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Structural Health Monitoring using Smart Material and Smart System

Manjeet Singh
P.G. Student
Department of Civil Engineering
ITM College Lucknow, Uttar Pradesh, India

Abstract

There is a phenomenal rise in construction activities in the field of civil engineering in the recent years. Major structures like building, bridges, dams, are subjected to severe loading and their performance is likely to change with time. It is therefore, necessary to check the performance of a structure through continuous monitoring. If performance deviates from the design parameter, appropriate maintenance is required. The life of the structure depends on initial strength and the post construction maintenance. It is for this reason that the necessity of structural health monitoring (SHM) is emphasized worldwide. A technique is required for structural health monitoring (SHM), which should carry out continuous monitoring of structure, as well as sensitive and cost effective. These Unique properties of direct and converse piezoelectric effects enable piezo electrio-ceramic (pzt) patch to act both as anactuator and as a sensor simultaneously. Making use of the sensing capability the of PZT patch, conductance signature of the structure can be obtained against which health monitoring of the structure can be done. Signature of the structure in healthy state is called the base line signature. It is compared with signature obtained after a time lapse, which is called secondary state conductance signature. The characteristic feature of the EMI technique is that it activates higher frequency modes of the structure.

Keywords: Damage Detection, Electro-Mechanical Impedance Technique, Conductance signature, PZT Sensors

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I. INTRODUCTION

Health monitoring is the continuous measurement of the loading environment and the critical responses of a system or its components. Health monitoring is typically used to track and evaluate performance, symptoms of operational incidents, anomalies due to deterioration and damage as well as health during and after an extreme event (Aktan et al, 2000). A successful health monitor design requires the recognition and integration of several components. Identification of health and performance metric is the first Component which is a fundamental knowledge need and should dictate the technology involved. Current status and future trends to determine health and performance in the context of damage prognosis are reported by Farrar et al. in a recent study (2003).

A. *Need for Structural Health Monitoring:*

The objective of SHM is to monitor the in-situ behaviour of a structure accurately and efficiently, to assess its performance under various service loads, to detect damage or deterioration, and to determine the health or condition of the structure. The SHM system should be able to provide, on demand, reliable information pertaining to the safety and integrity of a structure. The information can then be incorporated into bridge maintenance and management strategies, and improved design guidelines.

There are various advantages and positive ramifications of including Structural Health monitoring in civil structures.

1) Confirm the design parameter: Detection of damages during construction which can cause any change in properties than expected by design.
2) 2. Quality Assurance: By providing continuous and quantitative data, a monitoring system helps you in assessing the quality of your structure during construction, operation, maintenance and repair, therefore eliminating the hidden costs of damages caused by non-achieving the required designed standards.
3) 3. Complex Structures are well managed: Learning how a structure performs in real conditions will help you to design better structures for the future. When new materials, new technologies and methods are involved in construction monitoring is an effective way to know the real behaviour.
4) 4. To Ensure safety of people, nature and property: Early detection of performance degradation can save lives and property in time by stopping exploitation and access to the structure. This guarantees the safety of the structure and its users. It also gives us a way to assess the possible damages after a natural calamity or any other type of major event which can affect the structural properties and condition.
5) 5. Monitoring reveals hidden resources: Many times the structure performance is better than what it is designed for and this gives an extra freedom to play with for further designs and construction.
6) In effect, SHM:
   - allows an optimal use of the structure, a minimized downtime, and the avoidance of catastrophic failures,

- gives the constructor an improvement in his products,
- drastically changes the work organization of maintenance services:

1) by aiming to replace scheduled and periodic maintenance inspection with performance-based (or condition-based) maintenance (long term) or at least (short term) by reducing the present maintenance labor, in particular by avoiding dismounting parts where there is no hidden defect;
2) By drastically minimizing the human involvement, and consequently reducing labour, downtime and human errors, and thus improving safety and reliability.

Economically Structural health monitoring process is also very reasonable and is synonymous to buying an insurance policy for your health. One protects the individual, his/her depending family and finally gives a peace of mind. The same is true for SHM Policy, which gives a much more personal, local and national image for sustainability.

- The cost of installing a system and doing Health monitoring at a given time like construction or repairs is 0.5% to 3% of the total construction or repair costs respectively.
- The cost of doing Structural Health Monitoring for a period of 10 years is 2% to 5% of total structures building cost.
- The economic motivation is stronger, principally for end-users. In effect, for structures with SHM systems, the envisaged benefits are constant maintenance costs and reliability, instead of increasing maintenance costs and decreasing reliability for classical structures without SHM (see Figure 1.1)

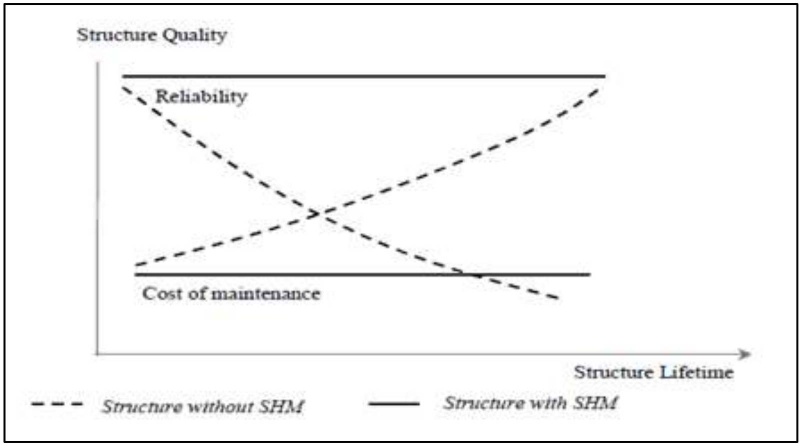


Fig. 1.1: Benefit of SHM for end-users

B. Process and Pre-Usage Monitoring as a Part of SHM:

Sensors for Health Monitoring can be incorporated into the components during the manufacturing process of the composite. Thus, in a global approach including the processing stage, the sensors can be used first of all to monitor the processing parameters in order to optimize the initial properties of the material. The physical parameters of the material that can be monitored during the process are varied: refractive index, visco-elastic properties, conductivity, etc. A range of techniques is available allowing their on-line monitoring: electrical techniques, electro-mechanical impedance techniques using embedded piezo-patches, acoustic-ultrasonic (or optical techniques using fibre-optic sensors. It could be interesting to mix such different sensors achieving multi detection.

There is an intermediate phase of the life of a structure that can need SHM too: between the end of the manufacturing process and the beginning of the functioning phase, for certain structures, a lot of handling and transportation operations take place. During this phase, which could be called the pre-usage phase of the structure, accidental loads, not known by the end-user, may occur and threaten the structure’s reliability.

C. Status and Need of SHM, India:

1) Residential Buildings and Commercial Structures India have received very less almost inexistent focus on structural health monitoring primarily due to owners not knowing about its availability and poor knowledge about them. In these cases SHM can only be made possible and implemented in these structures after some efforts have been made to make them aware and educate them or forcing them into it by legally making rules. Some insurance plans can also be worked out for them.
2) Dams In India dams are majorly owned by state government or the agencies governed by state government. A Report on dam safety procedures has revealed that on the instrumentation side, which is vital for monitoring of dam safety, there appears to be a communication gap between the officer-in-charge of design / construction and officers who take over maintenance. There are many instances where the officers in charge of maintenance are not aware of the instrumentation proposal that has gone into the dam and there exist many missing links. The initial readings of the instrument are rarely available for an instrument embedded in the dam, the absence of which has made subsequent analysis difficult.
3) Bridges are important lifeline structures, it is important for them to have elaborated inspection and maintenance programmes. Static and Dynamic Load testing’s carried out in today’s bridges to satisfy the IS codes and safety measures.

These tests are carried only during major events in the bridge lifespan especially the construction time and major repairs & retrofitting. Apart from this Permanent & Continuous monitoring are required for majority of bridges to prevent any human loss. These can be also useful to assess the distress during or following any major event like earthquake, landslides, storms etc.

Some work of installing advance Structural Health Monitoring has been done in India on very few bridges. One of the bridges is Naini Bridge over Yamuna River at Allahabad. This was probably the first installation of fully standalone new generation GPS combined with advance post processing software to continuously monitor the bridge for various changes in climate and operations with high accuracy for example 3D absolute deflections can be measured up to mm accuracy. This work was carried out by COWI/ Devcon Infrastructure Pvt. Ltd. But this kind of work has to be carried over all important bridges for their better understanding and safety.

D. *Research Objective:*

There is a phenomenal rise in construction activities in the field of civil engineering in the recent years. Major structures like building, bridges, dams, are subjected to severe loading and their performance is likely to change with time. It is therefore, necessary to check the performance of a structure through continuous monitoring. If performance deviates from the design parameter, appropriate maintenance is required. The life of the structure depends on initial strength and the post construction maintenance. It is for this reason that the necessity of structural health monitoring (SHM) is emphasized worldwide. A technique is required for structural health monitoring (SHM), which should carry out continuous monitoring of structure, as well as sensitive and cost effective.

II. TECHNIQUES OF HEALTH MONITORING

There are various approaches for addressing the problem of health monitoring and damage detection in structures. Basic principle is that any flaw/ damage change the characteristics/ response of the structure. Researchers have proposed various techniques based on different kinds of structural characteristics or responses. The various methods reported in the literature can be broadly classified into the following categories:

1) Global static response based techniques
2) Global dynamic response based techniques
3) Local damage detection techniques
4) Techniques using ‘smart materials’ and ‘smart system’ concept.

The following sections describe briefly the major developments in recent years in all the above mentioned areas.

A. *Global Static Response Based Techniques:*

A technique based on static displacement response was formulated by Banan et al. (1994). The technique involves applying static forces to the structure and measuring the corresponding displacements. It is not necessary to select entire set of forces and displacements. Any convenient subset may be selected. However, several load cases might be necessary to obtain sufficient information. The resulting equations have to be solved recursively to arrive at a set of member constitutive properties or the structural parameters. Any change in parameters from the baseline healthy state gives the indication of the presence of damage. The method has a number of shortcomings, particularly in the way of practical implementation. Measurement of displacements on a large-scale structure is not an easy task. As a first step, one needs to establish a frame of reference. For contact measurements, this can entail the construction of a secondary structure on an independent foundation. Employing a number of load cases can be very time-consuming. Also, the method requires a lot of computational effort. Sanayei and Saletnik (1996) proposed a technique based on static strain measurements. The advantage of this technique over the previous one is that strain measurements can be made with a higher degree of precision as compared to displacements. In addition, the establishment of an independent frame of reference is also circumvented. Strains on the surface are caused by both bending and axial deformations, and therefore are able to capture the element behavior well. However, like the displacement approach, this technique is also based on the least squared minimization of strain error function.

B. *Global Dynamic Response Based Techniques*

In these techniques, the test-structure is subjected to low-frequency excitations, either harmonic or impulse, and the resulting vibration responses (displacements, velocities or accelerations) are picked up at specified locations along the structure. The vibration pick-up data is processed to extract the first few mode shapes and the corresponding natural frequencies of the structure, which, when compared with the corresponding data for the healthy state, yield information pertaining to the locations and the severity of the damages. A damage in a structure alters its modal parameters such as modal frequencies, modal damping, and mode shapes associated with each modal frequency. Changes also occur in structural parameters, namely stiffness and damping matrices. These techniques have obvious advantages over the static response techniques and they are easy to implement. Even the ambient vibration data can be utilized to derive modal data.

Depending upon the modal parameters employed , these techniques can be divided into following types

1) Based on frequency change

2) Based on mode shape change
3) Based on mode shape curvature/strain mode shape change
4) Based on dynamically measured flexibility
5) Based on updating structural modal parameters
   - Optimum matrix update method
   - Sensitivity based update method
   - Eigen structure assignment method

Zimmerman and Kaouk (1994) developed “change in stiffness method” based on this principle. It identifies changes in the structural stiffness matrix resulting from damage. The stiffness matrix [K] is determined from mode shapes and modal frequencies derived from the measured dynamic response of the structure, as

$$[K] = [M][\Phi][\Omega][\Phi]^T[M] = [M]\left(\sum_{i=1}^{n} \omega_i^2 \phi_i \phi_i^T\right)[M] \qquad (1)$$

where [M] is the mass matrix and [Φ] the mode shape matrix. n is the total number of modes considered. Let [Δ K] represents the change in stiffness matrix due to damage. The indicator of damage in this method is a damage vector defined by

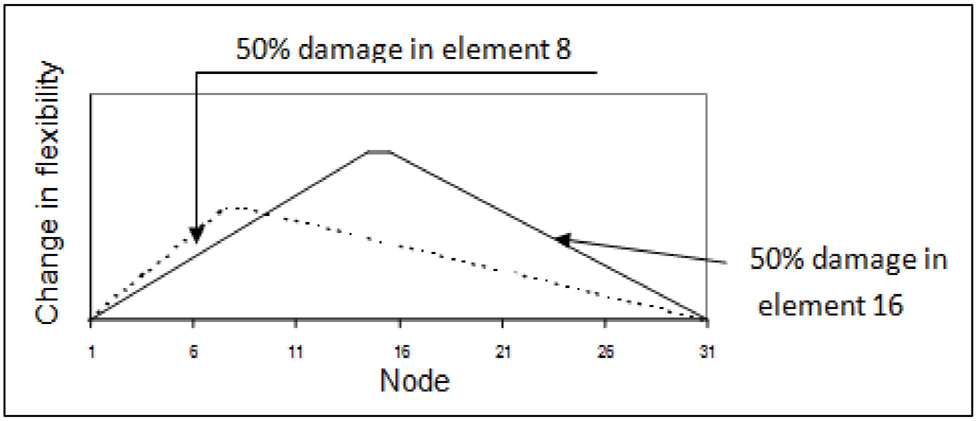
$$[D_i] = [\Delta K][\phi_i] \qquad (2)$$

where $[D_i]$ is the ith damage vector obtained from the ith mode shape vector $[\phi_i]$. The location of damage is indicated by the maximum parameter in the damage vector.

This method has a significant drawback. Higher modes are more important in the estimation of stiffness matrix, as can be seen from Eq. (1). The modal contribution to [K] increases as the modal frequency increases. Unfortunately, the dynamic vibration testing can yield only first few mode shapes. Hence, the estimated [K] is likely to be inaccurate.

This problem was addressed by Pandey and Biswas (1994), who developed the change in flexibility method. The basic principle used in this approach is that damage in a structure alters its flexibility matrix, which can be used to ‘identify’ damage. Secondly, damage at a particular location alters the respective elements differently. The relative amount by which the various elements are altered is used to ‘localize’ the damage. Like the change in stiffness method, mode shape vectors and resonant frequencies obtained from the dynamic response data (collected before damage and after damage) are used to obtain the flexibility matrix [F], which may be expressed as

$$[F] = [\Phi][\Omega]^{-1}[\Phi]^T = \sum_{i=1}^{n} \frac{1}{\omega_i^2} \phi_i \phi_i^T \qquad (3)$$



As can be seen from Eq.(3), [F] is proportional to the square of the inverse of the modal frequencies. Therefore it converges rapidly with increasing frequencies. Hence, only a few lower modes are sufficient for an accurate estimation of [F]. The maximum of the values at particular column $\overline{\delta}_j$ of [F] is taken as an index of flexibility for that particular degree of freedom. Any change in this parameter is regarded as an indicator of damage at that particular degree of freedom. In the case of a simply supported beam, the change is at maximum near the damaged element. The amount of change is a measure of the severity of damage. Fig. 1 shows the qualitative variation of flexibility index for a simply supported beam consisting of 30 elements and 31 nodes. Curves for two different damage locations are shown. 50% damage indicated in the figure implies that Young’s modulus for the element has reduced by 50%. It is obvious from the figure that the location of damage can be easily inferred to be the point of maximum flexibility change. Although the technique is an improvement over the change in stiffness method, the researchers did not investigate the case of multiple damage locations.

The major conclusions drawn based on the analysis of the response data by various methods are as follows:

1) Standard modal properties such as mode shapes and resonant frequencies are poor indicators of damage. No noticeable change in the measured resonant frequencies and mode shapes was observed until the final level of damage.

2) All the methods identified the damage location correctly for the most severe damage case, i.e a cut through the entire bottom half of the beam.
3) In some of the methods human judgment was required to correctly identify the location of damage. If they were applied blindly, it would have been difficult to locate the damage.
4) When the entire set of tests is considered, the damage index method is the one with the best performance.

C. Local SHM Techniques:

Another category of damage detection techniques is formed by the so-called local methods, which, as opposed to the global techniques (static/ dynamic), rely on localized structural interrogation for detecting damages. Some of the methods in this category are the ultrasonic techniques, acoustic emission, eddy currents, impact echo testing, magnetic field analysis, penetrant dye testing, and X-ray analysis.

1) Ultrasonic Technique:

The ultrasonic methods are based on elastic wave propagation and reflection within the material for non-destructive strength characterization and for identifying field in homogeneities caused by damages. In these methods, a probe (a piezo-electric crystal) is employed to transmit high frequency waves into the material. These waves reflect back on encountering any crack, whose location is estimated from the time difference between the applied and the reflected waves. These techniques exhibit higher damage sensitivity as compared to the global techniques, due to the utilization of high frequency stress waves. Shah et al. (2000) reported a new ultrasonic wave based method for crack detection in concrete from one surface only. Popovics et al. (2000) similarly developed a new ultrasonic wave based method for layer thickness estimation and defect detection in concrete. In spite of high sensitivity, the ultrasonic methods share few limitations, such as:

1) They typically employ large transducers and render the structure unavailable for service throughout the length of the test.
2) The measurement data is collected in time domain that requires complex processing.
3) Since ultrasonic waves cannot be induced at right angles to the surface, they cannot detect transverse surface cracks (Giurgiutiu and Rogers, 1997).
4) These techniques do not lend themselves to autonomous use since experienced technicians are required to interpret the data.

2) Acoustic Emission Technique:

In acoustic emission method, another local method, lastic waves generated by plastic deformations (such as at the tip of a newly developed crack), moving dislocations and disbonds are utilized for analysis and detection of structural defects. It requires stress or chemical activity to generate elastic waves and can be applied on the loaded structures also (Boller, 2002), thereby facilitating continuous surveillance. However, the main problem to damage identification by acoustic emission is posed by the existence of multiple travel paths from the source to the sensors. Also, contamination by electrical interference and mechanical ambient noise degrades the quality of the emission signals (Park et al., 2000a; Kawiecki, 2001).

3) Eddy Current Technique:

The eddy currents perform a steady state harmonic interrogation of structures for detecting surface cracks. A coil is employed to induce eddy currents in the component. The interrogated component, in-turn induces a current in the main coil and this induction current undergoes variations on the development of damage, which serves an indication of damage. The key advantage of the method is that it does not warrant any expensive hardware and is simple to apply. However, a major drawback of the technique is that its application is restricted to conductive materials only, since it relies on electric and magnetic fields. A more sophisticated version of the method is magneto-optic imaging, which combines eddy currents with magnetic field and optical technology to capture an image of the defects (Ramuhalli et al., 2002).

4) Impact Echo Technique:

In impact echo testing, a stress pulse is introduced into the interrogated component using an impact source. As the wave propagates through the structure, it is reflected by cracks and disbonds. The reflected waves are measured and analysed to yield the location of cracks or disbonds. Though the technique is very good for detecting large voids and delaminations, it is insensitive to small sized cracks (Park et al., 2000a).

5) Magnetic Field Technique:

In the magnetic field method, a liquid containing iron powder is applied on the component to be interrogated, subjected to magnetic field, and then observed under ultra-violet light. Cracks are detected by appearance of magnetic field lines along their positions. The main limitation of the method is that it is applicable on magnetic materials only. Also, the component must be dismounted and inspected inside a special cabin. Hence, the technique not very suitable for in situ application.

6) Penetrant Dye Technique:

In the penetrant dye test, a coloured liquid is brushed on to the surface of the component under inspection, allowed to penetrate into the cracks, and then washed off the surface. A quick drying suspension of chalk is thereafter applied, which acts as a developer and causes coloured lines to appear along the cracks. The main limitation of this method is that it can only be applied on accessible location of structures since it warrants active human intervention.

7) X-Ray Technique:

In X-ray method, the test structure is exposed to X-rays, which are then re-caught on film, where the cracks are delineated as black lines. Although the method can detect moderate sized cracks, very small surface cracks (incipient damages) are difficult to be captured. A more recent version of the X-ray technique is computed tomography, whereby a cross-sectional image of solid objects can be obtained. Although originally used for medical diagnosis, the technique is recently finding its use for structural NDE also (e.g. Kuzelev et al., 1994). By this method, defects exhibiting different density and/ or contrast to the surroundings can be identified.

Table - 2.1
Sensitivities of common local NDE techniques (Boller, 2002).

Method	*Minimum detectable crack length*	*High probability detectable crack length (>95%)*	*Remarks*
Ultrasonic	*2mm*	*5-6mm*	*Dependent upon structure geometry and material*
Eddy currents (low-frequency)	*2mm*	*4.5-8mm*	*Suitable for thickness <12mm only*
Eddy currents (high-frequency)	*2mm (surface)* *0.5mm (bore holes)*	*2.5mm (surface)* *1.0mm (bore holes)*	
X – Ray	*4mm*	*10mm*	*Dependent upon structure configuration. Better for thickness > 12mm*
Magnetic particle	*2mm*	*4mm surface*	
Dye penetrant	*2mm*	*10mm surface*	

D. Techniques based on 'Smart Material and Smart System':

Smart materials are those materials which have the ability to change their physical prosperities such as the shape, stiffness, viscosity, etc. in a specific manner under specific stimulus input. Smart materials are one of the components of smart structures. The piezoelectric materials and optical fibres are example of smart material. Smart structures have ability to sense change in their environment, optimally adjust themselves, and take appropriate action.

According to Ahmad(1988), a system is termed as 'smart' if it is capable of recognizing an external stimulus and responding to it within a given time in predetermined manner. In addition, it is supposed to have the capability of identifying its status and may optimally adapt its function to external stimuli or give appropriate signal to the user. Smart structures can, monitor their own condition, detect impending failure, control, or heal damage and adapt to changing environment. A smart system typically comprises of the following components:

1) Sensors:

Asmart system must gather information about its surrounding before taking the appropriate action. This work is done by sensors. Sensors recognize and measure the intensity of the stimulus (stress of strain) or its effect on the structure. They gather file information about the happening of the surrounding and finally transfer information to the actuators for appropriate action. There are several mart sensors like optical fibre sensors, piezo film and pizoceramic patches.

2) Actuators:

A smart system may additionally have embedded or bonded actuators, which respond to stimulus in predetermined manner.

3) Control Mechanism:

A smart structure must have a mechanism from intersection of sensors and actuators. Both sensors and actuators integrated in feedback architecture for the purpose of controlling the system states.

E. Piezoelectricity:

The piezoelectric effect was discovered in 1880 by Jacques and Pierre Curie.It comes in certain crystalline minerals, which when subjected to a mechanical force, become electrically polarized. Tension and compression generates voltage of opposite polarityand in proportion to the applied force.This is called the direct effect. The converse effect was discovered by Lippman in 1881 in which the crystal was exposed to an electric field, under which it lengthened or shortened according to the polarity of the electric field and in proportion to the strength of the field. These behaviours are called the direct piezoelectric effect and the converse piezoelectric effect, respectively. A smart system must have a mechanism for integrating the sensors and actuators. Piezoelectric material are smart material because they generate a surface charge in response to applied mechanical stress. Conversely, they undergo a material deformation in response to an applied electric field. This unique capability enables the material to be used as a sensor and an actuator.

In thr 20th century, metal oxide-based piezoelectric ceramic and other manmade materials enabled engineers to employ the direct and converse piezoelectric effects in several new applications. These materials are geneally physically strong and chemically inert, and they are relatively inexpensive to manufacture. The composition, shape and dimension of a piezoelectric ceramic element can be tailored to meet the requirement of a specific purpose. Ceramics manufactured from formulation of lead mzirconate/ lead titanate exhibit greater sensitivity and higher operating temperatures, relative to the ceramics of other compositions. 'PZT' material (lead zirconate titanate), is currently the most widely used piezoelectric ceramics.

F. Applications of Piezoelectric Material:

Since this thesis is primarily concerned with piezoelectric materials, some typical applications of these materials are briefly described here. Traditionally, piezoelectric materials have been well-known for their use in accelerometers, strain sensors (Sirohi and Chopra, 2000b), emitters and receptors of stress waves (Giurgiutiu et al., 2000; Boller, 2002), distributed vibration sensors (Choi and Chang, 1996; Kawiecki, 1998), actuators (Sirohi and Chopra, 2000a) and pressure transducers (Zhu, 2003). However, since the last decade, the piezoelectric materials, their derivative devices and structures have been increasingly employed in turbo-machinery actuators, vibration dampers and active vibration control of stationary/ moving structures (e.g. helicopter blades, Chopra, 2000). They have been shown to be very promising in active structural control of lab-sized structures and machines (e.g. Manning et al., 2000; Song et al., 2002). Structural control of large structures has also been attempted (e.g. Kamada et al., 1997). Very recently, the piezoelectric materials have been employed to produce micro and nano scale systems and wireless inter digital transducers (IDT) using advanced embedded system technologies, which are set to find numerous applications in micro-electronics, bio-medical and SHM (Varadan, 2002; Lynch et al., 2003b). Recent research is also exploring the development of versatile piezo-fibres, which can be integrated with composite structures for actuation and SHM (Boller, 2002).

The most striking application of the piezoelectric materials in SHM has been in the form of EMI technique, which evolved during the last decade. In brief, piezoceramic patches namely PZT wafers have substantial application as sensors, actuators, electric generators and ultrasonic transducers

G. Problems in Application of Piezoelectric Material for Structural Health Monitoring:

Piezoelectric ceramic elements are used to monitor the health of structures via the EMI technique since mid-nineties. Damage detection is based on comparison of signature with benchmark signature. Ideally, the change in signature should be due to deterioration of health of structure only, not from any other reason. However, it is possible that signature of PZT can change due to other reasons such as:

1) Aging:

PZT patches erode gradually, in a logarithmic relationship with time after polarization (PI Ceramic, 2009). Exact rates of aging depend on the composition of the ceramic element and the manufacturing process used to prepare it. It may possibly induce change in the benchmark signature.

2) Electrical Limitation:

PZT patch depolarize if it is exposed to a strong electric field of polarity opposite that of the polarizing field. The field of 200-500V/mm or greater typically have a significant depolarizing effect. The degree of depolarization depends on the grade of material, the exposure time, the temperature, and other factors. An alternating current will have a depolarizing effect during each half cycle during which polarity is opposite that of the polarizing field.

3) Mechanical Limitation:

Application of mechanical stresson piezo electric material beyond certain limit can destroy the alignment of dipole. This limit depends upon the type of grade and the brand of the material used to prepare the PZT patches.

4) Thermal Limitation and Temperature Fluctuations:

If a piezoelectric ceramic material is heated to above the Curie temperature, the domains become disordered and the material gets depolarized. The recommended upper operating temperature for a ceramic usually is approximately half –way between 0° and the Curie point. Within the recommended operating temperature range, temperature- associated changes in the orientation of the domains are reversible. On the other hand, these changes can create charge displacements and electric fields. Also, sudden temperature fluctuations can generate relatively high voltages, capable of depolarizing the ceramic element. A capacitor can be incorporated into the system to accept the superfluous electric element. A capacitor can be incorporated into the system to accept the superfluous electrical energy.

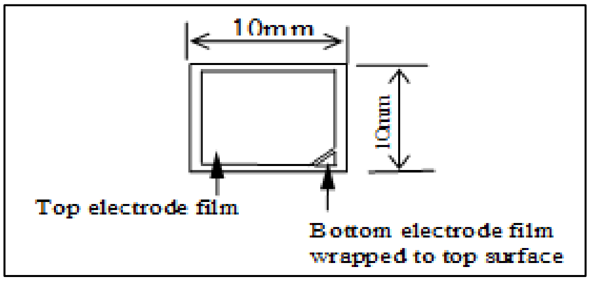


Fig. 6: A Typical commercially available PZT patch.

H. Geometrical details PZT Patches:

There are several types of PZT patches commercially available in market in different geometries (circular, rectangular and square) as well as varying thickness. Electrodes position varies from patch to patch. Electodes are situated on opposite side in some of the PZT patches whereas in others the electrode from the bottom edge is wrapped around the thickness, so that both the electrodes are available on one side of the PZT patch, while the other side is bonded to the host structure. In the EMI technique,PZT patches of sizes ranging from 5mm to 15mm and thickness from 0.1mm to 0.3mm are best suited for most structural materials such as steel and RC. Such thin patches usually have thickness resonance frequency of the order of few MHz. A typical PZT patch manufactured by PI Ceramic (2009) is shown in fig 2.1.

I. *Electro Mechanical Impedance (EMI) Technique:*

The EMI technique is a relatively new technique for SHM. The technique was first invented by Liang et al(1994) and then implored upon by Giurgiutiu and coworkers(1997,2000,2002); Park(2000) and Bhalla(2004). In this technique, basically a PZT patch is surface bonded or embedded inside the structures to the monitored,as shown in fig 2.2. The patch is assumed to be infinitesimally small and possessing negligible mass and stiffness as compared to the host structure. When an alternating electric field is applied to the patch, it expands and contracts dynamically in direction'1'. Hence, two end points of the patch can be assumed to encounter equal impedance Z from the host structure. The patch (length *2l*, width *w* and thickness *h*) behave as thin bar undergoing axial vibration. An electro-mechanical model of the system is shown in the Fig. 2.2(b), where the structure has been replaced by two equal mechanical impedances Z. The complex electro-mechanical admittance $\bar{Y}$ of the coupled system shown in this Fig can be derived as (Liang et. Al, 1994: Bhalla, 2004

$$\overline{Y} = 2\omega j \frac{wl}{h}\left[(\overline{\varepsilon_{33}^{T}} - d_{31}^{2}\overline{Y^{E}}) + \left(\frac{Z_a}{Z + Z_a}\right) d_{31}^{2}\overline{Y^{E}}\left(\frac{\tan \kappa l}{\kappa l}\right)\right] \qquad (2.1)$$

Where d_{31} is the piezoelectric strain coefficient of the PZT material, $\overline{Y^E} = Y^E(1+\eta j)$ is the complex Young's modulus under constant electric field , $\overline{\varepsilon_{33}^T} = \varepsilon_{33}^T(1-\delta j)$ is the complex electric permittivity (in direction '3') of the PZT material at constant stress, where $j = \sqrt{-1}$. Here, η and δ denote respectively the mechanical loss factor and the dielectric loss factor of the PZT material. Z_a the mechanical impedance of the PZT patch, ω the angular frequency and ϰ the wave numbers

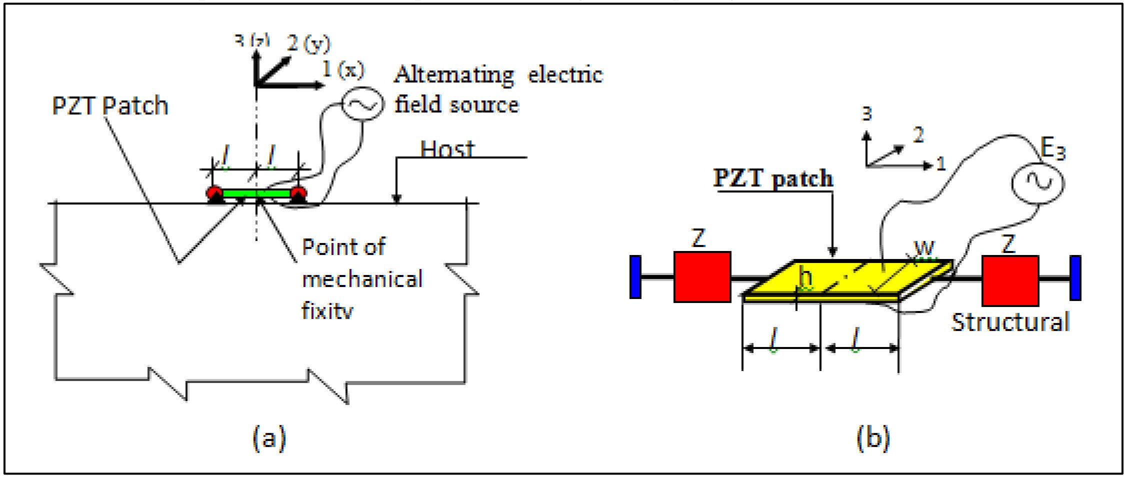


Fig. 1.4: Modelling PZT-structure interaction. (a) A PZT patch bonded to structure under electric excitation. (b) Interaction model of PZT patch and host structure.

technique can detect flexural and shear crack before they could be visible to the naked eyes.

J. *Method of Application:*

In the EMI technique, a PZT actuator/ sensor patch is bonded to the surface of the structure (whose health is to be monitored) using high strength epoxy adhesive. The conductance signature of the patch is acquired over a high frequency range (30-400 kHz).This signature is complex in nature, consisting of the real and the imaginary component called conductance and susceptance respectively. The LCR meter imposes an alternating voltage signal of 1 volts rms (root mean square) to the bonded PZT transducer over the user specified preset frequency range. The magnitude and the phase of the steady state current are directly recorded in the form of conductance and susceptance signatures in the frequency domain. In fact, Sun et al. (1995) reported that higher excitation voltage has no influence on the conductance signature, but might only be helpful in amplifying weak structural modes. This signature forms the benchmark for assessing the structural health. At any future point of time, when it is desired to assess the health of the structure, the signature is extracted again and compared with the benchmark signature. Any deviations in signature from bench mark signature indicate the crack /damage in structure.

K. Selection of Frequency Range:

The operating frequency range must be maintained in hundreds of kHz so that the wavelength of the resulting stress waves is smaller than the typical size of the defects to be detected (Giurgiutiu and Rogers, 1997). Typically, for such high frequencies, wavelengths as small as few mm are generated. Contrary to the large wavelength stress waves in the case of low frequency techniques, these are substantially attenuated by the occurrence of any incipient damages (such as cracks) in the local vicinity of the PZT patch. Sun et al. (1995) recommended that a frequency band containing major vibrational modes of the structure (i.e. large number of peaks in the signature), such as the one shown in Fig. 5, serves as a suitable frequency range. Large number of peaks signifies greater dynamic interaction between the structure and the PZT patch. Park et al. (2003b) recommended a frequency range from 30 kHz to 400 kHz for PZT patches 5 to 15mm in size. According to Park and coworkers, a higher frequency range (>200 kHz) is favourable in localizing the sensing range, while a lower frequency range (< 70 kHz) covers a large sensing area. Further, frequency ranges higher than 500Hz are found unfavourable, because the sensing region of the PZT patch becomes too small and the PZT signature shows adverse sensitivity to its own bonding condition rather than any damage to the monitored structure. It should also be noted that the piezo-impedance transducers do not behave well at frequencies less than 5kHz. Below 1kHz, the EMI technique is not at all recommended (Giurgiutiu and Zagrai, 2002).

L. Sensing Zone of Piezo- Impedance Transducers:

Sensing zone of PZT patch depends upon the propagation of stress waves. Denser or non-homogeneous the medium like concrete, lesser the sensing region. Hence, the PZT patches have limited sensing zone based on properties of material, operating frequency. Park et al.(2000a) reported tht the sensing radius of a typical PZT patch might vary anywhere from 0.4m on composite reinforced structure to about 2 m on simple metal beams.

M. Advantages of EMI Technique:

The major advantages of the EMI techniques over the prevalent global and local SHM techniques are summarized below

1) The EMI technique shows far greater damage sensitivity than the conventional global methods. Typically, the sensitivity is of the order of the local ultrasonic techniques (Park et el., 2003b). The data acquisition is much more simplified as compared to the traditional accelerometer-shaker combination in the global vibration techniques since the data is directly obtained in the frequency domain.
2) The PZT patches are bonded non-intrusively on the structure, possess negligible weight and demand low power consumption. Small and non-intrusive sensors can monitor inaccessible locations of structures and components. Easy installation (no sub-surface installation) makes the piezo-impedance transducers equally suitable for existing as well as to-be-built structures.
3) The use of the same transducer for actuating as well as sensing saves the number of transducers and the associated wiring.
4) The limited sensing area of the PZT patches helps in isolating changes due to far field variations such as boundary conditions and normal operational vibrations. Also, multiple damages in different areas can be picked easily.
5) The technique is practically immune to mechanical, electrical and electro-magnetic noise. This makes the technique very suitable for implementation during operating conditions, such as in aircraft during flight.
6) The PZT patches can be produced at very low costs, typically US$1 (Peairs et al., 2003) to US$10 (Giurgiutiu and Zgrai, 2002), in contrast to conventional force balance accelerometers, which may be as expensive as US$1000 (Lynch et al., 2003b) and at the same time bulky and narrow-banded.
7) (vii)Being non-model based, the technique can be easily applied to complex structures.

It is therefore needless to say that the EMI technique has evolved as a universal NDE method, applicable to almost all engineering materials and structures. If the damage location could be predicted in advance (i.e. ‘where to expect damage’), the EMI technique would be most powerful technique in such applications (Park et al., 2003b).

N. Limitation of EMI Technique:

In spite of many advantages over other techniques, the EMI technique shares several limitations as outlined below.

1) A PZT patch is sensitive to structural damages over a relatively small sensing zone, ranging from 0.4m to 2m only, depending upon the material and geometrical configuration. Though sufficient for monitoring miniature components and mechanical/ aerospace systems, the small sensing zone warrants the deployment of several thousands of PZT patches for real-time monitoring of large civil-structures, such as bridges or high rise buildings. The large number of PZT patches would warrant significant cost and effort for laying out the wiring system, data collection and data processing. Hence, critical locations must be judiciously decided based on the theory of structures.
2) Since all civil and mechanical structures are statically indeterminate, cracking of a few joints might not necessarily affect the overall safety and stability of the monitored structure. Thus, a drawback of the EMI technique as compared to the global SHM techniques is its inability to assess the overall structural stability. Rather, in this respect, global SHM techniques and the EMI techniques could easily complement each other.
3) PZT materials and the related technologies are only supplementary steps in addition to good designs of structures and machines. Many academicians argue that more research should be focused on improving material strength and design rather

than on sensors. But even the best-designed structures could have problems, therefore it is justified to explore the application smart materials to sense or detect damages in advance (Reddy, 2001).

III. NUMERICAL SIMULATION

In the present work numerical investigations were conducted on a lab sized RC frame using finite element for which experimental study was done by Bhalla. and Soh (2004).Part-1 of the major project, preliminarily conductance signature of the numerical RC lab sized frame was obtained. In part -2, further refinement of the model has been carried out and various types of damages have been simulated. The properties of the concrete are listed in the table 3.1. Properties of the PZT patch is shown in Table 3.2

Table - 3.1
Material properties of concrete

Physical parameter	**value**
Young's modulus (MPa)	2.74 × 104
Density (kg/m^3)	2400
Poison's ratio	0.3
Mass damping factor	0.001
Stiffness damping factor	1.5×10^{-8}

Table - 3.2
Mechanical and electrical properties of PZT

Physical parameters	value
Density (kg/m^3)	7800
Dielectric constant, ε_{33}^{T}	33 2.124×10^{-8}
Piezoelectric constant, d_{31} (m V^{-1})	-2.1×10^{-10}
Young's modulus, Y^{E}_{11} (MPa)	6.667×10^{10}
Dielectric loss factor, δ	0.015
Mechanical loss factor, η	0.001

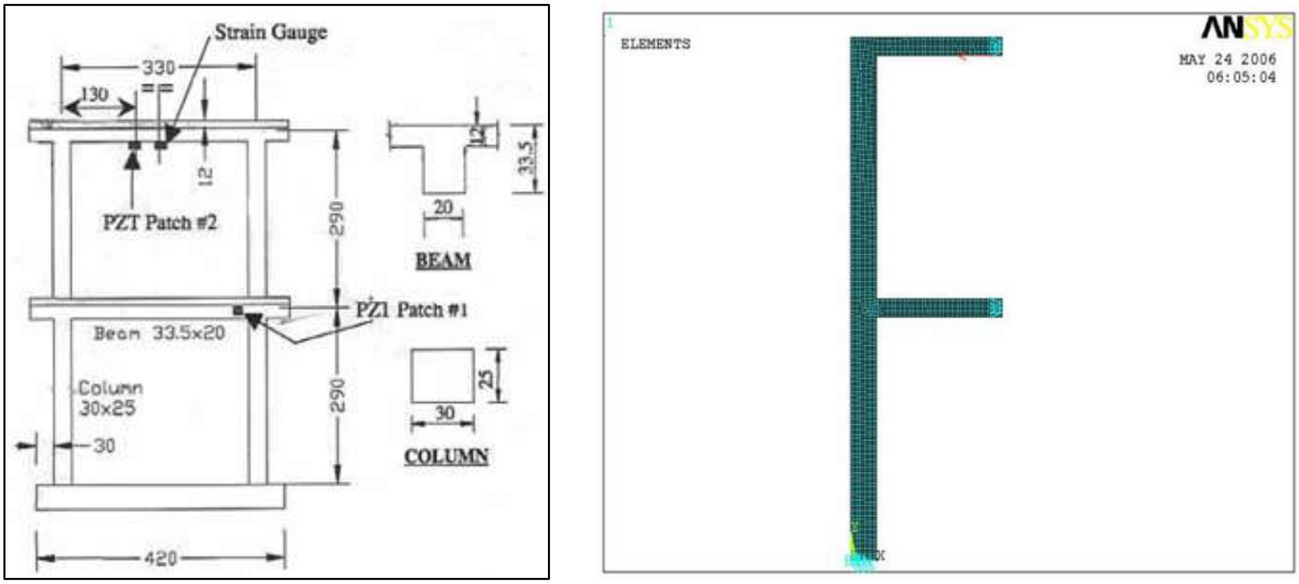


Fig. 3.1: and Fig. 3.2: give Details of the test frame (All dimensions are in mm) (Bhalla and Soh 2004).

As part of the project finite element model of the frame was developed using plane solid 42 element of 10 mm size using Ansys 9 software. A pair of self equilibrium harmonic forces of 100 kN are applied at the Location of PZT patch 2 to simulate the piezoceramic load on the frame. For simplicity PZT patch was located at the centre of the beam. Boundary conditions are simulated as it is on the experimental frame. Fig.3.2 shows the 2D finite element model of the symmetric left half of the experimental frame. Harmonic analysis of the frame was carried out by applying self-equilibrating constant axial harmonic forces at the PZT patch in the frequency range of 100 to 150 KHz. Translational displacements in x-direction at the location of PZT patch were obtained at frequency interval of 1 kHz in between 100 to 150 kHz. Structural impedance and electrical admittance were calculated at 1 kHz frequency interval using the equations 4.5 and 3.3 respectively. The process was initially carried with 10mm element size. The entire procedure was repeated with 5mm, 4mm, and 3mm element sizes. It was observed that convergence of the conductance signature attained at an element size of 3mm. Therefore conductance signature with 3mm element size is considered as healthy signature of the numerical study. Figure 3.3 the conductance signature corresponding to these three sizes.

Now a flexural damage in the form of vertical crack was introduced at PZT location and again Harmonic analysis is carried out for the numerical model to obtain conductance signature at the damaged state. It is assumed that vertical crack occurred at the PZT location. For introducing damage Young's modulus of the elements at the location of damage is reduced to 2×10^{5} N/M^{2}.

Deviation of this signature with healthy signature indicated the presence of damage. Numerical analysis results are compared with experimental results. The RMSD index with respect to the pristine state signature can determine

IV. RESULTS

The following results were obtained from numerical Analysis of Finite element model of RC Lab sized frame as part-1 of the project.Fig.4.1 shows the results of the numerical process when approached with 10mm, 5mm and 3 mm. sizes of the elements. Fig 4.1 Conductance signatures using 10mm, 5mm and 3mm size of the elements. From the figure 4.1 it is observed that pristine signature using 3mm elements converged with pristine signature corresponding to the 5mm elements. This is justified by the fact that most of the curve patterns are similar for these mesh sizes. Hence conductance signature obtained using 3mm element is considered as conductance signature of the RC model frame .This can be compared with the experimental signature shown in Fig 4.3(Bhalla& Soh, 2004)

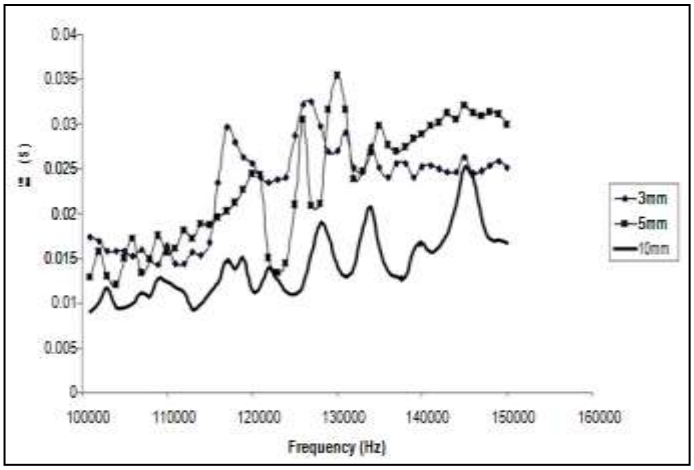


Fig 4.1 Conductance signatures using 10mm, 5mm and 3mm size of the elements.

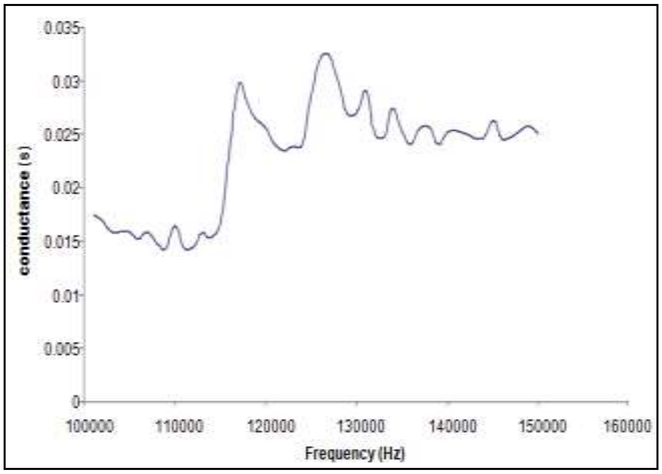


Fig 4.2 Numerical conductance signature of the pristine frame model.

Experimental Healthy conductance signature
Signature obtained by Bhalla (2003) is shown in fig. 4.3

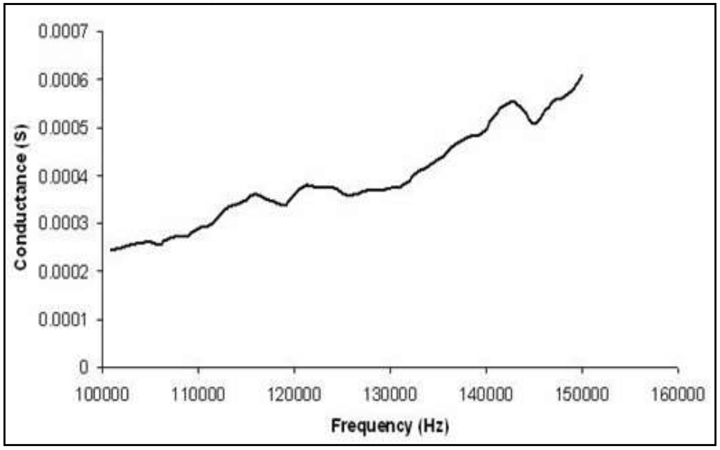


Fig. 4.3: Experimental conductance signature of the pristine frame model. (Bhalla and Soh 2003).

A. *Deviation in Conductance Signature with Flexural Damage:*

Healthy conductance signature has been compared with signature obtained by introducing small vertical flexural crack at PZT location. This is shown in Fig 4.4. From it can be observed that the conductance signature corresponding to damaged state shifted vertically and laterally from the healthy conductance signature. In this way structural health monitoring can be done using piezoceramic actuator/sensor patches.

B. *Study of Conductance Signature Pattern by Inducing Different Damages to the Numerical Model:*

As a second part of the project various damages at various locations were induced for the numerical model, and the resulting conductance signature was studied.

1) *Determination of Damping Constants:*

Before simulating damaged model an attempt was made to further refine the model developed during part-1 by determine the appropriate damping constants. For this purpose, the conductance signatures were obtained for different combinations of the damping constants α & β. Results are as shown in Fig 4.5

From this figure it can be observed that conductance signature with α=0, β=1e-09 leads to much better comparable results with experimental results. The validity of damping constants can be justified as follows.Mass damping constant (α) = 0, Stiffness damping constant (β) = 1e-09, We have , Damping ratio (ξ) = βω / 2, ω= mean frequency= $125\times10^{3}\times2\pi$ rad/sec.From the above Damping ratio (ξ) = 6.125%.From the dynamic analysis point of view damping ratio recommended for reinforced concrete is 3% to 6 %.(A.k.Chopra). hence the values of α , β used presently are reasonable & hence used in all future work. Fig 4.6 Numerical conductance signatures with modified damping constants. In part-1, numerically obtained results varied by 60 times with the experimental one. Now it came down to the 15 to 20 times. These results thus show better improvement compared to Giurgiutiu& Zagrai (2002) work.

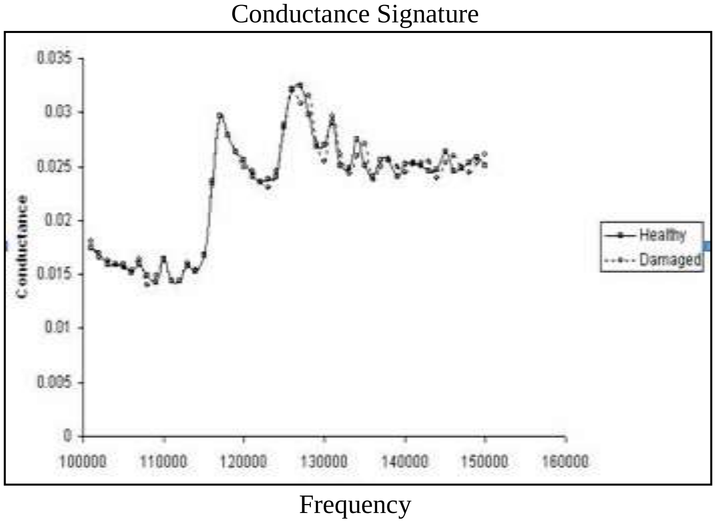


Fig. 4.4: simulated conductance signature of healthy and damaged state

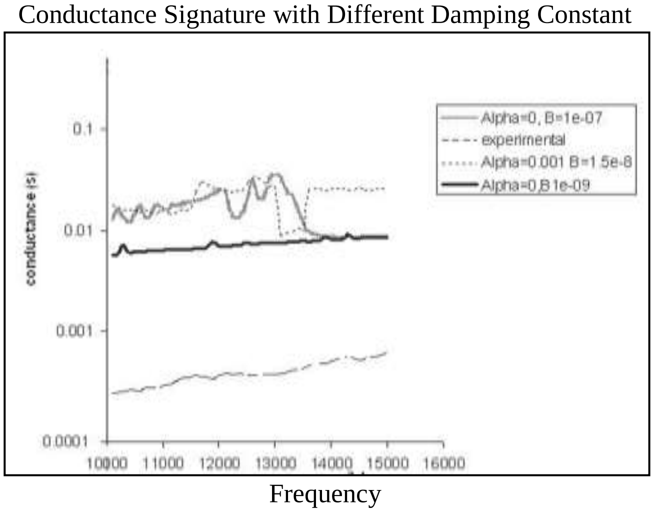


Fig. 4.5: conductance signatures with different damping constants.

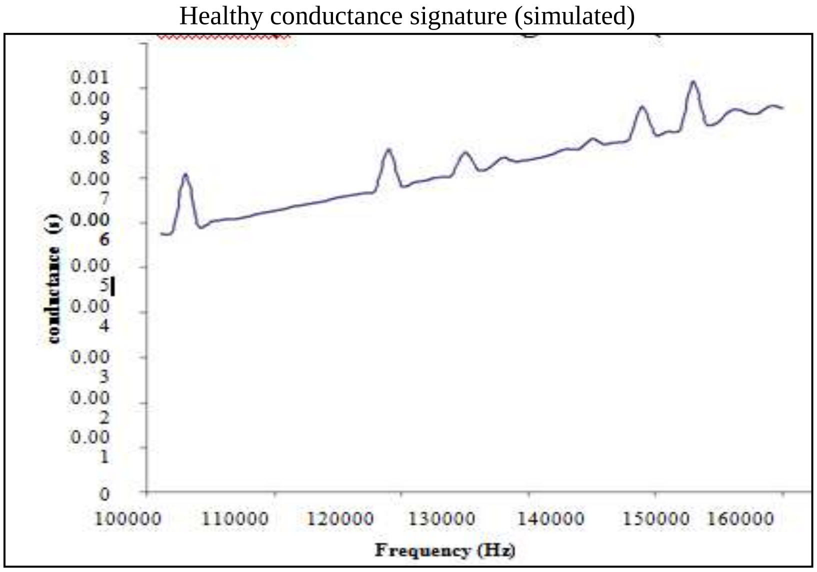


Fig. 4.6: Numerical conductance signatures with modified damping constants

C. *Study of Effect of Damage on Conductance Signature of Numerical Model RC Frame:*

1) *Effect of Flexural Crack:*

A flexural crack at the location of maximum bending moment on the top beam of the frame was induced by reducing the young's modulus of the elements at that location from 2.74E 10 to 1E-06. Frame model with flexural crack was shown in Fig 4.7 Deformations at the location of PZT patch at predetermined frequency range were obtained and Conductance signature of the damaged numerical frame was obtained shown in Fig 4.8. From the figure 4.7 it can be observed that conductance signature of numerical model with flexural damage was shifted laterally right and vertically up. Peak conductance also changed for a considerable amount. Root mean square deviation was found to be 16.82%

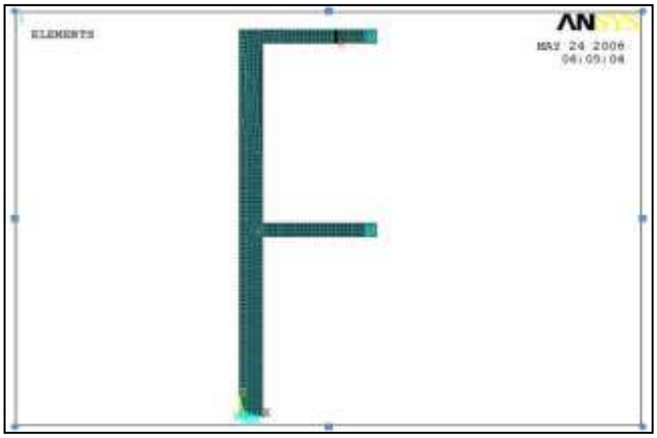


Fig. 4.7: simulated RC frames with Flexural cracks

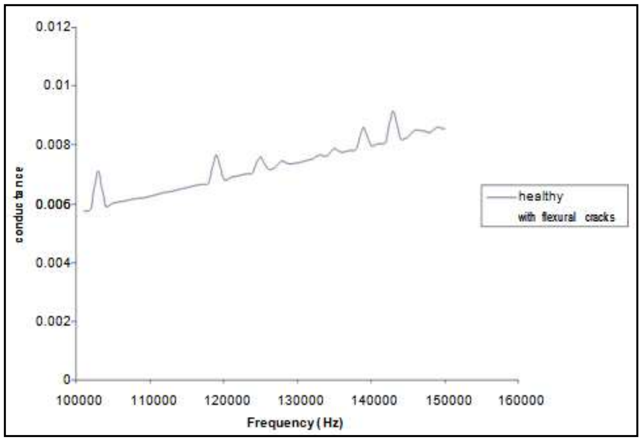


Fig. 4.8: Effect of flexural crack on conductance signature

D. Comparison of Experimental and Simulated Results:

Fig 4.9 shows the effect of damage experimentally observed on the conductance signature. In the experiment, the frame was subjected to different dynamic loads by changing frequency, velocity amplitude, acceleration amplitude, referring it state 1 to state 8. From Experimental results it was observed that there was some deviation in the signatures as compared to baseline signature, up to state 3. from state 4 to state 6 there was a prominent and sequential vertical shift in the signature as compared to the earlier states. At state 7 prominent crack was found around and conductance signature prominently downwards. At state 8 crack progresses through the PZT patch and sudden vertical shift of the conductance signature was observed clearly. it was clear that before visual observation of the damage, change in conductance signature explains us the presence of minute cracks.

From the results obtained numerically, it was observed that conductance signature followed the same pattern as that of experimental results. Simulated baseline signatures varied from the experimental signatures by nearly 20 times. With the occurrence of the flexural cracks at the location of maximum bending moment, conductance signature shifted vertically upward and laterally right. With the occurrence of shear cracks conductance signature shifted down wards. With both flexural and shear cracks, the conductance signature was found to be between above two curves. The presence of the damage up to a distance of 150 mm from the PZT location was significantly detected by the conductance signature. However, Beyond 150 mm distance, the PZT patch unable to detect the presence of damage.

Experimental conductance signatures

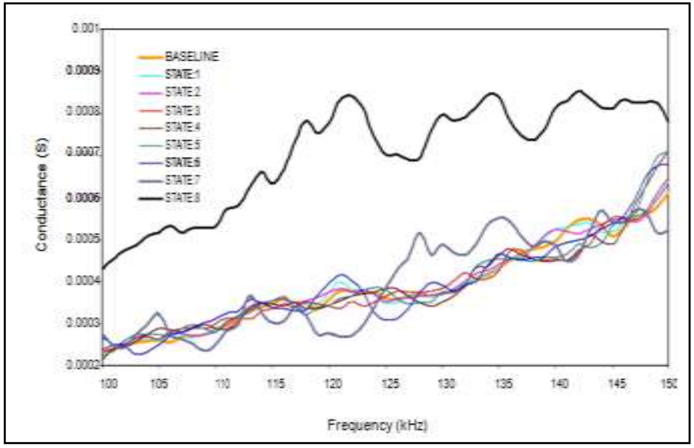


Fig. 4.9: Experimental Result

Simulated Result

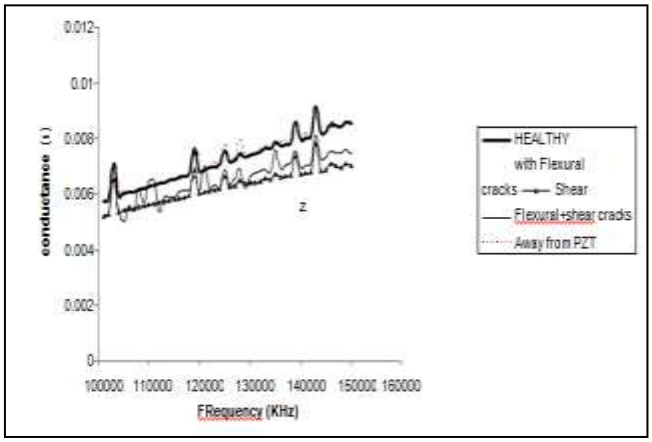


Fig. 4.10: Result Obtained From Numerical model

V. CONCLUSION

1) On this research Finite element model for an RC lab sized frame was developed using ANSYS 9 software, for which experimental results are obtained by Bhalla and Soh (2004). Self-equilibrium harmonic forces of 100 kN were applied at PZT location and Harmonic analysis was carried out at a frequency range of 100 kHz to 150 kHz. Translational displacements were obtained at PZT patches in the direction of applied forces at an interval of 1 kHz. Electrical admittance was obtained at each 1 kHz interval. Conductance signature for the PZT patch was drawn and compared with experimental

signature. The pattern of both signatures was observed as same manner. Both signatures obtained the peak conductance at the identical frequencies. But there is a variation in magnitude. These variations are due to high frequency analysis, boundary effects and uncertainty of concrete damping.

2) By reducing the young's modulus of elements in some locations the effect of different types of cracks was introduced. And again procedure was repeated and conductance signature of damaged state was obtained. Effect of different types of damages was clearly demarcated by the conductance signatures. Numerically obtained healthy and damaged signatures followed the same pattern as that of experimental results. Both experimental and numerical conductance signatures showed the peak conductance at identical frequencies. It is found that PZT patches can easily detect damages as far as 150mm.The results obtained by Giurgiutiu and Zagari (2002) are shown a variation of 100 times with the experimental. But in the present research, the deviation t was around 20 times only. Hence, this is the better simulation compared to earlier research
3) This numerical simulation is useful in future researches in smart structures concept. Using these simulations tedious experimental works can be avoided. It leads to saving of time and economic resources. According to Tseng and Wang (2004) detection of damage by a PZT patch limited to 500 mm from the PZT patch. Therefore, for lar civil engineering structures require more number of PZT patches and impedance analyzers are required. This difficulty can be overcome by using numerical simulation method. Using simulation method, conductance signature for various damage patterns can be studied without subjecting the structure to any cracks.

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