Међународна конференција
Савремена достигнућа у грађевинарству 24.-25. април 2014. Суботица, СРБИЈА

CRACK DETECTION IN REINFORCE CONCRETE BEAM ELEMENTSWITH PIEZOELECTRIC SENSORS

Nemanja Marković[1]
Dragoslav Stojić[2]
Radovan Cvetković[3]
Nikola Velimirović[4]

UDK: 539.421:624.072.2
DOI: 10.14415/konferencijaGFS2014.015

Summary: *Detection of cracks in reinforced concrete (RC) beam elements using non-destructive methods is a very demanding task because of physical and mechanical characteristics of the material. Cracking can occur in concrete structures for several reasons that can primarily be grouped into either mechanical loading or environmental effects. Determining the exact cause of the crack, their number, position and orientation is impossible in many cases. Crack detection in RC using piezoelectric (PZT) sensors and based on wave propagation is one of the non-destructive methods (NDM) presented in this paper. Principles and application of active monitoring systems of RC structures are presented in this work. Modelling damage detection methods, using the finite element method (FEM,) are very important for the numerical simulation of this problem.*

Keywords: *Monitoring, piezoelectric, reinforce concrete, cracks, finite element method*

1. INTRODUCTION

Reinforced concrete (RC) is the most applied material in the history of civil engineering. The largest number of major infrastructure, residential, public, etc., buildings was made of reinforced concrete. Because of this fact, the development of new monitoring systems that will increase the safety of RC buildings is even more important. In this paper an active monitoring system, using smart aggregate piezoelectric actuators/sensors based on the wave propagation, will be presented.

In flexural beam members cracks could develop under working load. Cracks occur in tensile zones because concrete is weak in tension. When the stress at the extreme tension fibers exceeds the concrete modulus of rupture, the first crack occurs. A crack is formed in concrete when a narrow opening of indefinite dimension has developed in the

[1] Nemanja Marković, dipl.inž. građ., University of Niš, Faculty of Civil Engineering and Architecture Niš, Aleksandra Medvedeva 14, Niš, Serbia, e – mail: nemanjamarkovic85“@gmail.com
[2] Prof. dr Dragoslav Stojić, dipl.inž. građ., University of Niš, Faculty of Civil Engineering and Architecture Niš, Aleksandra Medvedeva 14, Niš, Serbia
[3] Mr. Radovan Cvetković, dipl.inž. građ., University of Niš, Faculty of Civil Engineering and Architecture Niš, Aleksandra Medvedeva 14, Niš, Serbia
[4] Nikola Velimirović, dipl.inž. građ., University of Niš, Faculty of Civil Engineering and Architecture Niš, Aleksandra Medvedeva 14, Niš, Serbia

concrete beam as the results of internal tensile stresses. These internal stresses could be induced by one or more of the following [4]:

- External forces - such as direct axial tension, shear, flexure;
- Shrinkage;
- Creep;
- Internal expansion - resulting from a change of properties of the concrete constituents.

Despite of the reason of crack occurrence, the final crack pattern in reinforced concrete beam is usually very complicated, what significantly complicates its monitoring. Large number of experimental studies, in order to solve this problem, is made in recent years. Review paper of experimental examples of crack detection using piezoelectric transducers is presented in [5]. Detection of cracks using piezoelectric smart aggregates and detection of artificially made notches and holes in the beam, in order to confirm the application of methods for different types of defects, is presented in the paper [6].
Active damage detection systems based on piezoelectric transducers is first applied in aerospace industry on thin steel, aluminium and laminated structures. The paper [7] presents the basics and applications of damage detection method in aforementioned types of structures. Basic principles and application of active monitoring systems, with piezoelectric smart aggregates based on wave propagation, is presented in this paper.

2. DAMAGE DETECTION METHODS

Piezoelectric-based approaches have provided an innovative approach for the structural health monitoring of civil structures with the advantages of structural simplicity, low cost, quick response and high reliability. Non destructive damage detection can be active and passive. If the structure have embedded sensors and monitoring could be done due to the impact caused by the outside, then it is called a passive monitoring system. This method requires the presence of trained staff that will monitor the reinforced concrete (RC) structure. However, if the structure has sensors and actuators, then this system is called active monitoring system for structural damage detection. Development of the Wireless system made possible the monitoring of the structure without the presence of trained people on the structure. This type of monitoring provides the ability to monitor construction at any moment of time, reducing the cost and increasing speed of monitoring. The piezoelectric smart aggregate wave propagation structural health monitoring is the active monitoring system which has all the advantages mentioned above. In general, there are three major piezoelectric-based health monitoring approaches [2]:

1. The *impedance-based* health monitoring approach which is a real-time, qualitative damage detection method. The working principle is based on the electromechanical coupling property of piezoelectric materials.
2. The *vibration-characteristic approach* utilizes piezoelectric actuators to generate certain waves, which propagate within the structure, and compares the structural vibration-characteristic parameters (modal shape, model frequency), vibration-characteristic response curves (sweep sine or tone burst

response) or transfer function with those of the healthy state in order to detect damage.

3. Lamb wave-based health monitoring approach is used with PZT patches surface bonded to the structure to detect structural damage by generating a Lamb wave and monitoring its reflections. However, this approach is not suitable for concrete structures, which have complex geometries and are usually not thin-shell structures.

3. APPLICATIONS OF PZT SA WAVE PROPAGATION BASED METHOD

A large number of experimental studies of crack detection in reinforce concrete beam elements has been done in recent years. Smart aggregates (SA) were used as piezoelectric actuators and sensors. SA is thin piezoelectric (PZT) patch protected of water by some insulation and embedded in small mortar or concrete block (Figure 1) [1].

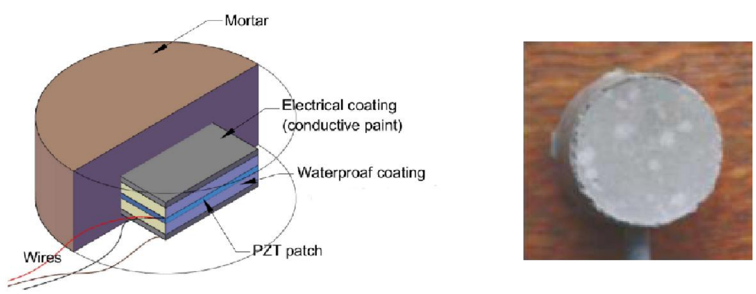

Figure 1. left - PZT SA layers, right - Fabricated smart aggregate.

Because of its piezoelectric properties, the SA can be used as the actuator (indirect piezoelectric effect) and as a sensor (direct piezoelectric effect). Indirect piezoelectric effect can be describe as mechanical deformations of piezoelectric materials caused (generated) by electrical charge, or conversely, mechanical deformation (or displacement) of piezoelectric element caused by applied electrical filed as direct piezoelectric effect. This feature allows active monitoring of RC beam elements with far less number of PZT paths and different configurations of actuator-sensors.

One piezoelectric smart aggregate is used as an actuator to excite the wave propagation and others SA are used as sensors to detect incoming wave. PZT SA is attached to reinforcement at the desired points in the reinforced concrete beam, so that after casting concrete in formwork, the SA will retain the same position and orientation (Figure 2-left). If in the beam cracks do not occurred, the wave propagation is carried out smoothly and the energy of the signal output is largest possible for that actuator-sensor configuration. But, if cracks appear in RC beam, the wave propagation distorts and the energy of incoming wave decreases. By monitoring the energy of signal output, it is possible to follow in time the occurrence and development of cracks in reinforced concrete beam. Figure 2-right shows one reinforced concrete beam prepared for the experimental analysis of crack detection using piezoelectric SA and based on the wave propagation [1].

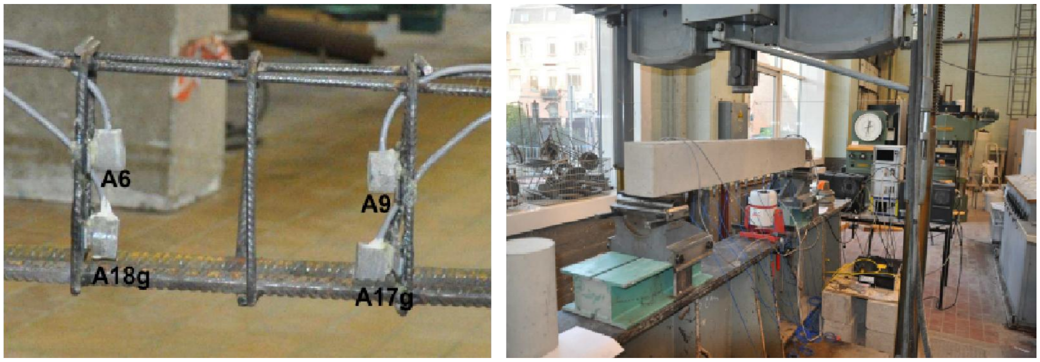

Figure 2. left - Attached PZT SA, right - Experimental research.

4. NUMERICAL MODELING

Development of personal computers to the current level, that allows to any scientific worker to calculate serious (numerically demanding) analysis, led to the fact that it is possible to do a large number of numerical simulations for a relatively short time period. This expend of numerical analysis makes possible the development of new methods for detecting damage and active monitoring system that first are performed numerically and later are confirmed experimentally. Some of the commonly used mathematical models from this tasks are the finite element methods (FEM), finite difference methods (FDM), boundary element methods (BEM) and spectral finite element methods (SFEM). FEM methods has the advantages compared to other methods: after application of commercial software availability (ABAQUS, ANSYS, etc.); it is easy to modelling of different geometric shapes, modelling of cracks and their propagation, etc.
For damage detection based on wave propagation the largest problem is how to efficiently create numerical model of wave propagation. FEM method provides the possibility of modelling the wave propagation by implicit and explicit methods. The starting point is the basic equations of dynamic equilibrium:

$$M\ddot{U} + C\dot{U} + KU = R \tag{1}$$

where M, C, K are the mass, damping and stiffness matrices; R is the vector of externally applied loads; and U, $\dot{U}$ and $\ddot{U}$ are the displacement, velocity and acceleration. The procedure that can be very effective in the solution of wave propagation modelling lays in is the central difference method with lumped mass matrices, in which it is assumed that:

$$\ddot{U}^t = \frac{1}{\Delta t^2}\left(U^{t-\Delta t} - 2U^t + U^{t+\Delta t}\right) \tag{2}$$

$$\dot{U}^{t} = \frac{1}{2\Delta t}\left(U^{t+\Delta t} - U^{t-\Delta t}\right) \tag{3}$$

Substituting the relations for $\ddot{U}^{t}$ and $\dot{U}^{t}$ in (2) and (3), respectively, into (1), could be obtained:

$$\left(\frac{1}{\Delta t^2}M + \frac{1}{2\Delta t}C\right)U^{t+\Delta t} = R - \left(K - \frac{2}{\Delta t^2}\right)U^{t} - \left(\frac{1}{\Delta t^2}M - \frac{1}{2\Delta t}C\right)U^{t-\Delta t} \tag{4}$$

where is possible to solve $U^{t+\Delta t}$. To calculated displacement in time step $t+\Delta t$ could be used for values from previous step t and for this reason this method is call explicit finite element method. This integration method do not required a factorization of the stiffness matrix in the step-by-step solution [3]. Unlike implicit method, where mass matrix must be performed for the whole system and the calculation of its has to be in inverse form, in explicit method it is much simpler. An explicit method is very easy and fast to resolve of a large number of steps, so it is possible to do a simulation of wave propagation with very small time step. This approach provides a satisfactory level of solution accuracy in very short calculation time.

5. QUANTITATIVE EVALUATION OF DAMAGE

Various kinds of damages methods have been developed for health monitoring of civil engineering structures in recent years. Root mean-square deviation (RMSD) is a commonly used damage index in relation to compare the difference between the signal outputs of healthy and damaged RC beam states:

$$RMSD = \sqrt{\frac{\sum_{j=1}^{2^n}(E_{i,j} - E_{h,j})^2}{\sum_{j=1}^{2^n} E_{h,j}^{\ 2}}} \tag{5}$$

where $E_{i,j}$ is energy vector for damage state and $E_{h,j}$ is energy vector for healthy reinforce concrete beam.

6. CONCLUSIONS

Active monitoring systems of reinforced concrete in the future will have a growing importance because of its comparative advantages compared to other methods and technology development. Experimental research has demonstrated that PZT SA damage detection method is active monitoring system which has characteristics of simplicity, low cost, quick response and high reliability. Numerical analysis is becoming more significant in relation of aspect of research in developing of new or improving existing monitoring systems. PZT SA active monitoring systems is currently very poorly represented in the real civil engineering structures. All current applications are mainly based on the test experiments, but the practice will probably change this in the future.

REFERENCES

[1] C. Dumoulin, G. Karaiskos, A. Deraemaeker: *" Monitoring of crack propagation in reinforce concrete beams using embedded piezoelectric transducers"*, VIII International Conference on Fracture Mechanics of Concrete and Concrete Structures, FraMCoS-8, Toledo, Spain, march 2013.
[2] G. Song, H. Gu, Y.L. Mo: „Smart aggregates: multi-functional sensors for concrete structures – a tutorial and a review", Smart materials and structures, vol. 17, 2008.
[3] Klaus-Jurgen Bathe: *"Finite element procedures"*, Prentice-Hall, 1996.
[4] M. N. Hassoun, A.A. Manaseer: *„Structural Concrete – Theory and Design"*, John Wiley & Sons, 2008.
[5] D. Stojić, T. Nestorović, N. Marković: *"The application of piezoelectric transducers in the structural health monitoring of reinforce concrete structures"*, International Multidisciplinary Scientific GeoConcference SGEM 2012, June 2012, Bulgary, pp 641-647.
[6] B. Hu, T. Kundu, W. Grill, B. Liu and V. Toufing: *"Embedded Piezoelectric Sensors for Health Monitoring of Concrete Structures"*, ACI Materials Journal, 2013.
[7] N. Marković, D. Stojić, T. Nestorović: „Damage Detection of Steel Structures with Piezoelectric Transducers and Lamb Waves", PhIDAC, Niš, September 2012, pp 353-358.

ДЕТЕКЦИЈА ПРСЛИНА У АРМИРАНО БЕТОНСКИМ ГРЕДНИМ ЕЛЕМЕНТИМА ПОМОЋУ ПИЕЗОЕЛЕКТРИЧНИХ СЕНЗОРА

Резиме: *Детекција прслина код армирано бетонских (АБ) гредних елемената помоћу недеструктивних метода је веома захтеван задатак због физичко-механичких особина материјала. Прслине у бетону могу да настану због више разлога, који могу да се групишу у механичко оптерећење или утицаје спољашње средине. Одређивање тачног узрока настанка прслина, броја прслина, њихове орјентације и места настанка у многим случајевима је готово немогуће. Детекција прслина у АБ помоћу пиезоелектричних сензора, а на бази пропагације таласа, је једна од недеструктивних метода која је представљена у овом раду. Принципи и примена ове активне методе мониторинга АБ конструкција је приказана у овом раду. Моделирање метода детекције оштећења помоћу методе коначних елемената (МКЕ) је веома битна за нумеричку симулацију овог проблема.*

Кључне речи: *Мониторинг, пиезоелектрични сензори, армирани бетон, прслине, метод коначних елемената.*