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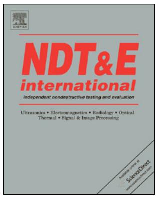

Experimental characterization of granite damage using nonlinear ultrasonic techniques

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ABSTRACT

In this paper, a nondestructive evaluation (NDE) technique based on the nonlinear second harmonic wave theory is developed and used to characterize damage of granite samples subjected to compressive loadings. The nonlinear parameter defined in the new NDE technique is measured and compared with two traditional parameters including ultrasonic pulse velocity and dynamic modulus. The nonlinear parameter is found to be much more sensitive to the damage development in granites than traditional parameters. It is shown that the increase of nonlinear parameter is close to an exponential trend with respect to the increased loading level, which also indicates a faster increase rate of the nonlinear parameter corresponding to the internal damage of granite samples. A practical damage index is thus defined based on the exponential increasing trend of the nonlinear parameter. The new damage index based on nonlinear parameter is found to have a positive correlation with the loading level. This observation suggests that the new damage index may become a valuable indicator of loading level (or correspondingly material degradation) of granites in the in situ NDE tests.

1. Introduction

Due to the long-time exposure to the severe serving environment, civil infrastructures inevitably undertake a wide variety of degradation such as mechanical, thermal and chemical damage. The accurate evaluation of damage state is therefore of great importance for the maintenance and rehabilitation of structures. In practice, fast and reliable nondestructive evaluation (NDE) methods are particularly desirable for the in situ inspection of structures. Over the decades, NDE methods based on the propagation of ultrasonic waves have been well developed for the diagnosis and assessment of heath condition of structures. Ultrasonic pulse velocity (UPV) and acoustic emission (AE) are two typical ultrasonic NDE techniques which have been broadly used on sites. For instance, the UPV method has been used for the evaluation of physical and mechanical properties of granites [1,2]. Different cracks are correlated with AE events during the triaxial compression tests for basalt and granite [3].

Rock is a typical heterogeneous material presented with microstructural defects such as microcracks, grain joints and microfractures. The complex microstructure of rock material results in the complicated wave propagation phenomena including scattering, reflection and refraction. The background noise signal caused by these phenomena easily masks the probing signal in the time domain, which makes the measurements of UPV and AE events insensitive to the occurrence of damage, particularly during the early age.

The principal assumption of the linear ultrasonic technique such as the UPV method is that the constitutive relation of damaged materials remains linear and the sole indication of the material degradation is the decrease of Young's modulus which leads to the reduction of pulse velocity. However, it has been found that consolidated materials such as rocks and concrete have a strong elastic nonlinear response during the deterioration process, which should be considered in the constitutive equation of materials [4–7]. The nonlinear constitutive relationship of materials ultimately results in different phenomena of nonlinear ultrasound/acoustics, such as the generation of second harmonic, the shift of resonance frequency and the modulation between two separate waves. Recent research has designed various experimental techniques based on nonlinear ultrasound/acoustics to measure nonlinear parameters describing the nonlinear signature for the damage characterization of consolidated materials. The nonlinear parameters showed a much higher sensitivity to the damage occurrence and development in consolidated materials, compared to linear parameters. For example, Chen et al. and Krzysztof et al.

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used the nonlinear wave modulation spectroscopy and nonlinear impact resonance acoustic spectroscopy to evaluate concrete damage caused by chemical attack and compressive loading, in which the nonlinear parameters are up to 15–20 times the value of linear measurements [8–13]. Shah et al. [14–16] used the harmonic generation technique to analyze the mechanical damage of concrete and compared with linear attenuation results. Ulrich et al. and Anderson et al. [17,18] used the time reversal ultrasonic technique to analyze the bonded mental disks and granites and compared with linear C scan ultrasonic imaging results. In addition, Meegan et al. and Van Den Abeele and Johnson [19–21] have theoretically and experimentally investigated the nonlinear parameters of sandstones based on the generation of higher harmonic, where the wave propagation distance and amplitude of source wave were found to have an effect on the measurement of nonlinear parameters.

In the paper, the experimental technique based on the theory of second harmonic wave is applied to characterize a typical damage type commonly seen in rocks, which is caused by the compressive loading. The nonlinear parameter is measured and compared with two typical linear measurements, the elastic modulus and the pulse velocity. Damage indices are defined based on linear and nonlinear parameters and analyzed for the correlation with sample degradation. It is found that the nonlinear parameter is much more sensitive to the damage occurrence and progress in rock samples than linear ones. The nonlinear parameter shows an exponential increase with the progressed damage and a new damage index in the exponential form is then assumed based on the nonlinear parameter. The damage index based on the nonlinear parameter keeps a very good correlation with the compressive loading levels, which indicates that the new damage index could be a useful indicator in the practical assessment of rock damage.

2. Research significance

Different from some previous research focused on the theoretical derivation and corresponding experimental verification of nonlinear ultrasonic response of consolidated materials [4–6,19–21], the aim of this study is to have a thorough experimental investigation of the nonlinear second harmonic technique in damage characterization for rock materials. First, the study is aimed at verifying the high sensitivity of the nonlinear ultrasonic technique by comparing with typical linear methods. Second, the study is aimed at defining a practical damage index based on the nonlinear parameter similarly in the classical damage mechanics, which could be useful in the in situ evaluation. The scope of the study is the development of nondestructive evaluation experimental techniques with high reliability and sensitivity for rock materials and the definition of novel damage index which could quantitatively reveal damage state of materials. With the validation of high sensitivity of the developed experimental technique and the observation of good correlation of defined damage index with damage state, it has the potential to develop a reliable and the robust NDE method based on the present study for the in situ damage assessment of complicated civil engineering structures, which is an essential concern of professionals in the field of civil engineering.

Instead of simply comparing nonlinear parameters with linear parameters which have been conducted in many previous researches [14–16,23], the novelty of this study is focused on the finding of exponential increase trend of nonlinear parameter with respect to the compressive loading level and the definition of a new damage index which is more straightforward to quantitatively reflect damage state of rock samples, which could be a quick and reliable measurement for the damage assessment in practice.

3. Theory of second harmonic wave

The classical wave propagation theory assumes linear material media, which follow Hooke's law, i.e., the linear stress–strain relation. The most characteristic example is that separate waves can be simply superposed without disturbing each other. In reality, however, materials are usually not perfectly linear even without damage. Linear elasticity considers elastic energy as a function of strain up to the second order, omitting the higher orders which actually cause the so-called atomic nonlinearity [22]. Practically, the atomic nonlinearity is too small to measure so that the material is reasonably deemed as the linear medium in the intact condition. Nagy, Donskoy et al. and Van Den Abeele et al. found out that the nonlinear signature in the material constitutive relation is significantly enhanced when the material undergoes microstructural damage such as imperfections (inclusions) and defects(cracks). The increase of nonlinear parameters is orders of magnitude higher than linear parameters [23–25]. A classical constitutive relation in one dimension describing the atomic nonlinearity based on Landau's theory is

$$\sigma = E_0[1+\beta\varepsilon+\delta\varepsilon^2+\cdots]\varepsilon \tag{1}$$

where E_0 is the modulus of (linear) elasticity, β and δ are the quadratic and cubic nonlinearity parameters describing the anharmonicity.

A typical nonlinear wave propagation phenomenon is the generation of second harmonic. Therefore, extra wave component having a frequency 2ω occurs when a time-harmonic wave of frequency ω travels through the nonlinear media. If the constitutive relation of the nonlinear media is described by Eq. (1), the amplitude of second harmonic wave can be quantitatively related to the amplitude of fundamental wave by the perturbation method [26,27]

$$A_2 = \frac{\beta k_L^2 x A^2}{8} \tag{2}$$

where k_L is the wave number, A_2 is the amplitude of second harmonic, A is the amplitude of fundamental signal, and x is the wave propagation distance.

The relative value of quadratic nonlinear parameter can thus be obtained by measuring the amplitude of fundamental wave and second harmonic wave provided that k_L and x remain constant

$$\beta = \frac{8A_2}{k_L^2 x A^2} \tag{3}$$

4. Material samples and experimental procedure

4.1. Materials

The samples used in the experiments are granite collected in Hangzhou, China in March 2013. The petrographic analysis shows the main components of granite samples are plagioclase (33%), mica (22%), quartz (16%), amphibole (12%), and feldspar (7%).

Four samples used in the experiments are 100 mm-height cylinders with a diameter of 50 mm. The dimension of samples is selected based on the requirements of ASTM standard D2845-08 [28]. The top and bottom surfaces of samples are well polished to ensure a good contact with transducers.