# STONE BASED SMART AGGREGATE FOR STRUCTURAL HEALTH MONITORING OF RC COLUMNS UNDER SEISMIC EXCITATIONS

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## ABSTRACT

Health monitoring of reinforced concrete structures has received considerable attention in recent years. Rather than using traditional inspection methods (x-ray, C-scan, etc) In this paper , health monitoring of RC column specimen subjected to seismic excitations is studied using embedded piezoelectric transducer PZT. PZT (Lead Zirconium Titanate) has piezoelectric effect(the generation of electricity when stress is applied and vice versa). During the experiment, one embedded PZT patch is used as an actuator to generate high frequency waves, and the other PZT patches are used as sensors to detect the propagating waves. With the increasing number and severity of cracks, the magnitude of the sensor output decreases. Wavelet packet analysis is used to analyze the recorded sensor signals. A damage index is formed on the basis of the wavelet packet analysis. The experimental results show that the existence and severity of cracks inside the concrete structure under seismic excitations created by cyclic load through actuator.

**Keywords:** PZT, actuator, sensor, piezoelectric effect, Wavelet packet analysis, damage index.

## 1. Introduction

Most infrastructure construction is made of concrete and reinforced concrete, and it is generally a very expensive national investment. Concrete structures have a long service life compared to other mechanical, electrical and electronic commercial products. Further, like all construction materials, concrete structures also age and deteriorate with time, the deterioration of concrete and reinforced concrete can arise from a number of sources such as aging of the material, exposure to aggressive environmental conditions, excessive use, overloading, insufficient maintenance and lack of proper inspection methods and repair strategies. All these factors lead to a progressive degradation of the structure as internal and external. Damages develop and progress to affect its safety and structural integrity. The development and implementation of damage detection strategies, and the continuous health assessment of concrete structures then become a matter of utmost importance. A wide variety of very effective classical non-destructive methods of inspection and monitoring the serviceability performance of concrete structures have been used in the past and reported in literature. However, many of these methods are often cumbersome, and suffer from many practical difficulties. On the other hand, smart materials/sensors, such as fibre optic sensors, piezoelectric materials and magnetostrictive sensors, offer a more integrated structural health monitoring system which can provide continuous and on-line techniques to detect the location and extent of damages in concrete structures. Piezoelectric ceramics have the advantage that they can work as both transmitter and receiver of ultrasonic waves. They have been made available as small plates of different thickness, and can be cut to sensors of arbitrary geometry

## 2. Smart Aggregate In Health Monitoring Of Concrete

### 2.1 PZT - LEAD ZIRCONIUM TITANATE

PZT, or lead zirconate titanate (Pb[Zr(x)Ti(1-x)]O3), is one of the world's most widely used piezoelectric ceramic materials. When fired, PZT has a perovskite crystal structure, each unit of which consists of a small tetravalent metal ion in a lattice of large divalent metal ions. In the case of PZT, the small tetravalent metal ion is usually titanium or zirconium. The large divalent metal ion is usually lead. Under conditions that confer a tetragonal or rhombohedral symmetry on the PZT crystals, each crystal has a dipole moment.

PZT materials ,and piezoelectric materials more generally, exhibit a unique range of properties. In a basic sense, if a piezoelectric material is deformed, an electric charge is generated in what is known as the piezoelectric effect. The opposite of this phenomenon also holds true: If an electric field is applied to a piezoelectric material, deformation occurs in what is known as the inverse piezoelectric effect.

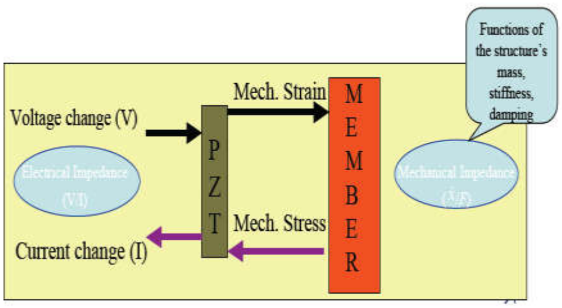



**Fig:1 Piezoelectric Effect Of PZT**

PZT is a metallic oxide based piezoelectric material developed by scientists at the Tokyo Institute of Technology around 1952. In comparison to the previously discovered metallic oxide based piezoelectric material Barium Titanate (BaTiO3), PZT materials exhibit greater sensitivity and have a higher operating temperature.

In PZT plates, the major faces are electroded. When these plates are to be glued to a surface / structure, one has to provide electrical connections to the bonded surface also. In order to facilitate electrical connections on one side, the bottom electrode (which is bonded to the structure) is brought to un-bonded surface so that both the lead-wires are connected on one side.

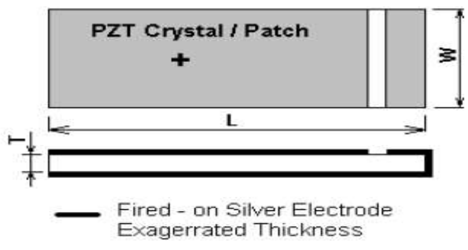



**Fig:2 Geometry Of PZT**

The maximum operating field of SP-5H is as follows:
AC(rms) – 80V/mm; DC (forward) 400 V/mm; DC (Reverse) 200 V/mm.The voltage ratings are Volts per 1mm thick crystal. Thus if the crystal is 0.4mm thick, the max AC operating field would be 80 x 0.5 = 40 volts, rms. The PZT patches can be glued on to the structure using structural Araldite epoxy-resin available in the market. Recommended Grade AV138M/HV 998.

## 2.2 Fabrication Of Sensor Into Stone Based Smart Aggregate

The proposed SA consists of a piece of PZT patch connected with a piece of two-wire cable and a pair of marble blocks. The commercially available soft PZT ceramic referred to as P-5H with a major composition of Pb(TiZr)O3 was chosen. The PZT's properties, measured by the supplier, are listed in Table1 . Young'smodulus of the marble and the epoxy was 51.5GPa and 2.5GPa, respectively, as supplied by the manufacturer. The size of the PZT patch was 15 × 15 mm, and the thickness was 0.4 mm. The marble blocks were 25 × 25 × 12mm in size. When the marble blocks were aligned together along the 12mm long edge, a hole with a diameter of 3mm and depth of 10mm was bored to accommodate the cable and the soldering points on the PZT patch. Then the PZT patch was sandwiched between the marble-block pair with structural Araldite epoxy-resin. The calibration test had been conducted and showed that the SA had constant sensitivity at a relatively high stress level. Sensitivity obtained from the calibration test was 1.23 × 105 pC/MPa.

**Fig:3 Fabricated Smart Aggregate**

## 3. Materials And Specimen Used

### 3.1 Cement

Ordinary Portland cement of 53 grade available in local market is used in the investigation. The cement used has been tested for various properties as per IS: 4031-1988 and found to be confirming to various specifications of IS: 12269-1987 having specific gravity of 3.15

### 3.2 Fine Aggregate

Locally available clean, well-graded, natural river sand having fineness modulus of 2.66 conforming to IS 383-1970 was used as fine aggregate.

### 3.3 Coarse Aggregate

Crushed granite angular aggregate of maximum size of 12mm nominal size from local source with specific gravity of 2.66 was used as coarse aggregate.

### 3.4 Water

Locally available potable water conforming to IS 456 is used.

## 3.5 SENSOR USED-PZT

| PZT property | Value |
|---|---|
| Young's modulus (GPa) | 46 |
| Density (kg/m$^3$) | 7.45 |
| $d_{31}, d_{32}$ (pC/N) | −186 |
| $d_{33}$ (pC/N) | 670 |
| $d_{15}$ (pC/N) | 660 |

**Table:1 PZT property snapshot from the journal**

## 3.6 SPECIMEN USED

**FIG:4 RC Column Specimen**

**Fig:5 Column Setup Embeded With SA**

## 4. Experimental Setup And Loading Procedure

The experimental study was performed in order to investigate the seismic performance of column specimen. the damage detection has been studied by applying the cyclic load using servo-hydraulic test machine (MTS 810).

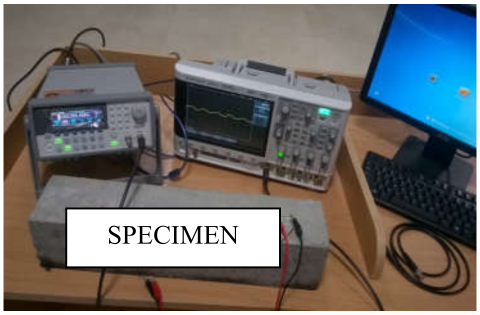



**FIG:6 SPECIMEN CONNECTED TO FUNCTION GENERATOR, DSO AND PC**

The wave propagation tests were conducted using the smart aggregates embedded at the three ends (one serving as actuator, and the others as sensor) for damage detection. A stress wave was generated by the embedded smart aggregate at one end and the response signal was captured by the smart aggregate at the other ends). Since the in-plane dimension of the thin square PZT plate actuator in its plane is much larger than its thickness, the major effect of PZT actuation is perpendicular to the beam length direction. Although both the compressive and shear waves are generated, it is anticipated that the captured shear wave is dominating in terms of signal magnitude.

An Agilent 33120A function generator was used to generate the tone burst excitation signal for actuator sensor. A power amplifier was used to amplify the excitation signal in order to drive the PZT actuator inside the smart aggregate. A HP 54603B oscilloscope was used to capture the response signal generated by the PZT sensors at the sampling frequency of 2 MHz. The captured response signal data was then transmitted into a laptop for damage detection analysis.

In function generator, it is set as sinusoidal and sweep waves. The sweep range used here is 750MHZ to 1KHz in the time period of 9s with 10v.

## 5. Damage Analysis

The sensor signal measured by a PZT sensor is decomposed into sub-signals by the wavelet packet algorithm. The energy of the decomposed signal is calculated to form the energy vector. The damage index is calculated by comparing the energy vector of healthy state with the energy vector of the damaged state.

### 5.1 Wavelet Packet Analysis

In this paper, the wavelet packet analysis is used as the signal processing tool to analyze the sensor signal of the embedded PZT patch in the concrete structures. In this study, the wavelet packet energy index is proposed to identify the locations and severity of damage. The formula used to split waveform is

$$E_{f_j^i} = \int_{-\infty}^{\infty} f_j^i(t)^2 \, \mathrm{d}t.$$

### 5.2 Damage Index By RMSD

Various kinds of damage indices have been developed for health monitoring civil structures in recent years. Rootmean- square deviation (RMSD) is a suitable damage index to compare the difference between the signatures of the healthy state and the damaged state.

In this paper, the damage index is formed by calculating the RMSD between the energy vectors of the healthy state and the damaged state. The energy vector for healthy data is denoted as $E_h = [E_{h,1}, E_{h,2}, \ldots, E_{h,2n}]$. The energy vector for the damaged state at time index $i$ is represented by $E_i = [E_{i,1}, E_{i,2}, \ldots, E_{i,2n}]$. The damage index at time $i$ is defined as

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

The proposed damage index represents the transmission energy loss portion caused by damage. When the damage index is close to zero, it means it is in a healthy state. When the damage index is bigger than a certain threshold, this means damage appears. In this case, the greater the index, the more serious the damage is.

## 6. Experimental Results

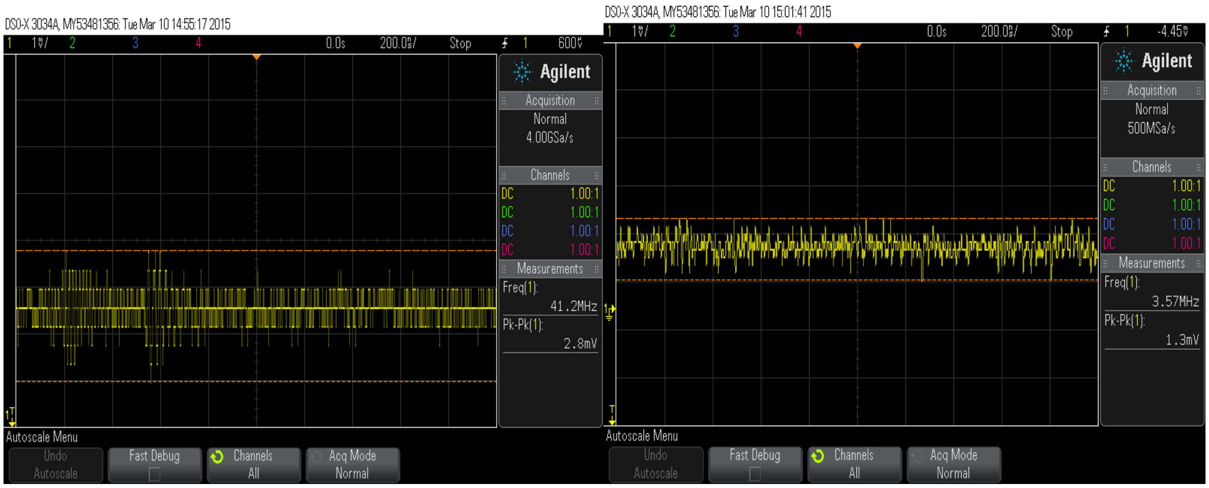
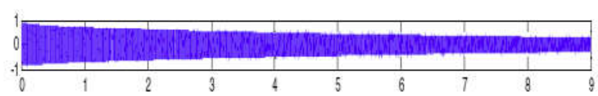
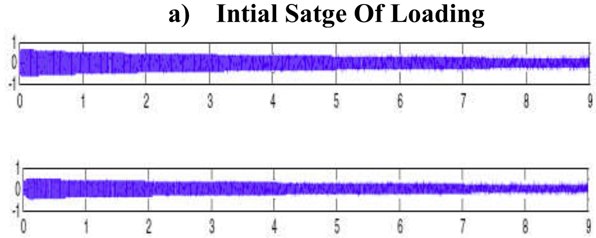



**Fig:7 Output From Oscilloscope**

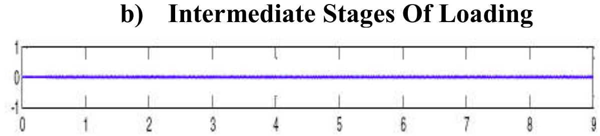
The magnitude of the PZT output, as a sensor, decreases with the increasing load value. The maximum senor output value in test 1 is close to 1 V, while that in later tests it is close to zero. This means that the concrete structure (testing specimen) was a good conduit for wave propagation in test 1, when the structure was healthy, and the wave propagation was almost totally block.



**a) Intial Satge Of Loading**



**b) Intermediate Stages Of Loading**



**c) Final Stage Of Loading**

**Fig:8 Result Showing Decrease In Voltage After Cyclic Loading Of Specimen At Each Step Taken By Dso.**

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In later test due to loading, damage occurs, in which the waves with lower frequencies attenuate much less than those with higher frequencies. For the time history response of the PZT sensor during each test, the magnitude decreases with time. Since the excitation signal was a sweep sine wave from a low frequency (750KHz) to a high frequency (2MHz) with respect to time, it can be concluded that the PZT sensor magnitude decreases with the increasing wave frequency, i.e., the waves with lower frequencies attenuate much less than those with higher frequencies.

A dramatic drop in sensor responses means dramatic increases in crack width, which is often caused by structural failure. It is noted that there is a dramatic reduction of the sensor output from test 6 to test 7, which means the damage in the structure, mainly cracks, became so severe.

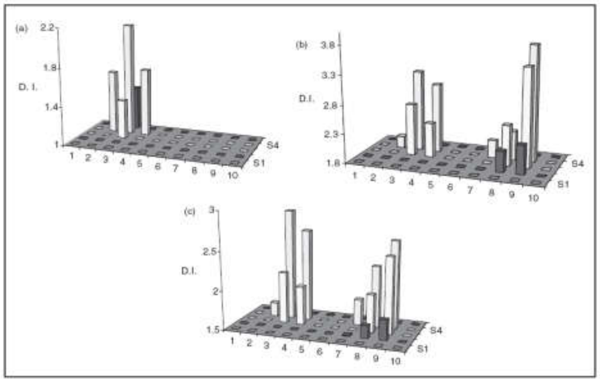

**Fig : 9 Graphical Results From RMSD**

## 7. Conclusion

This paper presents a new in situ PZT-based health monitoring approach for a RC column specimen. Piezoceramic patches (PZT) were embedded in the specimen prior to casting. The PZT patches were used as both actuator and sensors to detect possible internal cracks inside the reinforced concrete column. The proposed method has the ability not only to detect the existence of the cracks but also to monitor the growth of cracks. The critical state of damage indicated by the proposed method is earlier than that by LVDT and microscope, which proves that the proposed method is more sensitive and effective than the traditional methods.

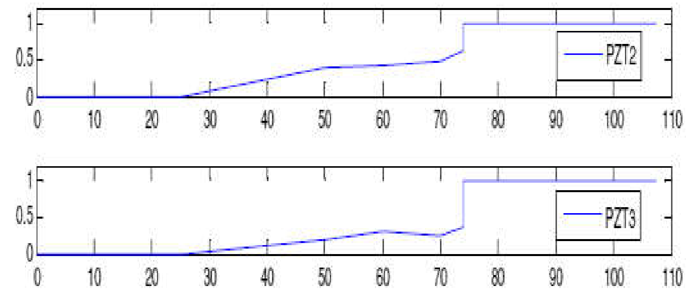


**Fig : 10 Crack Width Increased At Different Stages Of Loading (Extracted Result From Matlab)**

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