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Structural Health Monitoring using Piezoceramic Based Smart Aggregates

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Abstract

Structural Health Monitoring (SHM) is an important issue in the field of civil engineering especially large infrastructures. In this project, an innovative piezoceramic based approach is developed for the structural health monitoring of various structures. The piezo-electric property of the PZT is used for Structural Health Monitoring and Damage detection. A ceramic based piezoelectric material PZT (Lead Zirconate Titanate) and piezoceramic based disc is used for compressive and seismic stress monitoring. Piezoelectric material converts the mechanical strain applied on it into electric charge, and vice-versa. Hence, both the properties will be used alternatively in actuator and sensor. The results will be used for damage analysis and categorization.
Keyword- SHM, Piezoelectric, Damage detection, Concrete

I. INTRODUCTION

Concrete is such a widely used building material around the world, it is important to monitor its health to prevent disaster. The idea of imbedding PZT patches in concrete is still relatively new. PZT patches can be an effective way to measure concrete health. However, the lack of mass production techniques makes it hard to be installed in numerous structures.

The piezoelectric effect is a useful way to monitor the health of cast concrete. PZT patches can be embedded in small concrete blocks called a “smart aggregate” then cast in larger structures for concrete strength monitoring. They are designed to monitor the early age concrete strength development, impact detection and structural health. Piezoceramic materials exhibit the phenomenon of piezoelectricity. Piezoelectricity describes the event of generating an electric charge in a material when subjecting it to mechanical stress, and conversely, generating a mechanical strain in response to an applied electric field.

Innovative piezoceramic-based devices, called smart aggregates, are used as transducers for the structural health monitoring of reinforced concrete columns under a cyclic loading procedure. The proposed smart aggregates are low-cost, piezoceramic-based multi-functional devices, capable of performing comprehensive monitoring of concrete structures, including early-age strength monitoring, impact detection and evaluation, and structural health monitoring. For structural health monitoring purposes, a smart aggregate-based active sensing system was developed. In the proposed active sensing system, one smart aggregate is used as an actuator to generate a sweep sine signal, while the other smart aggregates are used as sensors to detect the signal response. The propagation energy of the waves will be attenuated by cracks in the concrete structure. By analyzing the sensor signal, the health status of the concrete structure is evaluated. In the proposed health monitoring approach, wavelet packet analysis is used as a signal-processing tool.

II. STRUCTURAL HEALTH MONITORING

A. General

Civil infrastructure systems are valuable national assets that require proper maintenance to ensure public safety and a high quality of life. the condition of our current aging infrastructure and recent natural disasters highlight safety as a current primary concern, calling for efficient inspection and maintenance operations. Structural Health Monitoring (SHM), the research area focusing on condition assessment of different structures, offers a proactive approach to monitoring the state of our infrastructure, aiding in both safety and sustainability.

While many formal definitions of SHM have been proposed, the one most suitable to this study defines SHM as the measurement of the operating and loading environment, as well as the critical responses of a structure to track and evaluate the symptoms of incidents, anomalies, damage and/or deterioration that may affect operation, serviceability, or safety and reliability (Aktan et al. 2000).

In recent years, there has been an increasing awareness of the importance of damage prognosis systems in aerospace, civil and mechanical structures. It is envisaged that a damage prognosis system in a structure would apprise the user of the structure’s health, inform the user about any incipient damage in real-time and provide an estimate of the remaining useful life of the structure.

B. Scope

A structure can be monitored during its whole lifetime, from construction to operation and finally to demolition. SHMS can be incorporated into a new structure when integrated prior to construction or added afterwards to existing structure. Several factors benefited for intense development in Structural Health Monitoring (SHM) and sensory technology. Shortened construction periods, increased traffic loads, new high speed trains causing new dynamic and fatigue problems, increased traffic loads and quantities, new materials, new construction solutions, slender structures, limited economy, need for timesaving etc. are factors that demand better control and makes SHM as a necessary tool in order to manage, maintain and also be able to guarantee the quality and safety for end-users.

The use of structural health monitoring technologies will not only provide safety benefits or enable new possibilities for maintenance concepts, but can also have a significant influence on the design concepts. The change in design of lightweight structures from a safe life to a damage tolerant design supported by a monitoring system is, although far from reality, also considered as a potential weight-saving benefit. After the occurrence of any catastrophic events such as earthquake and explosions there is no quantifiable method to check whether the buildings are safe to reoccupy or the bridges are safe to use (Farrar and Worden, 2006)

C. Benefits

The potential benefits that would accrue from such a technology are enormous. Below are some to mention.

- The maintenance procedures for structures with such systems could change from being schedule-driven to condition-based, thereby cutting down on the time period for which structures are offline and correspondingly resulting in cost-savings and reducing their labor requirements.
- Operators could also possibly establish leasing arrangements that charge by the amount of system life used during the lease instead of charging simply by the time duration of the lease.
- The condition of the structure after any natural calamity like Earthquake can be precisely determined and necessary actions can be taken.
- They potentially can reduce the maintenance costs and increase the operational availability of a system.
- Moreover, most importantly, the safety of the users of the structure is better ensured.

III. PIEZOELECTRICITY

Piezoelectricity can be defined as an event of generating an electric charge in a material when subjected to mechanical stress, and conversely, generating a mechanical strain in response to an applied electric field.

The direct piezoelectric effect was discovered when electric charges were created by mechanical stress on the surface of tourmaline crystals. This discovery was not by chance; rather such an effect was anticipated by the Curie brothers from consideration of crystal structure and the pyroelectric phenomena (thermo-electric coupling effect) (Cady, 1964). However, it was through thermodynamic reasoning which led Lippman to predict the converse piezoelectric effect that prompted the Curie brothers to discover it shortly after.

The first major practical application of piezoelectric materials came in the Great War where it was used as resonators for ultrasound sources in sonar devices. Since then development of the materials has led to new and better types of piezoelectric materials such as Barium Titanate and recently in the field of smart structures, piezoceramics and piezopolymers. Even more recently, breakthrough in single crystal growth technique has enabled the development of high strain and high electric breakdown piezoceramics. The advantages of piezoelectric materials being used as sensors and actuators include ease of integration into existing structures, easily controlled by voltage, low weight, low power requirements, low-field linearity and high bandwidth (allowing large range of applications).

A. Manufacturing

Piezoelectric materials can be natural or man-made. The most common natural piezoelectric material is quartz (see next section for more details), but man-made piezoelectric materials are more efficient and mostly ceramics. Due to their complex crystalline structure, the process with which they are made is very precise and has to follow very specific steps. As explained in Electroceramics: Materials, Properties and Applications [5], to prepare a piezoelectric ceramic, "fine PZT powders of the component metal oxides are mixed in specific proportions, then heated to form a uniform powder. The piezo powder is mixed with an organic binder and is formed into structural elements having the desired shape (discs, rods, plates, etc.). The elements are fired according to a specific time and temperature program, during which the piezo powder particles sinter and the material attains a dense crystalline structure. The elements are cooled, then shaped or trimmed to specifications, and electrodes are applied to the appropriate surfaces." However, piezoelectric material exhibits an electric behavior and acts as a dipole only below a certain temperature called Curie temperature. Above the Curie point, the crystalline structure will have a simple cubic symmetry so no dipole moment (see first sketch of Figure 1). On the contrary, below the Curie point, the crystal will have tetragonal or rhombihedral symmetry hence a dipole moment.

In order for the material to be polarized, it is exposed to a strong and direct current electric field whose goal is to align all dipoles in the material. Of course this transformation has to be made below the Curie point so that dipoles are present. Thanks to this polarization, the material gets its dipoles almost aligned with the electric field and now has a permanent polarization. This permanent polarization is the remanent polarization after the electric field is removed, due to a hysteretic behavior.

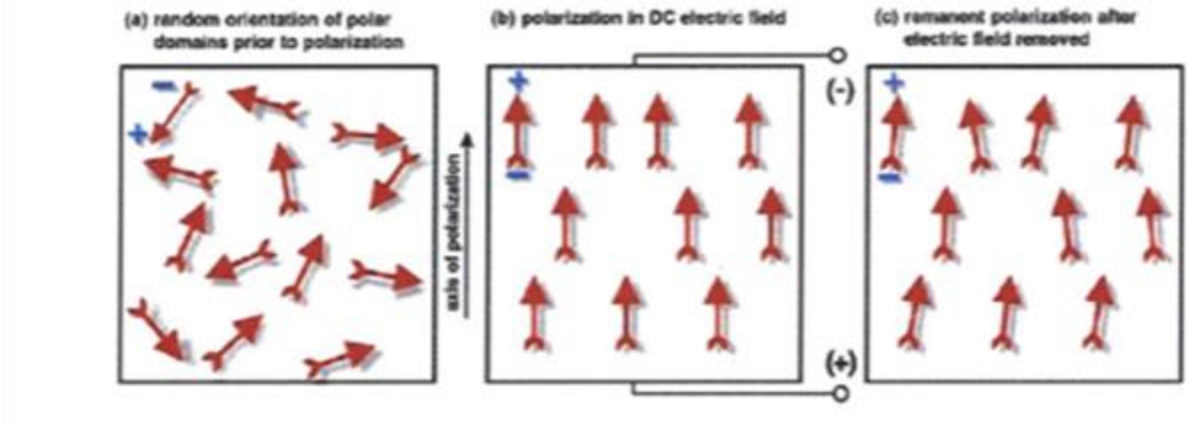

Fig. 1: Poling Of Piezoelectric Material

IV. TEST SETUP

Our material for this test was Piezo-disc which is cheaply available. It was bought from local electronics store at Surat. The disc was soldered to a standard gauge electric communication wire which was also local standard. The other end was open for connection with measuring devices such as Multimeter or CRO meter. We used a standard 15x15x15 cm^3 cube mold and grease for lubrication. A mold with piezoelectric disc was finished as shown in figure. The piezo-disc was placed keeping its axis in the direction of load application. The concrete grade was M25 and it was tested by UTM.

Fig. 2: Piezodisc Cube 1

Another cube was also made for Damage analysis using Frequency Generator for actuator and CRO meter for sensor chip. This cube was also of M25 Grade and cured for 7 days. This cube was tested for zero damage. It is further to be tested for after damage analysis. The results will be used for damage Index calculation as per formula given by Yashar Moslehy, Haichang Gu, Abdeljalil Belarbi, Y.L. Mo and Gangbing Song[12]

A wavelet is a waveform of effectively limited duration that has an average value of zero. The advantage of the wavelet packet analysis is that it enables the inspection of relatively narrow frequency bands over a relatively short time window. In the proposed structural health monitoring algorithm, the sensor signal S is decomposed by an n-level wavelet packet decomposition into 2n signal sets. Xj is expressed as

$$Xj = [x_{j,1}\ x_{j,2}\ \dots x_{j,m}]$$

Where m is the amount of sampling data. The energy of the decomposed signal is defined as

$$E_{i,j} = \|X_j\|_{\wedge 2}$$

In the proposed approach, a wavelet-based damage index is formed by calculating the Root Mean Square Deviation (RMSD) between the energy vectors of the healthy state and the damaged state.

The proposed damage index at time i is defined as

$$I = \sqrt{\sum_{j=1}^{2^n} (E_{i,j} - E_{h,j})^2 \Big/ \sum_{j=1}^{2^n} E_{h,j}^2} .$$

Where $E_{i,j}$= The energy of the decomposed signal, $E_{h,j}$= The energy vector for healthy state

Fig. 3: Test Cube 2

A. Results

The first test was for the feasibility of the use of piezodisc in concrete which gave positive results. The concrete strength was not compromised and the chip gave a voltage spike on strain.

Concrete Grade	*M25*
Strength of concrete detected by UTM	*20 N/mm²*
The current rise detected at	*14 N/mm²*
Initial Multimeter reading	*40μA*
Final Multimeter reading	*600μA*

The second cube was tested for zero damage analysis and results have indicated the zero damage pattern. The cube will be further tested for post-damage analysis and damage index detection.

V. Conclusions

- Our research concluded that it is possible to build smart aggregates cheaply and efficiently.
- Our testing showed that the smart aggregates imbedded in the concrete cubes had no negative effect on the ultimate strength.
- A wavelet-packet-based damage index and a sensor-history damage index matrix were developed to evaluate the damage status based on the attenuation of the transmitted wave.
- Further tests are required for successful interpretation of behavior of piezoelectricity and application for practical purposes.

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