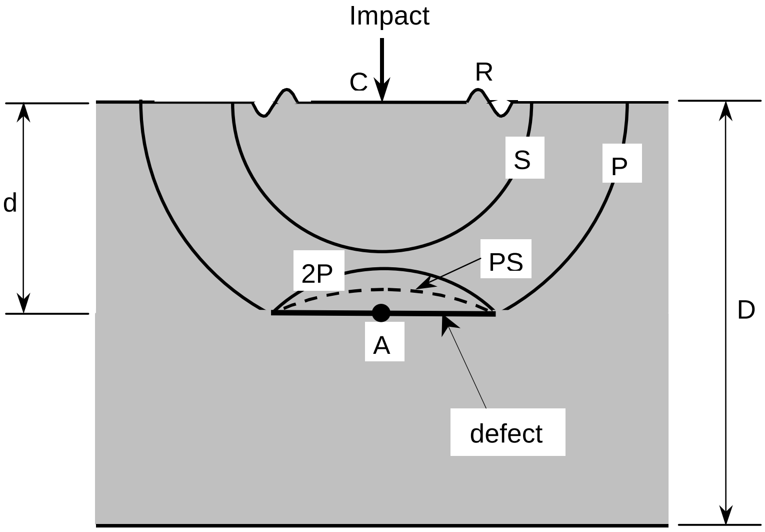


Figure 1: Wavefronts produced by point impact on an infinite plate containing a defect parallel to surfaces (schematic)

Obviously, Eq. (2) is valid only if the acoustic impedance $r \times C_p$ of the defect is smaller than that of the solid, such as in the case of a traction-free surface of a crack-like defect. Note that a thickness vibration with period $T_D = 2D/C_p$ due to back-wall reflection might also occur.

Let us consider a penny-shaped crack parallel to the free surface in an infinite plate. In the case of a shallow defect (low values of the depth *d*), the solid portion above the crack might act as a plate-like structure undergoing flexural vibrations. In the specific case under consideration, such a portion can be treated as a circular plate having diameter 2*a* and thickness *d*. The analytical expression for the first natural period T_{fx} (and frequency f_{fx}) of flexural vibration of a simply supported circular plate is as follows [6]:

$$T_{fx} = \frac{1}{f_{fx}} = 1.259\sqrt{\frac{12\left(1-n^2\right)r\,a^4}{Ed^2}} \qquad (3)$$

Typically, the velocity C_p in concrete ranges from 3000 m/s to 4000 m/s. For instance, assuming *d* = 50 mm to 100 mm, the frequency f_d of thickness vibration varies from 15 kHz to 40 kHz. On the other hand, the value of the frequency f_{fx} for a defect of 200 mm in diameter and 50 mm to 100 mm in depth ranges from 3.4 kHz to 9.2 kHz. Generally speaking, the value of the frequency f_{fx} is lower than that of the frequency f_d, and the amplitude of surface velocity due to flexural vibration is higher than that due to thickness vibration.

INSTRUMENTATION

A schematic view of the proposed non-contacting NDT method for concrete is shown in Fig. 2. Impact on the free concrete surface, inducing thickess vibration and/or flexural vibration, is produced by shock waves whose impact duration is longer than about 10 ms. Such waves are generated by a shock tube containing high-pressure air [2]. In addition, so-called expansion waves are generated by the expanding compressed air in the shock tube. Thickness and flexural vibrations are detected by laser Doppler vibrometers, measuring time history of surface velocity components. It should be noted that both devices for generating impact and measuring vibrations are non-contacting ones. Length and location of defects can be detected by analysing output velocity data. Measured time histories of velocity are transformed to frequency domain via Fast Fourier Transform (FFT) to indentify periodic phenomena [7].

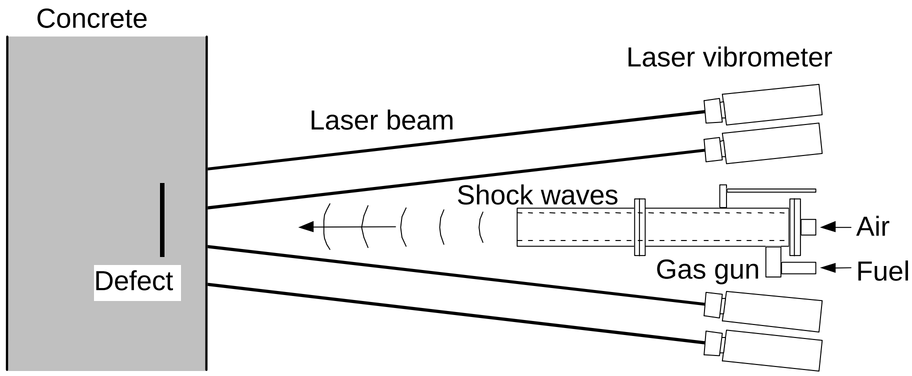


Figure 2: Schematic view of the proposed NDT method

The depth of the defect can be obtained from Eq. (2), in which the measured peak frequency of thickness vibration is introduced and an estimated (from the Young's modulus E and the density r) or measured value of the velocity C_p is known. Once the depth d has been determined, the length $2a$ of the defect can be calculated using Eq. (3) from the value of flexural vibration frequency. Length of defects can also be estimated when a grid of measuring points of surface velocity is considered. As a matter of fact, peak frequencies related to thickness vibration or flexural vibration can be detected only when the measuring surface point is located above the inside of the defect.

EXPERIMENTAL INVESTIGATION

Experimental tests on cubic concrete specimens, with side D of 430 mm, containing artificial defects were carried out. Three laser Doppler vibrometers were placed to measure velocity components at three points on the specimen surface, i.e., specimen centre and at a distance from the centre of 50 and 100 mm, respectively. A sampling frequency of 500 kHz and a sample number of 50,000 (the total sampling time is equal to 100 ms) was adopted for velocity measurement.

As a reference a solid concrete specimen was tested, along with 4 specimens containing a central penny-shaped crack parallel to the free surface (with finite width equal to 10 mm), having the following geometric parameters: d = 25 mm and 2a = 100 and 200 mm (shallow defects), d = 50 mm and 2a = 200 mm, d = 100 mm and 2a = 200 mm (deep defect). The value of P-wave velocity C_p in the concrete mix under study was determined from the measured P-wave travel time through the thickness D in the solid specimen. Note that an alternative measurement method of P-wave velocity can be performed by measuring R-wave velocity [8], as for instance, when the back-wall surface of the actual concrete structure is not accessible. A value of C_p equal to 3770 m/s was measured for the present concrete mix. From the measured value of the concrete density (r = 2380 kg/m^3), an estimated value of the Young's modulus E is calculated to be equal to about 33800 MPa ($E \approx C_p^2 \cdot r$).

Conversely to conventional contacting NDT methods (e.g. impact-echo method [2]), characterised by a point impact, the proposed impact method using shock tube produces a pressure loading acting over a certain portion of the concrete surface. Moreover, the time history of the induced surface pressure is very different from, for instance, a simple half sinusoidal wave characterising the time history of the impact of a steel ball [3]. In order to strengthen the results obtained with the present impact method, a point impact produced by a hammer was also used to determine flexural vibration frequencies in the flawed specimens.

NUMERICAL SIMULATION

Three-dimensional finite element (FE) analyses were performed to simulate the experimental tests. The commercial package ANSYS 56 was used [9]. A transient dynamic analysis, based on the explicit central difference method, was carried out. Eight-node isoparametric linear solid elements were employed. Concrete was treated as a linear-elastic, isotropic and homogeneous material. Young's modulus was assumed to be equal to 33800, while a typical value of Poisson ratio for concrete (*n* = 0.15) and the measured value of density (*r* = 2380 kg/m3) were input in FE models. A uniform pressure, with a time history corresponding to a triangular pulse of 35-kPa peak and 28-μs duration, was applied to an entire face of the model. This is a strong simplification of the actual pressure time history generated by shock waves [3], but it is deemed not to affect significantly the following comparison between experimental and FE results in terms of dominant frequencies.

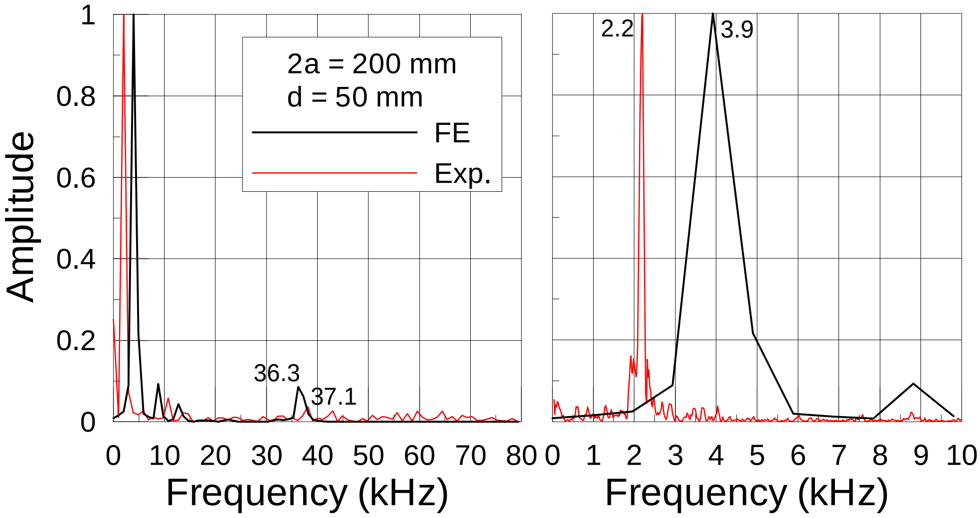
Results from experimental and numerical studies were analysed mainly in terms of normalised spectrum of normal-to-surface velocity at the central surface point C of the specimens (see Tab. 1 where detected peak frequencies of thickness and flexural vibrations obtained from experimental and FE models as well as from the theoretical formulae of Eqs (2) and (3) are reported). As an illustrative example, the spectrum related to the model with 2*a* = 200 mm and *d* = 50 mm is plotted in Fig. 3 for the overall (0-80 kHz) and low (0-10 kHz) frequency ranges to highlight peak frequencies due to thickness vibration and flexural vibration, respectively.

TABLE 1: First natural frequency of thickness vibration (f_D, f_d) and flexural vibration (f_{fx})

2*a* x *d* (mm)	Thickness vibration (kHz)		Flexural vibration (kHz)		
	FE*	Exp. (A)	FE*	Exp. (A)	Exp. (B)
Solid	3.9	3.9	N/A	N/A	N/A
100x25	N/A	N/A	8.8	2.2	2.8
200x25	N/A	73.2	2.9	1.3	1.4
200x50	36.3	37.1	3.9	2.2	2.3
200x100	19.1	26.4	9.0	3.0	3.4

*Spectrum resolution ≈ 0.9 kHz; (A) Shock tube; (B) Hammer

For the solid specimen, both experimental and FE models show a peak value of frequency at 3.9 kHz, which is in good agreement with the theoretical value f_D. As far as the flawed specimens are concerned, it is seen that there is a good agreement between theoretical and FE results in terms of the first natural frequency of flexural vibration (Tab. 1). The theoretical values of f_{fx} should be a lower bound for FE results, although this is not always the case because of the relatively course resolution of FE spectrum, equal to about 0.9 kHz. Both proposed (shock tube) and conventional (hammer) impact devices show a perfect agreement in the flexural vibration frequency (Tab. 1). The discrepancies between experimental and numerical values of flexural vibration frequency might partly be related to differences in the actual crack length in laboratory specimens with respect to the nominal one input in FE models (e.g. a crack having an actual length 10% higher than the nominal one, produces a reduction in the value of flexural vibration frequency of about 20%).



(a) (b)

Figure 3: Normalised velocity spectrum at central surface point for specimen with 2*a* = 200 mm and *d* = 50 mm : (a) thickness vibration; (b) flexural vibration

Considering the peak frequencies due to thickness vibration, the comparison between experimental and FE results appears to be more difficult than for flexural vibration [3]. This might be due to the low frequency content of impact energy (the relatively long duration of shock wave impact generates a low frequency content of impact energy) which in turn encounters difficulties in detecting the high frequencies of thickness vibration. Moreover, when such frequencies are detectable, a general discrepancy possibly caused by interference phenomena between laser beam and expansion waves occurs [3]. As a matter of fact, the laser beam measuring surface velocity travels through the air subjected to pressure waves. Then the velocity of the beam changes and the frequency measured by the laser fluctuates.

CONCLUSIONS

A new nondestructive testing (NDT) method for defect detection in concrete structures is presented. The method is based on the dynamic response of flawed concrete structures subjected to impact loading. A periodic response due to thickness vibration and, in the presence of shallow defects, plate-like flexural vibration can be detected in the time history of the measured surface velocity. The method uses non-contacting devices for both impact generation (a shock tube producing shock waves) and response monitoring (laser vibrometers measuring surface velocity). Experimental and numerical (finite element) studies on a solid specimen and 4 flawed specimens containing artificial defects (penny-shaped cracks parallel to the free surface with varying length and depth) have been carried out to assess the effectiveness of the proposed NDT method.

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