Construction and Building Materials 149 (2017) 716–723

Contents lists available at ScienceDirect

Construction and Building Materials

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

Experimental study on alarming of concrete micro-crack initiation based on wavelet packet analysis

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HIGHLIGHTS

- The micro-damage alarming method of concrete based on wavelet analysis is proposed.
- The method relies on damage strain field obtained by DIC technology.
- The method can automatically identify micro-damage and realize real-time alarming.
- The position and the degree of micro-damage can be determined by the strain field.

ARTICLE INFO

Article history:
Received 16 January 2017
Received in revised form 23 April 2017
Accepted 21 May 2017

Keywords:
Concrete
Micro-crack
Micro-damage alarming
Digital image correlation
Wavelet packet analysis
Structural health monitoring

ABSTRACT

Wavelet packet analysis and digital image correlation (DIC) have been applied extensively owing to their respective advantages. In this work, a novel approach is presented to realize micro-damage alarming and identification of concrete by the coupling of wavelet packet transform and DIC technology. DIC measurement system is utilized to measure the damage strain field of static three-point bending of concrete specimen. According to excellent characteristic of time-frequency localization of wavelet packet analysis, the strain nephograms are decomposed by wavelet packet transform. Through wavelet packet analysis, the eigenvectors of the component energy are constructed, based on which the alarming index of concrete micro-crack initiation is obtained. The experimental results show that our novel approach can effectively predict the micro-crack initiation and can automatically achieve alarming. Furthermore, the initiation position of micro-cracks and micro-damage degree can be accurately determined by damage strain field. It is beneficial to damage prediction and safety control of concrete structures.

1. Introduction

The health monitoring of engineering structures, especially concrete structures, has long-standing interest as an important indicator to assess the safety of engineering structures [1–3]. In long-term complex service environment, concrete structures are subjected to various loads and other factors, so that the local damage is inevitable and may propagate quickly. For numerous concrete structures, the most intuitive information to characterize damage is the appearance and propagation of cracks [4–6]. The development state of cracks directly affects the mechanical properties of damage structures, to some extent, which determines the safety, durability and applicability of the structures and even becomes a measurement of structure lifespan [7]. If the early stage of crack initiation of concrete structures can be monitored, the occurrence of cracks can be effectively predicted and the structural safety can be controlled in time [8]. Therefore, structural health monitoring systems are asked to monitor the crack initiation, to determine precisely the location of damage and to predict the path of damage, thus providing the basis for safety control and predictive maintenance of concrete structures, reducing maintenance costs and prolonging the lifetime of structures.

Concrete as a typical class of brittle materials, its damage process is generally beginning with the cracks, as well as the time of crack propagation is short [9–12]. In order to control the safety of concrete, it is indispensable to study the damage of concrete at the level of micro-cracks (e.g.,<100 μm) and to issue alarming on the stage of concrete micro-crack initiation, which can timely and effectively control the occurrence of concrete failure. The extraction of damage characteristic factors is the core of damage detection. Its basic function can illuminate the damage degree [13].

In recent decades, based on wavelet packet component energy, damage alarming and damage identification have been extensively studied [14–17]. Yen and Lin [18] defined the wavelet packet node energy and proved that the node energy is more robust than the

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http://dx.doi.org/10.1016/j.conbuildmat.2017.05.159
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wavelet packet decomposition coefficient to reflect the signal features. The signal can be decomposed in any fine frequency bands using wavelet packet transform. The component energies are further calculated to form the eigenvectors. Therefore, the variation of characteristic frequency band energy is normally mapped as the damage factor of concrete to identify the damage [19,20].

Alternatively, digital image correlation (DIC) technology as a kind of nondestructive testing method has been broadly applied to detect the deformation and damage of concrete at the mesoscopic scale and to achieve continuous measurement of the full-field strain [21–25]. The basic objective of this method is to obtain the strain field by analyzing the speckle image before and after the deformation of a specimen surface via image correlation matching [26–28]. However, the preponderance of previous researches has focused on macroscopic cracks inducing structural damage alarming and damage identification, and little is known about micro-cracks that are applied to evaluate the alarming and identification of concrete. It is our objective in this work to address this gap.

This article attempts to study the alarming of micro-crack initiation of concrete, at the aim of automatically identifying micro-damage and realizing real-time alarming. This work presents a test method that incorporates the wavelet packet component energy into DIC technology, and provides a method for alarming and identification of structure micro-damage. In this paper, the Wavelet packet analysis is firstly introduced to obtain the strain nephograms of static three-point bending of concrete specimen. Subsequently, the strain nephograms are decomposed by wavelet packet transform. Also, the eigenvectors of component energy of the reconstructed signal are constructed. Moreover, the alarming index of micro-crack initiation is obtained.

2. Wavelet packet analysis

Wavelet packet was introduced by Coifman et al. [29,30] by extending the connection between multi-resolution analysis and wavelet. Let $\{h_k\}_{k\in z}$ be the low-pass conjugate orthogonal filter corresponding to the orthogonal scale function $\phi(t)$, where t is serial number of discrete time and the subscript Z is an integer. Plus, $\{g_k\}_{k\in z}$ is the high-pass conjugate orthogonal filter corresponding to the orthogonal wavelet function $\psi(t)$. h_k and g_k are a pair of orthogonal mirror filters for decomposition that h_k is a low-pass filter and g_k is a high-pass filter. They satisfy $g_k = (-1)^k h_{1-k}$. Meanwhile, they meet the two-scale equation and wavelet equation:

$$\begin{cases} \phi(t) = \sqrt{2}\sum\limits_{k\in z} h_k \phi(2t-k) \\ \psi(t) = \sqrt{2}\sum\limits_{k\in z} g_k \phi(2t-k) \end{cases} \tag{1}$$

If h_k has a finite and even length L, $g_k = (-1)^k h_{L-1-k}$ ($k = 0, 1, \cdots, L-1$), where L is length of the filter coefficients. To facilitate the representation of wavelet packet function, the new functions $\mu_0(t)$ and $\mu_1(t)$ is selected. They satisfy $\mu_0(t) = \phi(t)$ and $\mu_1(t) = \psi(t)$. Then the Eq. (1) can be expressed as

$$\begin{cases} \mu_0(t) = \sqrt{2}\sum\limits_{k\in z} h_k \mu_0(2t-k) \\ \mu_1(t) = \sqrt{2}\sum\limits_{k\in z} g_k \mu_0(2t-k) \end{cases} \tag{2}$$

The Eq. (2) can be extended the general form, that is

$$\begin{cases} \mu_{2n}(t) = \sqrt{2}\sum\limits_{k} h_k \mu_n(2t-k) \\ \mu_{2n+1}(t) = \sqrt{2}\sum\limits_{k} g_k \mu_n(2t-k) \end{cases} \tag{3}$$

The function set $\{\mu_n(t)\}_{n\in 0,1,2,\cdots}$ defined by the Eq. (3) is called the wavelet packet determined by orthogonal scale function $\mu_0(t) = \phi(t)$. The function set $\{2^{-j/2}\mu_n(2^{-j}t-k)\}_{j,k\in z,n\in 0,1,2,\cdots}$ composed of wavelet packets is called as the wavelet library, and extracted from the wavelet library, a set of standard orthogonal bases which can form function space $L^2(\boldsymbol{R})$ are a wavelet packet base of $L^2(\boldsymbol{R})$. For the fixed decomposition layer j, $\{2^{-j/2}\mu_n(2^{-j}t-k)\}_{k\in z,n\in 0,1,2,\cdots}$ constitutes a wavelet packet base of $L^2(\boldsymbol{R})$ called as fixed scale wavelet packet base or sub-band base, and its corresponding decomposition of $L^2(\boldsymbol{R})$ is $L^2(\boldsymbol{R}) = U_j^0 + U_j^1 + U_j^2 + \cdots + U_j^n + \cdots$, where U_j^n ($n = 0,1,2\cdots$) represents subspace of $L^2(\boldsymbol{R})$ .Wavelet packet decomposition:

$$\begin{cases} d_j^{2n}[k] = \sum\limits_{l\in z} h_{l-2k} d_{j+1}^n[l] \\ d_j^{2n+1}[k] = \sum\limits_{l\in z} g_{l-2k} d_{j+1}^n[l] \end{cases} \tag{4}$$

Wavelet packet reconstruction:

$$d_{j+1}^n[k] = \sum_{l\in z} h_{k-2l} d_j^{2n}[l] + \sum_{l\in z} g_{k-2l} d_j^{2n+1}[l] \tag{5}$$

where d_j^n is the n-th wavelet packet coefficient in the j-th level; j is a positive integer; l and k are parameters related to the scaling function with compact support; $n = 0,1,2,\cdots$; g and k are wavelet filters related to wavelet functions and scaling functions, respectively.

For a particular signal, the signal can be divided into different frequency bands by a set of low-pass, high-pass combined conjugate orthogonal filters H and G. The orthogonality and completeness of the wavelet packet can keep the original signal information intact.

3. The alarming method of micro-crack initiation

3.1. Damage alarming theory based on wavelet packet energy

Wavelet multi-resolution analysis can perform effectively time-frequency decomposition of the signal, but its scale is binary. Consequently, the frequency resolution in the high-frequency bands and the time resolution in the low-frequency bands are both poor. Wavelet packet analysis as a finer signal analysis method divides the frequency bands into multi-layers and further decomposes the high-frequency bands which are not subdivided by the multi-resolution analysis. Meanwhile, wavelet packet analysis can adaptively select the corresponding frequency bands according to the characteristics of the analyzed signal to match the signal spectrum, thereby further improving the time-frequency resolution. Hence, the wavelet packet decomposition can detect the transient anomaly information in the normal signal and show its components [31,32].

Image texture features are reflected in different frequency bands. For example, the low-frequency bands stand for the approximate information and the high-frequency bands correspond to the detailed information. The change of an image texture represents the variation of gray values in certain areas of the image. Accordingly, the information of each frequency band of the image decomposed by wavelet packet also changes in the frequency domain. When an image texture is changed, there are different effects on the suppression and enhancement of frequency components of the image, which reduces the energy in some frequency bands and increases the energy in other frequency bands. Therefore, the energy of each frequency band in an image contains abundant image information. In doing so, the difference of images can be