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A Study on Nonlinear Resonance Frequency Shift of Fire-damaged Concrete

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ABSTRACT

This paper concentrates on the clarification of amplitude-dependent resonance characteristics of fire-damaged concrete. In the case of fire, concrete damage occurs in response to changes in chemical and physical, that directly affects the nonlinear resonance behavior of the concrete. Tests were performed on fire-damage concrete specimens in order to determine the amplitude-dependent resonance frequency shift, and test results verify that the nonlinear resonance characteristic is enlarged as increasing thermal-defects.

1. INTRODUCTION

In the event of a fire accident, concrete structures may suffer severe damage. During fire, thermal degradation of concrete occurs as the shrinkage of cement paste matrix, the spalling of concrete, and the delamination of concrete (Bazant and Kaplan 1996). Furthermore, micro-defects are diversely distributed in the concrete, which causes the overall reduction of mechanical properties: previous researches show the presence of thermally-induced micro-defects using scanning electron microscope (Yim et al. 2012) and the reduction in the residual material properties of concrete (Yim et al. 2013). Therefore, the assessment of thermally damaged concrete necessarily includes the micro-scale evaluation to determine the damage state and the reuse of concrete. Previous studies show that nonlinear ultrasonic methods, based on nonlinear acoustics, represent enough sensitivity for characterizing thermal damage of concrete (Payan et al. 2007, Yim et al. 2012, Yim et al. 2013). In ultrasonic method, the contact between the test specimen and the ultrasonic transducers is the essential part, because it may be one of the major reasons that cause noise signal. Also, file damage causes serious

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damage to the local site of concrete structure, but the size of the test specimens that was used in the previous studies is relatively large. For these reasons, additional research is required to overcome these drawbacks.

This study concentrates on the nonlinear resonance frequency shift of fire-damaged concrete for the assessment of fire damage. The main features of this study are as follows: the amplitude-dependent resonance characteristics of thin concrete disks, impact vibration tests, and the evaluation of thermally induced damage of concrete. The evaluation method using thin concrete disk reduces the size of specimen, so it is suitable for the determination of the fire-damaged site. Second, the experiments were performed by impact vibration, so the experimental apparatus is simple: just an accelerometer and a data acquisition system. Finally, nonlinear resonance vibration is used to evaluate thermal damage experimentally. Tests were performed on specimens that are made of different mix proportions, and suffered different thermal damages. The test results represent that fire-damaged concrete can be sensitively characterized by nonlinear resonance frequency shift.

2. NONLINEAR RESONANCE FREQUENCY SHIFT

The fundamental principle of nonlinear resonance frequency shift is nonlinear acoustics, which focuses on the frequency change between the input and the output signal. This phenomenon is due to the nonlinear elastic behavior of a medium which has damage; such as micro-defects, discontinuity, etc. This phenomenon is mainly related with the radiation and propagation of a large amplitude (finite-amplitude) wave interacts with interfaces, voids, contact-type defects, and etc. Therefore, nondestructive evaluation methods based on nonlinear acoustics have been researched and developed in several decades; that show the remarkable sensitivity for various materials when compared to the conventional nondestructive evaluation methods (Zheng et al. 2000, Jhang 2009).

According to the previous researches on nonlinear acoustic evaluation methods, the damaged concrete has the hysteretic nonlinearity due to internal micro-defects, and it represents following amplitude-dependent resonance characteristics: the nonlinear attenuation, the modal damping ratio, and the nonlinear resonance frequency shift (Chen et al. 2011). Among these characteristics, the amplitude-dependent resonance frequency shift is the main focus of this study. The relationship between resonance frequency shift and strain amplitude can be expressed as follows (Van Den Abeele et al. 2001)

$$\frac{f_0 - f}{f_0} = \alpha_{\mathrm{h}} \Delta\varepsilon \tag{1}$$

where f_0 is the linear resonance frequency at low amplitude input, f is the measured resonance frequency including the amplitude-dependent effect, and α_h is the hysteretic nonlinearity parameter. In general, the tendency to the measured resonance frequency of concrete is reduced, and the amount of decrement has a direct relationship with the hysteretic nonlinear characteristics of the media. As increasing the micro-defects, concrete demonstrates highly hysteretic nonlinear behaviors through wave propagation, and then the hysteretic nonlinearity parameter is also rapidly increased. Therefore, fire-induced damage of concrete can be represented as measured hysteretic nonlinearity parameter.

3. EXPERIMENTS

3.1 Preparation of test samples

The cylindrical concrete specimens were casted and molded into 100mm of diameter and 200mm of height cylindrical molds. The mixture proportion of concrete was 0.50:1.00:2.88:2.88, which is expressed as the weight ratio of water, cement, fine aggregate, and coarse aggregate. Specimens were made of Type I Portland cement for cementitous material, crushed gravel for coarse aggregate, and river sand for fine aggregate. After 28 days of water curing, the cylindrical concrete specimens were cut into thin disks, approximately 25mm of thickness, using diamond saw blade. To prevent hygrothermal spalling, concrete disks were placed in a drying machine for 24 hours at 100°C before the exposure to high temperature.

After the drying period, specimens were exposed to high temperatures immediately, without requiring time for temperature elevation. Target temperatures were 200°C, 400°C, 600°C, and 800°, during an hour. An electrical furnace was used for maintaining the target temperature. After the end of the exposure period, the samples of high temperature were soaked in water immediately for cooling. For each target temperature, 5 damaged samples were prepared.

3.2 Experiments for nonlinear resonance frequency shift

The amplitude-dependent resonance frequency shift of thermally damage concrete disks was measured via mechanical impact to determine the hysteretic nonlinearity parameter (α_h). Fig. 1 shows the schematic diagram of the experiments and the experimental setup.

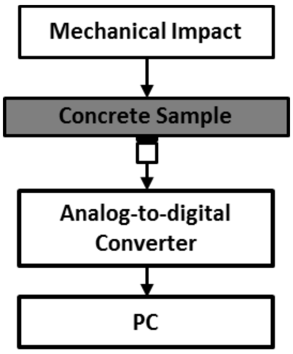

Fig. 1 Schematic diagram of nonlinear resonance frequency shift test

As a typical example of amplitude-dependent characteristics, the experimental results of a damaged sample subjected to 400°C are shown in Fig. 3.(a); which indicates the relationship between resonance frequency and acceleration representing the amplitude of the impact. In order to determine the nonlinearity parameter (α_h) on the basis of the Eq. (1), the slope between the acceleration and the normalized frequency shift is computed by the linear regression analysis, as shown in Fig. 3.(b).

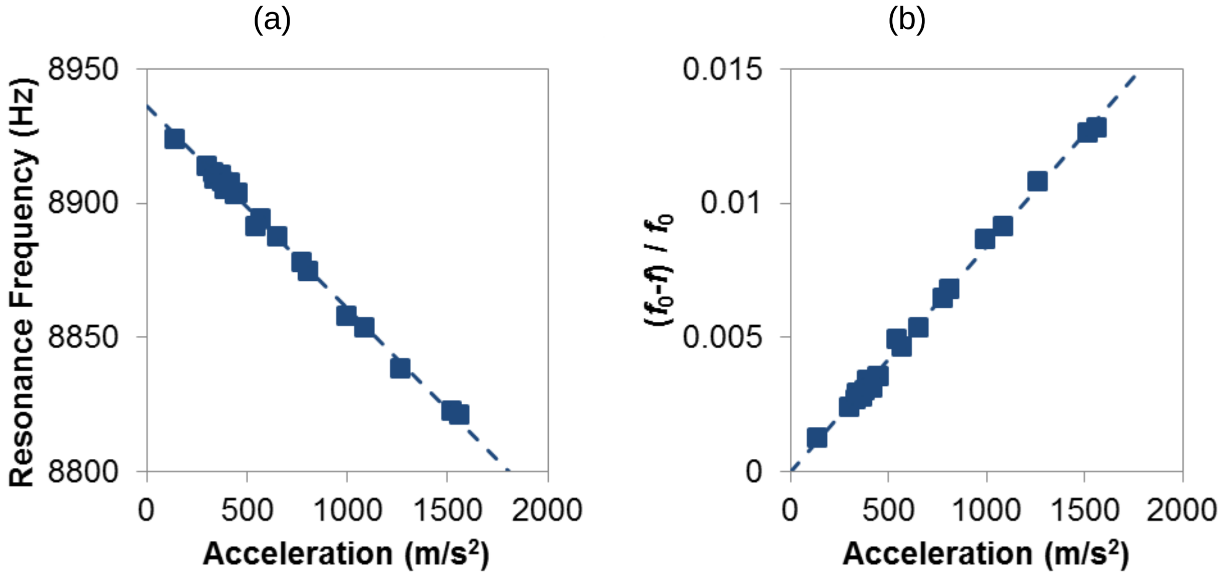

Fig. 2 Experimental results of a damaged-sample at 400°C: (a) amplitude-dependent resonance frequency shift; (b) the measurement of hysteretic nonlinearity parameter

3. EXPERIMENTAL RESULTS

The amplitude-dependent resonance characteristic was measured to compute hysteretic nonlinearity parameter ($\alpha_{h)}$ of entire samples. The test results are summarized as Table 1. For all the casting groups, the ratio of resonance frequency shift is greater with the elevation of the target temperature. Based on the results, it can be concluded that the thermal damage has a significant impact upon the increase of hysteretic nonlinear behavior of concrete. Therefore, not only the determination of the presence or absence of thermal damage, the proposed technique can also evaluate the extent of thermal damage of concrete.

Table 2 Hysteretic nonlinearity parameter (α_h)

Target Temperature (°C)	*20*	*200*	*400*	*600*	*800*
α_h ($\times 10^{-7}$)	7.490	33.74	78.73	179.7	413.7

4. CONCLUSION

The results of this study represent that the thermal damage induces the hysteretic nonlinear behavior of concrete, which indicates the presence of micro-defects. The target temperature mainly effects on the variation of the hysteretic nonlinearity parameter. Thus, the nonlinear resonance frequency shift provides a reliable measure for determining the state of thermally damaged concrete. For the further study, nonlinear resonance frequency shift will be able to estimate the target temperature of thermally-damaged concrete and to estimate the material properties of concrete.

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