Fire Safety Journal 69 (2014) 36–42

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Nonlinear resonance vibration method to estimate the damage level on heat-exposed concrete

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ARTICLE INFO

Article history:
Received 11 June 2013
Received in revised form
1 July 2014
Accepted 6 July 2014
Available online 29 August 2014

Keywords:
Fire-damage
Evaluation method
Concrete
Nonlinear resonance
Peak temperature
Hysteretic nonlinearity parameter

ABSTRACT

After exposing concrete structures to fire, a promising *in-situ* evaluation method is required to evaluate the subsequent durability of the concrete. Fire-damage to concrete includes the formation of contact-type defects based on physicochemical changes, which are a dominant factor in fire-damage. The phenomenon of nonlinear resonance vibration is the shift of resonance frequency depending on input amplitude and it can sensitively reflect the occurrence of contact-type defects. This study attempts to estimate damage level to which concrete under heat-exposed, based on the proposed method to measure a hysteretic nonlinearity parameter. The experimental study was performed on 100 concrete samples with different mix proportions and fire scenarios. As a result, a relationship is proposed by which to estimate damage level on heat-exposed concrete, based on the correlation with the peak temperature and the hysteretic nonlinearity parameter.

1. Introduction

While concrete is recognized as a fire-resistant material, the structural performance of concrete structures is degraded after a fire. Several factors (e.g., temperature, scale, and duration of fire) determine the degree of fire damage. Such conditions may lead to severe damage such as the shrinkage of the cement paste matrix, and the spalling or delamination of concrete [1]. Defects generated at the micro scale are dominant for fire-damaged concrete, are diversely distributed, and cause the overall degradation of mechanical properties. Previous research have shown the presence of contact-type defects (opening and pores) induced by fire-damage using scanning electron microscopy [2], and also the reduction of the properties of the residual materials in fire-damaged concrete [3–8]. Thus, micro-scale evaluation is necessary to determine the current condition and potential for reuse of fire-damaged concrete.

Various techniques have been proposed to evaluate fire-damaged concrete due to considerations about the safety and reliability of damaged structures. These techniques are classified according to the method for measuring the target scope of the structure. There are techniques for the purpose of overall inspection (ultrasonic pulse velocity, ultrasonic pulse-echo, and impact echo) and techniques for the purpose of surface evaluation (Schmidt rebound hammer, Windsor probe, and spectral analysis of surface waves). Other techniques focus on the response of specific points by obtaining concrete samples from different locations (small-scale mechanical testing, differential thermal analysis, thermogravimetric analysis, scanning electron microscopy, and thermoluminescence analysis) [9–12]. Some of these techniques are appropriate for *in-situ* test, but it is hard to use these (e.g., ultrasonic pulse velocity, Schmidt rebound hammer, Windsor prove, or impact echo) to sensitively represent contact-type defects. Others (e.g., differential thermal analysis, thermogravimetric analysis, scanning electron microscopy) can sensitively evaluate contact-type defects, but involve either time-consuming processes or limited potential for laboratory experiments due to their location.

To overcome these drawbacks, evaluation techniques based on nonlinear acoustics have been proposed to enhance both the sensitivity for contact-type defects and the convenience of application. The difference between linear and nonlinear acoustic methods rests on an assumption about the frequency components of propagating waves [13]. The nonlinear acoustic method is mainly focused on distortions of the propagating wave. These are represented as new frequency components: generation of sub-harmonics and higher-harmonics during monochromatic wave propagation [14,15]; mixing of waves of different frequencies [16]; and amplitude-dependent resonance characteristics [17]. These techniques were used to characterize various types of damage, such as compressive loading [15,18] and alkali–silica reaction [19–22]. In addition, in previous studies

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http://dx.doi.org/10.1016/j.firesaf.2014.07.003
0379-7112/

nonlinear ultrasonic methods were reported to be promising for sensitively characterizing fire-damaged concrete, based on the occurrence of contact-type defects [2,3,23,24].

This study proposes an improved method for evaluation of fire-damaged concrete based on nonlinear resonance vibration. The proposed method is appropriate for estimating damage level of concrete while maintaining high sensitivity for contact-type defects. Analysis comparing the measurement of linear acoustic methods (ultrasonic pulse velocity and dynamic modulus) and nonlinear acoustic methods (nonlinearity parameters) was performed to validate the sensitivity of the proposed method for contact-type defects. For the linear acoustic methods, although there are differences in the phase and amplitude of the input and output signal due to the presence of damage, the frequency does not change; however, the methods based on nonlinear acoustics also take into account of the change in frequency. Experimental evaluation of fire-damaged concrete was also carried out using nonlinear resonance vibration. About 100 disk samples of fire-damaged concrete, representing 20 cases based on different fire scenarios and concrete mix-proportions, were prepared. As a result, a relationship for estimating the peak temperature, as damage level on heat-exposed concrete, was developed via regression analysis of the correlation with the hysteretic nonlinearity parameter (HNP).

2. Nonlinear resonance vibration

The conventionally used linear acoustic techniques measure wave velocity or attenuation based on differences in the phase and amplitude of the input and output signals due to the presence of damage [11,25]. The nonlinear acoustic techniques such as nonlinear resonance vibration or nonlinear ultrasonic methods focus on the frequency difference between the input and the output signals during wave propagation through a nonlinear elastic medium. This phenomenon is mainly related to the interactions of the large amplitude input signal and micro-discontinuities, which directly affect the nonlinear elastic behavior of materials. Therefore, the nonlinear acoustic techniques show remarkably greater sensitivity than conventional linear acoustic techniques for various materials having dispersed damage at the micro-scale [13,26].

Construction materials, such as rock and cement-based materials have inherent, distributed contact-type defects due to the heterogeneity of their constituents. When damage occurs in these materials, nonlinear acoustic behavior is enhanced according to the increase of contact-type defects, which can be dominantly represented as the hysteretic nonlinearity [27–30]. The constitutive relationship between the stress σ and elastic modulus M as a function of the strain ε and $\dot{\varepsilon}$ can be written as follows [16]:

$$\sigma = \int M(\varepsilon, \dot{\varepsilon}) d\varepsilon \tag{1}$$

$$M(\varepsilon, \dot{\varepsilon}) = M_0(1 - \beta\varepsilon - \delta\varepsilon^2 \cdots) + M_0\{-\alpha[\Delta\varepsilon + \varepsilon(t)\mathrm{sign}(\dot{\varepsilon})] + \cdots\} \tag{2}$$

where β and δ are the quadratic and the cubic order nonlinearities respectively, α is the hysteretic nonlinearity, $\dot{\varepsilon} = d\varepsilon/dt$ is the strain rate, $\Delta\varepsilon$ is the strain amplitude change over the previous period, and sign $(\dot{\varepsilon}) = 1$ if $\dot{\varepsilon} > 1$ or sign $(\dot{\varepsilon}) = -1$ if $\dot{\varepsilon} < 1$. According to previous research, the hysteretic nonlinearity of cement-based materials can be measured by nonlinear resonance vibration based on the following hysteretic nonlinear characteristics: nonlinear attenuation, the modal damping ratio, and the nonlinear resonance frequency shift [17, 20–23]. In this study, the HNP was measured to evaluate fire-damaged concrete in accordance with an amplitude-dependent shift in resonance frequency. The relationship between change in the strain amplitude and relative difference of resonance frequency can be expressed as follows [31]:

$$\frac{f_0 - f}{f_0} = \alpha_h \Delta\varepsilon \tag{3}$$

where f_0 is the linear resonance frequency, f is the measured resonance frequency including the amplitude-dependent effect, and α_h is HNP measured by amplitude-dependent resonance frequency shift.

3. Experiments

3.1. Concrete disk samples

The cylindrical concrete specimens were cast and molded into $\varnothing 100 \times 200\ \text{mm}^2$ cylindrical molds with four different mix proportions: two different water-to-cement ratios and two different fine-to-coarse ratios. Samples were labeled C1–C4 depending on the mix proportions, and these are described in Table 1. All samples were made of Type I Portland cement, crushed gravel for coarse aggregate (maximum size 19 mm), and river sand for fine aggregate. Admixture was not added. The specific gravity of the cement, surface-dry saturated gravel, and sand was 3.15, 2.73, and 2.31, respectively. After 28 days of water curing, the cylindrical concrete specimens were cut into disks 25 mm thick, using a diamond saw blade. Therefore, a total of 100 concrete disk samples were prepared.

Thus prepared, the samples were exposed to high temperatures using an electric furnace, which had already reached each peak temperature (200 °C, 400 °C, 600 °C, or 800 °C). The concrete disks were placed in a drying machine for 24 h at 100 °C before exposure to higher temperatures in order to prevent hygrothermal spalling. Each sample was exposed to peak temperature for an hour; a sufficient time for the internal temperature of the sample to reach the peak temperature. Five damaged samples were prepared for each peak temperature. After the end of the exposure period, the samples at elevated temperatures were immediately soaked in water for cooling.

Prepared samples include the various thermal degradation phenomena as peak temperature: the physically combined water is vaporized above 100 °C; the cement gel is dehydrated at around 180 °C; the $Ca(OH)_2$ in cement paste is decomposed quickly at around 500 °C; α-quartz transforms to β-quartz at around 570 °C in aggregate; the calcium silicate hydrates is decomposed at around 700 °C; the $CaCO_3$ is decomposed at around 800 °C. In addition, coefficients of thermal expansion differed according to the types of constituent material, such as cement paste or types of aggregate, and according to the temperature [1]. Therefore, the occurrence and degree of distributed, contact-type defects in fire-damaged samples was determined by the maximum temperature to which they were exposed [2].

3.2. Experimental setup

Fig. 1 shows the schematic diagram and experimental setup for nonlinear resonance vibration. A detailed description of the apparatus and configuration follows. The concrete disk sample was located on a soft mat. This was used to isolate the

Table 1
Mix proportions of concrete samples (kg/m^3).

Label	Water	Cement	Fine aggregate	Coarse aggregate	Water-to-cementratio	Fine-to-coarse aggregate ratio
C1	160	320	744	1100	0.5	0.68
C2	171	285	744	1100	0.6	0.68
C3	160	320	922	922	0.5	1
C4	171	285	922	922	0.6	1