Mechanics Research Communications 64 (2015) 15–22

Contents lists available at ScienceDirect

Mechanics Research Communications

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

Numerical modeling of damage detection in concrete beams using piezoelectric patches

Nemanja Markovic[b,*], Tamara Nestorovic[a], Dragoslav Stojic[b]

[a] Mechanics of Adaptive Systems, Ruhr University Bochum, Germany
[b] Faculty of Civil Engineering and Architecture, University Nis, Serbia

ARTICLE INFO

Article history:
Received 9 April 2014
Received in revised form
22 December 2014
Accepted 30 December 2014
Available online 7 January 2015

Keywords:
Piezoelectricity
Smart aggregates
Health monitoring
Modeling
Wave propagation
Concrete
Damage detection

ABSTRACT

Research and development of active monitoring systems for reinforced concrete structures should lead to improved structural safety and reliability. Numerical models of active monitoring and damage detection systems can help in the development and implementation of these systems. Modeling of damage detection process in a concrete beam with piezoelectric sensors/actuators based on wave propagation is investigated in this paper. Numerical modeling process is divided into two parts: (1) piezoelectric smart aggregates (SA), and (2) wave propagation models. Displacement obtained in the SA model is used as an input parameter for the modeling of wave propagation. Wavelet analysis is used as a signal processing tool and the damage index is calculated based on the wave energy. In this paper root-mean-square deviation (RMSD) damage index is used. Damage indices obtained by this numerical analysis are compared with experimental results. Very good fit between the finite element (FE) results and experimental results confirm a good FE approach of this problem.

1. Introduction

Concrete is the most widely used construction material in the history of civil engineering. Most architectural and infrastructural buildings are built of concrete, such as skyscrapers (Empire State building, Commerzbank Headquarters, Burj Dubai), dams (Hoover dam, Three Gorges dam, Glen Canyon, Gordon dam), bridges (Millan bridge, Mauchac Swamp bridge), parking structures, pipes, etc. Concrete has good compressive strength but very low tensile strength. In flexural beam members cracks develop under working load, and since concrete is weak in tension, cracks occur in tensile zones. When the stress at the extreme tension fibers exceeds the modulus of rupture of concrete the first crack occur. However, tensile stress is not the only cause of cracks in concrete; there are a large number of factors that influence the development of cracks such as temperature change, creep, shrinkage and shear stress. Crack pattern of a reinforced concrete (RC) element is very complicated, because cracks have different orientation, length, width, some of them are stationary while others are propagating. Furthermore, the cause of their occurrence is different and they can be very small micro cracks or large macro cracks. Therefore, monitoring of concrete structures is a very demanding and challenging task. Traditional health monitoring methods (C-scan, X-ray etc.) are expensive and ineffective for large scale concrete structures with limited or no accessibility. Piezoelectric health monitoring systems are characterized by low cost, quick response, active sensing, availability in different sizes and shapes and simplicity of in-city implementation [2]. Development and application of such active monitoring systems can increase the overall safety and reduce the number of accidents caused by the building collapse. Active monitoring systems based on piezoelectric transducers have been becoming very popular in the scientific community in recent years.

There are a large number of experimental studies in this research area; however, according to the authors' best knowledge there are almost no numerical models which analyze the entire damage detection process. In this paper, we present efficient finite element (FE) models of active monitoring systems and damage detection using piezoelectric smart aggregate actuators/sensors. Experimental damage detection can be performed using smart aggregates for different structural elements under static load, such as beams [1,11,16], bridge "T" bent-cap [10], and piles [13]. Monitoring and detection of cracks caused by dynamic effects is performed to the shear walls [15], columns [17,18] and reinforce concrete frames [2]. Deboned detection using embedded piezoelectric elements in reinforced concrete beams was analyzed in paper [7]. Smart

* Corresponding author. Tel.: +381 652937763.
E-mail address: nemanja.markovic@gaf.ni.ac.rs (N. Markovic).

http://dx.doi.org/10.1016/j.mechrescom.2014.12.007
0093-6413/

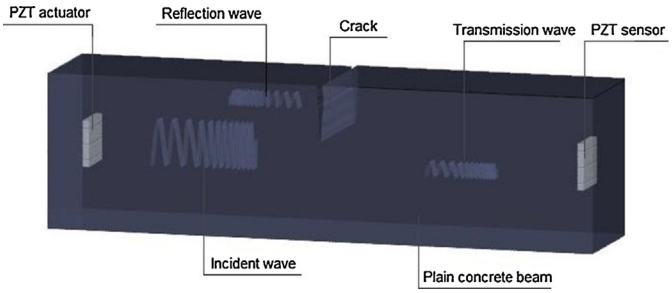

Fig. 1. Health monitoring based on wave propagation.

aggregates were also used for early-age concrete strength monitoring [2], impact detection [2] and water seepage [8]. User-defined piezoelectric shell elements for modeling and analysis of active structures are presented in papers [9,20].

The motivation of this study comes from the following three points: (1) in the available relevant literature efficient numerical models of active monitoring systems using smart aggregates are under-represented; (2) performed experimental studies have shown great potential of this method for real-time monitoring of large scale RC structures and a large space for further method improvement; (3) creating a reliable and efficient numerical model can improve implementation of smart aggregate active monitoring systems on real large-scale civil engineering structures.

In this paper three-dimensional finite element (FE) model of a smart aggregate is developed using standard Newton's method and explicit central-difference time integration rule with lumped mass matrixes is used for wave propagation models. Wavelet analysis is used as a signal processing tool to decomposed output signals into approximations (low-pass filter) and details (high-pass filter). Damage index is calculated based on the wave propagation energy. In this paper we use root-mean-square deviation (RMSD) damage index and the results are compared with the experimental analysis.

2. Structural health monitoring method

Damage detection system based on piezoelectric transducers represents an active monitoring system, with a very wide field of applications in reinforced concrete structures. There are two main approaches to this method: (1) wave propagation based method and (2) impedance-based method. Piezoelectric actuator/sensor can be embedded into RC structure or attached to the surface. If the piezoelectric patch is protected by waterproof insulation and embedded into a small concrete block, it forms a so-called "smart aggregate" (SA), patented by Song et al. [19]. In this way, it is possible to embed and protect very fragile and sensitive piezoelectric patch in reinforce concrete element.

The piezoelectric effect represents phenomenon of generating an electric field when piezoelectric material is subjected to a mechanical stress (direct piezo effect), or opposite, generating a mechanical strain in response to an applied electric field (inverse piezo effect). For linear piezoelectric materials, the relation between the electrical and mechanical variables can be described by linear relations of mechanical and electrical variables [14]. There are four basic forms of constitutive equations for piezoelectric materials: strain–charge, stress–charge, strain–voltage and stress–voltage [12]. Which constitutive form will be used for modeling piezoelectric elements directly depends on the software program that is used and the selected input data.

When electrical voltage is applied to piezoelectric actuator patch in certain finite time duration, the initial state of equilibrium is distorted and the wave begins to propagate through the structure. The second piezoelectric element (sensor) produces an electric voltage caused by mechanical stress due to incoming wave. If a crack exists between the actuator and the sensor, the propagation energy of the traveling waves will be attenuated. By monitoring the sensor output signals it is possible to detect the occurrence and development of cracks in reinforced concrete structures. Fig. 1 represents basic crack detection using wave propagation, which can be applied for health monitoring of structures.

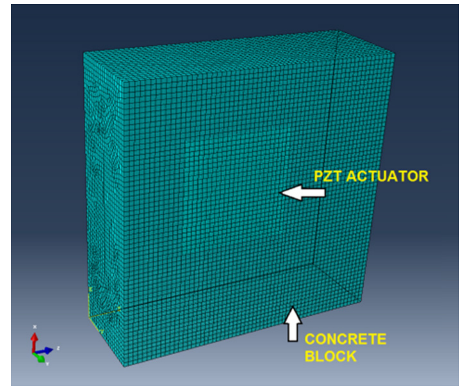

Fig. 2. Smart aggregate model.

Because of piezoelectric properties, the smart aggregates can be used as the actuator and as a sensor. This piezoelectric material property significantly reduces the required number of PZT SA for monitoring of RC structures.

3. Finite element modeling of piezoelectric smart aggregate

In this section, piezoelectric smart aggregate is studied based on three-dimensional finite element model. Smart aggregate model consist of two parts, a piezoelectric patch (12.7 × 12.7 × 0.25 mm) and a small concrete block (30 × 30 × 10 mm), as shown in Fig. 2.

FE modeling of piezoelectric materials is based on constitutive equations for coupled electro-mechanical behavior. ABAQUS uses first two forms of constitutive piezoelectric material equations: strain–charge (2), stress–charge (1). Basic equations for a piezoelectric linear medium are defined in terms of the piezoelectric stress coefficient matrix e^{φ}_{mij} (1), or in terms of the piezoelectric strain coefficient matrix d^{φ}_{mij} (2). The electrical behavior is defined by Eq. (3).

$$\sigma_{ij} = D^{E}_{ijkl}\varepsilon_{kl} - e^{\varphi}_{mij}E_m \quad (1)$$

$$\sigma_{ij} = D^{E}_{ijkl}(\varepsilon_{kl} - d^{\varphi}_{mkl}E_m) \quad (2)$$

$$q_i = e^{\varphi}_{ijk}\varepsilon_{jk} + D^{\varphi(\varepsilon)}_{ij}E_j \quad (3)$$

with following notation: σ_{ij}; ε_{ij} – mechanical stress and strain tensor; q_i – is the electric "displacement" vector; D^{E}_{ijkl} – material's elastic stiffness matrix defined at zero electrical potential gradient; e^{φ}_{mij}, d^{φ}_{mkl} – material's piezoelectric stress and strain coefficient matrices; E_i – electrical potential gradient vector; $D^{\varphi(\varepsilon)}_{ij}$ – material's dielectric properties strain matrix.

The piezoelectric effect is governed by coupled mechanical equilibrium and electric flux conservation equations [6]. The mechanical equilibrium equation is:

(4) $\int_V \boldsymbol{\sigma} : \delta\varepsilon \, dV = \int_S \boldsymbol{t} \cdot \delta u \, ds + \int_V \boldsymbol{f} \cdot \delta u \, dV$ where σ is the Cauchy stress, t is the traction across a point of the surface of the body; f is the body force per unit volume.

The electrical flux conservation equation is:

(5) $\int_V \boldsymbol{q} : \delta E \, dV = \int_S q_S \cdot \delta\varphi \, dS + \int_V q_V \cdot \delta\varphi \, dV$ where $\boldsymbol{q}$ is the electric flux; q_s is the electric flux per unit area entering the body at a