FINITE ELEMENT MODELLING OF SMART STRUCTURES

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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, anomaliesdue to deterioration and damage as well as health during and after an extreme event (Aktan et al, 2000). Health monitoring has gained considerable attention in civil engineering over the last two decades. Although health monitoring is a maturing concept in the manufacturing, automotive and aerospace industries, there are a number of challenges for effective applications on civil infrastructure systems. While successful real-life studies on a new or an existing structure are critical for transforming health monitoring from research to practice, laboratory benchmark studies are also essential for addressing issues related to the main needs and challenges of structural health monitoring. Health monitoring offers great promise for civil infrastructure implementations. Although it is still mainly a research area in civil infrastructure application, it would be possible to develop successful real-life health monitoring systemsif all components of a complete health monitoring design are recognized and integrated.

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).

New advances in wireless communications, data acquisition systems and sensor technologies offer possibilities for health monitoring design and implementations (Lynch et al, 2001, Spencer, 2003). Development, evaluation and use of the new technologies are important but they have to be considered along with our “health” and “performance” expectations of the structure. Yao (1985) defined the term damage as a deficiency or deterioration in the strength of the structure, caused by external loading or environmental conditions or human errors. So far visual inspection has been the most common tool to identify the external signs of damage in buildings, bridges and industrial structures. These inspections are made by trained personnel. Once gross assessment ofthe damage location is made, localized techniques such as acoustic, ultrasonic, radiography, eddy currents, thermal, or magnetic field can be used for a more refined assessment of the damage location and severity. If necessary, test samples may extract from the structure and examined in the laboratory. One essential requirement of this approach is the accessibility of the location to be inspected. In many cases critical parts ofthe structure may not be accessible or may need removal of finishes. This procedure of health monitoring can therefore be very tedious and expensive. Also, the reliability of the visual inspection is dependent, to large extent, on the experience of the inspector. Overthe last two decades number of studies have been reported which strive to replace the visual inspection by some automated method, which enable more reliable and quicker assessment of the health of the structure. Smart structures was found to be the alternative to the visual inspection methods from last two decades, because of their inherent ‘smartness’, the smart materials exhibit high sensitivity to any changes in environment.

STRUCTURAL HEALTH MONITORING (SHM): AN OVER VIEW

Increase in population necessitated the more civil infrastructural facilities in every country. Wealth of the nation can be represented by well conditioned infrastructure.Civil engineering structures under go damage and deterioration with age and due to natural calamities. Nearly all in-service structures require some form of maintenance for monitoring their integrity and health condition. Collapse of civil engineering structures leads to immense loss of life and property. Appropriate maintenance prolongs the lifespan of a structure and can be used to prevent catastrophic failure. Current schedule-driven inspection and maintenance techniques can be time consuming, labor-intensive, and expensive. SHM, on the other hand, involves autonomous in-service inspection of thestructures. The first instances of SHM date back to the late 1970s and early 1980s. The concept of SHM originally applied to aerospace and mechanical systems is now being extended to civil structures.

Objectives of health monitoring are as follows.

a) To ascertain that damage has occurred or to identify damage
b) To locate the damage
c) To determine the severity of damage.
d) To determine the remaining useful life of the structure.

SHM consists of both passive and active sensing and monitoring. Passive sensing and monitoring is used to identify the location and force–time–

history of external sources, such as impacts or acoustic emissions. Active sensing and monitoring is used to localize and determine the magnitude of existing damages. An extensive literature review of damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics is given by Doebling et al. (199

PASSIVE SENSING DIAGNOSTICS

For a passive sensing system, only sensors are installed on a structure. Sensor measurements are constantly taken in real time while the structure is in service, and this data is compared with a set of reference (healthy) data. The sensor-based system estimates the condition of a structure based on the data comparison. The system requires either a data base, which has a history of prestored data, or a structural simulator which could generate the required reference data.

Passive sensing diagnostics are primarily used to determine unknown inputs from changes in sensor measurements. Choi and Chang (1996) suggested an impact loadidentification technique using piezoelectric sensors. They used a structural model and a response comparator for solving the inverse problem. The structural model characterised the relation between the input load and the sensor output. The response comparator compared the measured sensor signals with the predicted model.

ACTIVE SENSING DIAGNOSTICS

Active sensing techniques are based on the localized interrogation of the structures. They are used to localize and determine the magnitude of an existing damages. Local or wave propagation-based SHM is therefore advantageous since much smaller defects can be detected. Chang (2000) concentrates his research on wave- propagation-based SHM. He developed Lamb-wave-based techniques for impactlocalization /quantification and damage detection. Wilcox et al. (2000) examined the potential of specific Lamb modes for detection of discontinuities. They considered large, thick plate structures (e.g. oil tanks) and thin plate structures (e.g. aircraft skins). They showed that the most suitable Lamb mode is strongly dependent on what the plate is in contact with. Bhalla and Soh (2005) presented the technique using wave propagation approach for NDE using surface bonded piezoceramics. They utilized simple, economicaland commercially available hardware and sensors, which can be easily employed for real time and online monitoring of critical structures, such as machine parts and aircraft components. Lemistre and Balageas(2001) presented a robust technique for damage detection based on diffracted Lamb wave analysis by a multire solution wavelet transform. Berger et al. (2004) employed fibre optic sensors in order to measure Lam waves. Benz et al. (2003) and Hurlebaus et al.(2002) developed an automated, non-contact method for detecting discontinuities in plates. Laser ultrasonic techniques were used to generate and detect Lamb waves in a perfect plate and in a plate that contains a discontinuity. The measured signals were first transformed from the time–frequencydomain using a short-time Fourier transform (STFT) and subsequently into the group– velocity–frequency domain. The discontinuity is then located through the use of a zzcorrelation in the group–velocity–frequency domain. The smart layer presented by Lin and Chang (1998) makes use of a PZT-sensing element, whereas the smart layer presented by Hurlebaus et al.(2004) uses PVDF-sensing elements. Finally, in the study byLin and Chang (2002) PZT transducers were placed at a few discrete points on the smart layer; and in the study by Hurlebaus et al. (2004), the PVDF polymer covers the entire surface of the smart layer.

SELF–HEALING & SELF–REPAIRING

Peairs et al. (2004) presented a method for the self-healing of bolted joints based on piezo electric &.shape memory alloys . The loosening of a bolted joint connection is a common structural failure mode. They reported a real-time condition monitoring and active control methodology for bolted joints in civil structures and components. They used an impedance-based health-monitoring technique which utilizes the electromechanical coupling property of piezoelectric materials to identify and detect bolt connection damage. When damage occured, temporary adjustments of the bolt tension could be achieved actively and remotely using shape memory alloy actuators.Specifically, when a bolt connection became loose, the bolted members can movedrelative to each other. The heat produced by this motion caused a Nitinol washer to expand axially, thereby leading to a tighter, self-healed bolt connection.

Hagood and von Flotow(1991) established the analytical foundation for generalsystems with shunted piezoelectrics. Their work characterised the electromechanical interactions between a structure and the attached piezo network, and offers some experimental verification. Davis and Lesieutre(1995) extended previous studies by using the modal strain energy approach to predict the structural damping produced by a network of resistively shunted piezoceramic elements. Using this approach, the amountof added damping per mode caused by an individual ceramic element can be computed. It was also demonstrated that increased damping could be achieved in several modes simultaneously via proper placement of the piezoceramics. demonstrates the effectivenessof shunted piezoelectricity for three different resistance values. A structural vibration control concept using piezoelectric materials shunted with real-time adaptable electrical networks has also been investigated by Wang et al. (1994). Instead of using variable resistance only, they implemented variable resistance and inductance in an external RL circuit as control inputs. They created an energy-based parametric control scheme to reduce the total system energy while minimising the energy flowing into the main structure. Furthermore, they proved stability of the closed-loop system and examined the performance of the control method on an instrumented beam. Hagood and von Flotow pr esented a passive damping mechanism for structural systems in which piezoelectric materials are bonded to the structure of interest.

In previous days health monitoring concept was limited to electrical and mechanical systems. In present days, it is extended to large civil structures also. Civil engineering structures are huge, heavy, expensive and more complex than electrical and mechanical systems. The need for quick assessment of state of health of civil structures has necessitated research for the development of real time damage monitoring and diagnostic systems.

TECHNIQUES OF HEALTH MONITORING

Conventional Techniques for Structural Health Monitoring

(a) Static response based techniques

This technique was formulated by Banan et. al. (1994). In this methodstatic forces applied on structure and corresponding displacements are measured. It is not necessary to select the entire set of forces and displacements. Any subset could beselected, but a number of load cases may be necessary in order to obtain sufficient information for computation. Computational method based on least scale error function between model and actual measurement is used. The resulting equations are to be solved to arrive at a set of structural parameters. Any change in the parameters from the baseline healthy structure is an indicator of damage. The short comings of this technique are measurement of displacements is not an easy task. It requires establishment of frame of reference. Employing a member of load cases can be very time consuming. Besides, the computational effort required by the method is enormous.

Sanayei and Saletnik (1996) proposed a technique based on static strain method. The advantage of this technique is strain measurement can be made accurately compared to displace measurement. Although the method has some advantages over the static displacement method, its application on real life structures remains tedious.

(b) Dynamic response based techniques

In this method structure is subjected to low frequency vibrations, and dynamic response of the structure are measured and analysed. By this analysis a suitable set of parameters such as modal frequencies, and modal damping, and mode shapes associated with each modal frequency. changes also occur In structural parameters namely the stiffness matrix and damping matrix. In this method structure is exited by appropriated means and the response data processed to obtain a quantitative index or a set of indices representative of the condition of the structures.

These techniques have advantageous over static response since they are comparatively easier to implement. Few methods using low frequency dynamic techniqueare described below.

Casas and aparcio (1994) presented a method of localizing and quantifying cracks in bridges based on the first few natural frequencies and mode shapes extracted from the dynamic response measurements.

Zimmerman and kaouk (1994) developed this damage detection method basedon changes in the stiffness matrix. The stiffness matrix is determined from mode shapes and modal frequencies derived from the measured dynamic response of the structure.

The stiffness matrix matrix [K] may be expressed in terms of mode shape matrix [ϕ], the mass matrix [M], and the modal stiffness matrix [Ω].

$$[K] = [M][\phi][\Omega]^T[M] \qquad (2.1)$$

Change in flexibility method.

This method of damage detection and localization in beams was proposed by Pandey and Biswas (1994). 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 loation alters the respective elements differently. The relative amount by which different elements are altered is used to localize the damage. Like 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

STRUCTURAL HEALTH MONITORING WITH PIEZO ELECTRIC ACTUATOR/SENSOR PATCHES

PIEZOELECTRICITY AND PIEZO ELECTRIC MATERIALS

The unique property of piezoelectric materials to play the dual roles of actuators and sensors is utilized in this particular application.

Piezo electricity is the effect of interaction between electrical and mechanical systems. it occurs in certain type of anisotropic crystals, in which electrical dipoles are generated upon applying mechanical deformations. The same crystals also exhibit the converse effect, that is, they undergo mechanical deformations when subjected to electricfields. This phenomena was discovered by Pierre and Paul-Jacques Curie in 1880.

Present research is “FINITE ELEMENT MODELLING OF SMART STRUCTURES”. Particularly working of structure with piezo electric patch was studied. That’s why these things were discussed in detailed manner as follows.

The principal commercially available piezoelectric materials are

1. Piezoceramics, such as Lead Zirconate Titanate(PZT).
2. Piezopolymers, such as Polyvinvylidene Fluoride(PVDF).

FUNDAMENTAL PIEZOELECTRIC RELATIONS

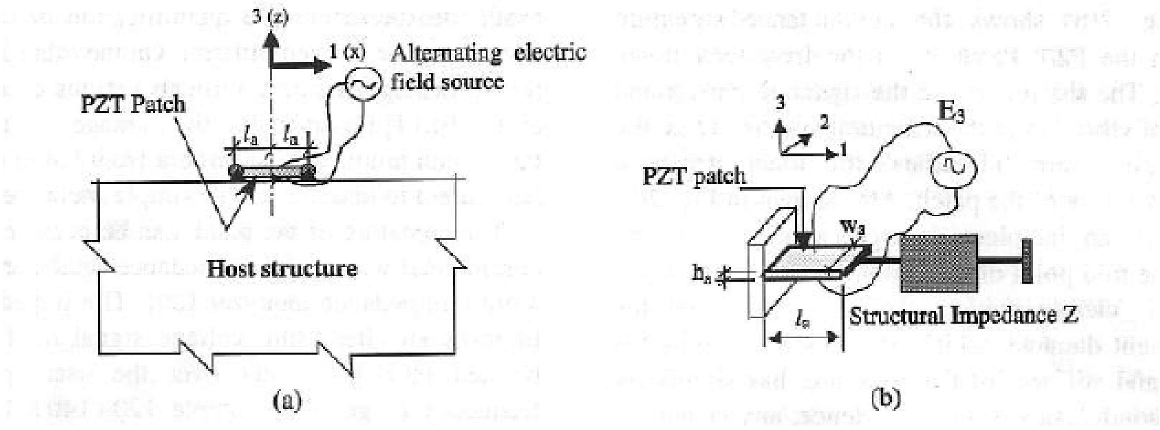


Fig 3.1 (a) A PZT bonded to the structure (b) Interaction model of one half of PZT and host structure. (Bhalla and Soh (2002)).

Consider a piezoceramic actuator bonded to host structure as shown in fig 3.1 by means of high strength epoxy adhesive and electrically excited by means of impedance analyzer .It is assumed that the patch expands and contracts in direction 1only when the electric field is applied in direction 3. h_a, l_a and w_a are the thickness,length , and width respectively of the PZT patch. T is stress applied in direction 1, and E_3 is the electric field applied in direction 3.

Fundamental relationships of the PZT patch may be expressed as (Ikeda, 1990)

$$S_1 = \frac{T_1}{\overline{Y^E_{11}}} + d_{31} E_3 \quad (3.1)$$

$$D_3 = \overline{\varepsilon^T_{33}} E_3 + d_{31} T_1 \quad (3.2)$$

where

S_1 = strain

D_3 = electric charge density over PZT

$\overline{Y^E_{11}} = Y^E_{11}(1+\eta j)$ is the Young's modulus of the PZT patch at zero electric field.

η = mechanical loss factor

$\overline{\varepsilon^T_{33}} = \varepsilon^T_{33}(1-\delta j)$ is the complex permittivity of the PZT material at zero stress

δ = dielectric loss factor

for d_{31} first subscript signifies the direction of electric field and second subscript signifies the direction of the resulting stress or strain.

PRINCIPLE AND METHOD OF APPLICATION

As suggested by Sun et al(1995) by inducing an alternating current source, pzt patch Imposes a dynamic force on the structure it is bonded to. The structural response in turn modulates the current flowing through the PZT i.e. affects the electrical Admittance. The electrical admittance is therefore is a unique function of the mechanical impedance of the structure at the point of attachment. Any variation in mechanical impedance will alter the electrical admittance, which can be used as an indicator of damage. A frequency range is selected for extracting conductance as a function of frequency. This is called conductance signature. This frequency is kept typically high, in the order of kHz using an impedance analyzer. The conductance signature is recorded for the healthy structure as a bench mark. At any subsequent state, when structure health is required to be assessed, the procedure is repeated. If any change in signatures is found, it is an indication of damage.

The surface bonded piezoelectric patches, because of their inherent direct and converse mechatronic coupling, can be effectively utilized as mechatronic impedance transducers(MITs) for SHM. The MIT – based technique has evolved during the last 8 years and is commonly called the electro mechanical impedance (EMI) technique in the literature.

Description of EMI Technique

The PZT patch is assumed to be infinitesimally small and possessing negligible mass and stiffness as compared to host structure.

Liang et al.(1994) solved the governing equilibrium equation for the system shown in fig3.1(b), using impedance approach. Using Liang's derivation following equation can be written for the complex electro mechanical admittance Y (inverse of electrical impedance), of the coupled system shown in figure 3.1.

$$\bar{Y} = 2\omega j \frac{w_a l_a}{h_a}\left[\bar{\varepsilon}_{33}^{T} + \left(\frac{Z_a}{Z + Z_a}\right) d_{31}^{2}\, \bar{Y}_{11}^{E} \left(\frac{\tan kl_a}{kl_a}\right) - d_{31}^{2}\, \bar{Y}_{11}^{E}\right] \qquad (3.3)$$

d_{31} = piezoelectric strain coefficient,

$\overline{Y_1}^{E}$ =complex Young's modulus of the PZT patch at constant electric field.

1

$\underline{\in}^{T}$ =complex electric permittivity of the PZT material at constant stress.

33

Z =mechanical impedance of the structural system
Z_a =mechanical impedance of the PZT patch
ω = angular frequencyk
=wave number.

Equation (3.3) is used in the damage detection in the EMI technique .The mechanical impedance Z in the equation is a function of structural parameters i.e. the stiffness, the damping and mass. Any damage to the structure will cause these parameters to change, and hence changes the mechanical impedance Z. consequently,

electro mechanical admittance *Y*, will undergo change, and serves as an indicator of state of health of the structure. Z cannot be measured easily but *Y* can be measured easily by using an electrical impedance analyzer. The measured admittance is a complex quantity consists of real and imaginary parts, the conductance(*G*) and the suceptance (*B*), respectively. The real part actively interacts with the structure and is therefore preferred in SHM applications. A plot of G over frequency serves as a diagnostic signature of the structure and is called the conductance signature.

Improvements of EMI technique in recent years

Major developments and contributions made by various researchers in the field of EMI technique during last ten years are summarized as follows. (Park et al., 2003b)

(1) Application of EMI technique for SHM on a lab sized truss structure was first developed by Sun et al.(1995). This study was then extended to a large scale prototype truss joints by Aryes et al.(1998).
(2) Lopes et al. (1999) trained neural networks using statistical damage quantifiers (Area under the conductance curve, root mean square (RMS)of the curve, rooy mean square deviation (RMSD) between damaged and undamaged curves and correlation coefficients) using experimental data from a bolted joint structure.
(3) Park et al.(2000a) reported significant proof of concept applications of EMItechnique on civil structural components such as composites reinforced masonary walls, steel bridge joints and pipe joints. The technique was found to be very tolerant to mechanical noise and also to small temperature fluctuations.
(4) Park et al. (2000a) extended the EMI technique to high temperature applications (typically>500^0c), such as steam pipes and boilers in power plants. Besides he also developed practical statistical cross section correlation based methodology for temperature compensation.

(5) Park et al.(2000b) were integrated the EMI technique with wave propagation modeling for thin beams (1Dstructures) under 'free-free' bopundary conditions, by utilizing axial modes. The conventional statistical indices of the EMI technique were used for locating damage in the frequency range 70-90 KHz.
(6) After the year 2000, numerous papers appeared in the literature demonstrating successful extension of the technique on sophisticated structural components suchas restrengthened concrete members and jet engine components under high temperature conditios (Winston et al., 2001).
(7) Inman et al. (2001)proposed a Novel technique to utilize a single PZT patch for health monitoring as well as for vibration control.
(8) Abe et al.(2002) developed a new stress monitoring technique for thin structural elements (such as springs, bars and plates) by applying wave propagation theory to the EMI measurement data in the moderate frequency range (1-10KHz).
(9) Giurgiutu et al.(2002) combined the EMI technique with wave propagation approach for crack detection in aircraft components. While EMI technique was employed for near field damage detection, the guided ultrasonic wave propagation technique (pulse echo) was used for far field damage detection.

ADVANTAGES OF EMI TECHNIQUE

(1) EMI technique shows greater damage sensitivity than the global SHM techniques.It does not need expansive hard wares like the ultrasonic techniques. The PZT patches possess negligible weight can be bonded non-intrusively on thestructure. No need to dismantle the structure.
(2) As PZT can be used both as actuator and sensor, reduces the number oftransducers and eliminates complicated wiring .
(3) The PZT patches are available at very low costs, hence can be used at anynumber of locations.
(4) This technique does not need to interfere the functioning of structures.
(5) The method can be implemented at any time in the life of a structure.
(6) Since PZT patches are commercially available and portable, there are used inwide range of applications.

LIMITATIONS OF EMI TECHNIQUE

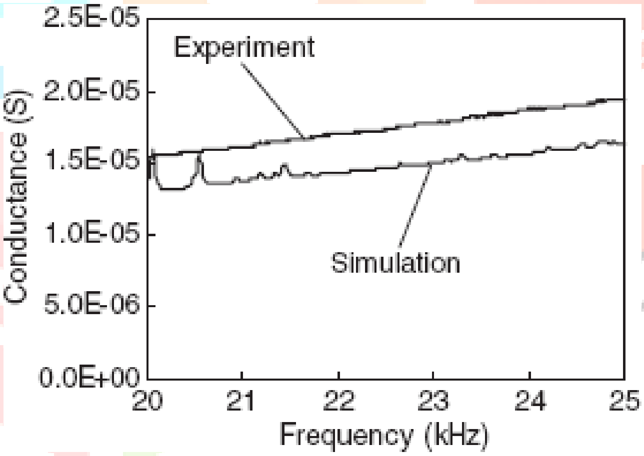
1. since the sensing zone PZT patch is limited to 0.4 to 2m only, thousands of PZT patches are required for real life monitoring of civil engineering structures like bridges and multi storied buildings.
2. This technique does not give the over all stability of structure. Since civil engineering structures are of indeterminate in nature, occurrence of cracks atsome places may not affect the overall stability of structure.

FINITE ELEMENT MODELLING OF SMART STRUCTURES

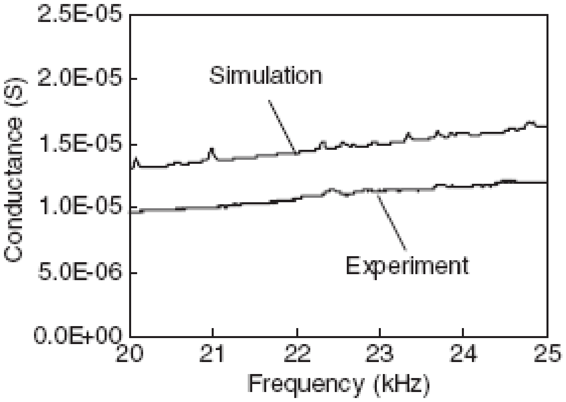
IMPORTANCE OF NUMERICAL SIMULATION

Since the last two decades, the use of smart structures in area of structural monitoring has been increased tremendously. Research in area of smart structures need tobe developed to meet the future requirements in civil engineering field. In research it is not preferable to built the structures to under go damages to study the behaviour of smart structures. This necessitates finite element modelling of smart structures. Numericalmodeling of structures eliminates the tedious and time consuming laboratory work. It is necessary to determine the conductance signatures by numerical simulation at high frequencies in addition to experimental methods. In addition to develop robust pattern recognition algorithms that can classify situations other than those in the laboratory, numerical simulation at high frequency are needed to study the signatures associated withadditional type of damage. As the experimental work are tedious and expansive, numerical simulations can significantly reduce R&D cost.

Tseng and Wang (2004) conducted numerical study on a concrete beam with a progressive damage on its surface. They investigated signature in a frequency range of 20-25 kHz, considering only one dimensional vibration. They are concluded that PZT patch are not capable of detecting damage, when damage is located 500 mm from the damage. Results of Tseng and Wang are shown in fig 4.1. From the figures 4.1(a) and 4.1(b) it could be observed that peak conductance was not obtained at the same frequencyin experimental and simulation cases.



(a)



(b)

Fig 4.1(a) Pristine conductance signatures on specimen 1. (Tseng and Wang 2004).
(b) Pristine conductance signatures on specimen 2 (Tseng and Wang 2004).

Giurgiutiu and Zagari (2002) numerically studied a beam structure with PZT patch on its surface. They made an attempt to study the effect of PZT patches in comparison with conventional sensors. Numerical study was conducted on four types of beams narrow thin, narrow thick, wide thin , wide thick. Results obtained for double thickness beams were found to be less precise due to in homogeneity introduced by the layer of glue between single thickness beams. This inhomogeneity altered the electromechanical impedance response of a beam. They conducted the study at ultrasonic frequency range. The results of their study are reproduced in fig 4.2.

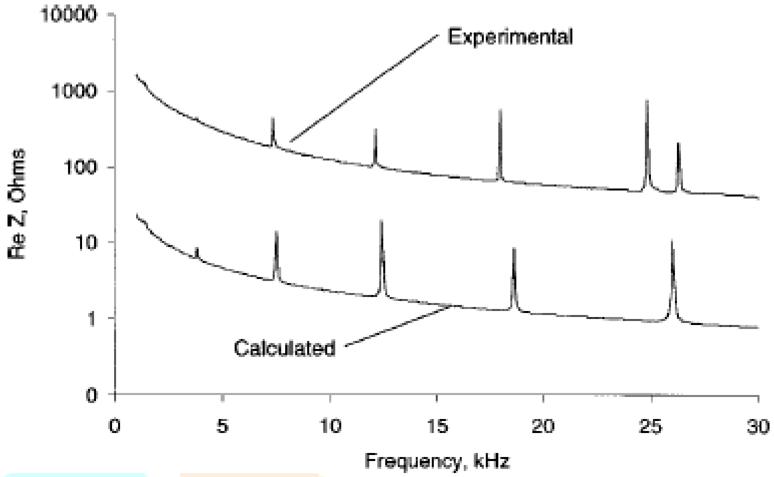


Fig 4.2 Experimental and calculated impedance vs frequency(Giurgiutiu and Zagari2002).

From fig 4.2 it is observed that the calculated impedance (or conductance) values are deviated more than 100 times from the experimental impedance (or conductance). The reason was given as nonhomogeneity introduced by the material.

In the present study, for understanding the conductance signature of the RC frame, a numerical simulation study was carried out, using the finite element method. The frequency range was kept as 100 to 150 kHz, since the experimental study by Bhalla and soh (2004) confined to this range only.

Liang’s impedance equation (Liang et al.) is used to determine electrical admittance spectrum measured at the terminals of the PZT patches. From the literature it is know that closed form solutions are available for structural impedance at low frequency techniques only. In this study it is intended to compare experimental results with numerical solutions at high frequencies typically in kHz.

When PZT patch is bonded on a structure and harmonic voltage used to activate, dynamic force of the PZT patch on the host structure is represented as pair of self - equilibrating harmonic forces of constant amplitude is given by

$$F(t) = \bar{F}e^{i\omega t} \qquad (4.1)$$

Where,

$\bar{F}$ = Amplitude of the harmonic exciting force,

ω = exciting angular frequency

t = time

The structural impedance Z at the location of the PZT patch is defined as the force acting on the driving point divided by the response velocity of the transducer *v(t)*

$$Z = \frac{F(t)}{v(t)} \qquad (4.2)$$

In response to harmonic excitation the displacement of PZT patch is given by

$$X = \bar{X}e^{i\omega t} \qquad (4.3)$$

FINITE ELEMENT MODELLING OF RC FRAME

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 numericalRC 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 4.1. Properties of the PZT patch is shown in Table 4.2

Table 4.1 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 4.2 Mechanical and electrical properties of PZT.

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

The RC frame on which experimental study was carried out is shown in fig4.3

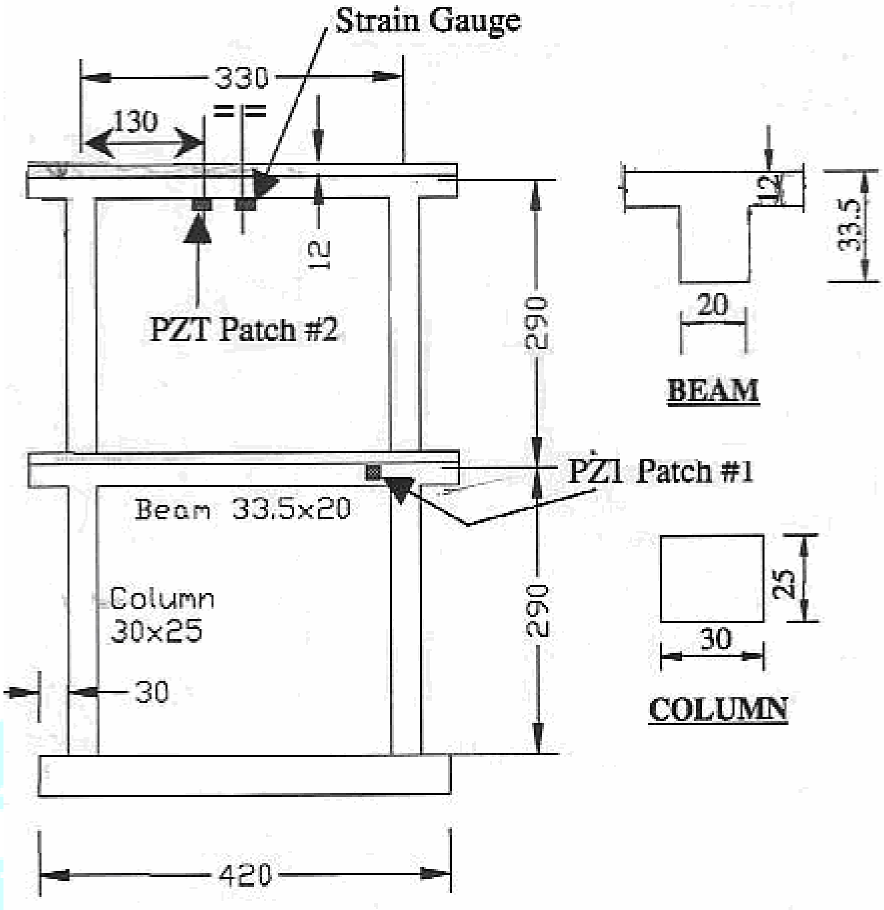
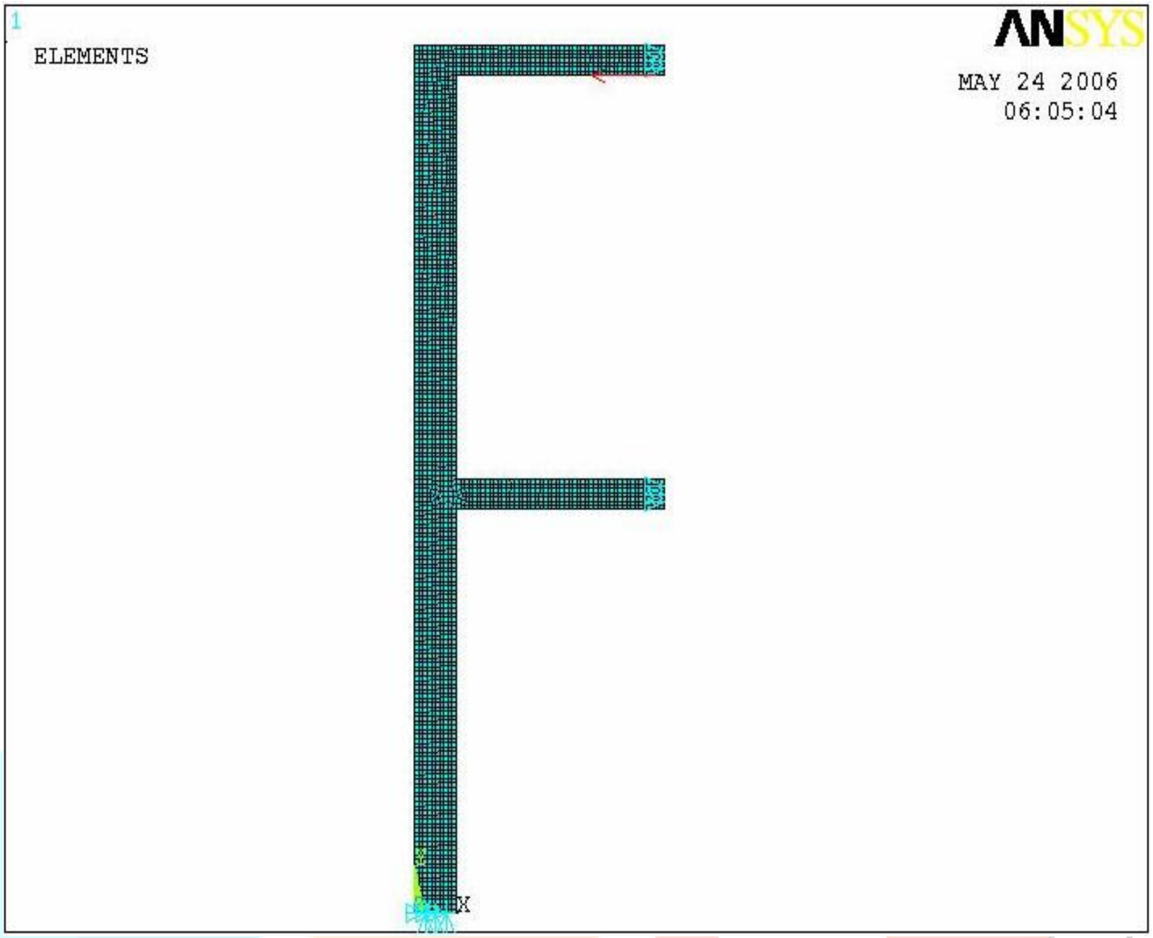


Fig 4.3 Details of the test frame (All dimensions are in mm) (Bhalla and Soh 2004).

As part of the project finite element model of the frame was developed usingplane solid 42 element of 10 mm size using Ansys 9 soft ware. 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.4.4 shows the 2D finite element model of the symmetric left half of the experimental frame.



. Fig 4.4 Finite element model of lab sized RC frame.

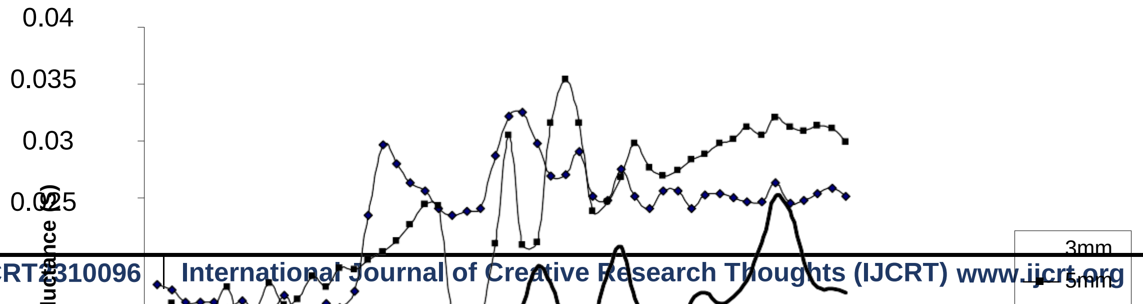
Harmonic analysis of the frame was carried out by applying self equilibratingconstant axial harmonic forces at the PZT patch in the frequency range of 100 to 150 KHz. Translational displacements in x-direction at the location of PZT patch were obtained at frequency interval of 1 kHz in between 100 to 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, 3mm element sizes. It was observed that convergence of the conductance signature attainedat an element size of 3mm. Therefore conductance signature with 3mm element size is considered as healthy signature of the numerical study. Figure 4.5 the conductancesignature 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 thelocation 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 withexperimental results. The RMSD index with respect to the pristine state signature can determined by equation (3.4)

RESULTS

The following results were obtained from numerical Analysis of Finite elementmodel of RC Lab sized frame as part-1 of the project.

Fig.4.5 shows the results of the numerical process when approached with 10mm, 5mm and 3 mm. sizes of the elements.



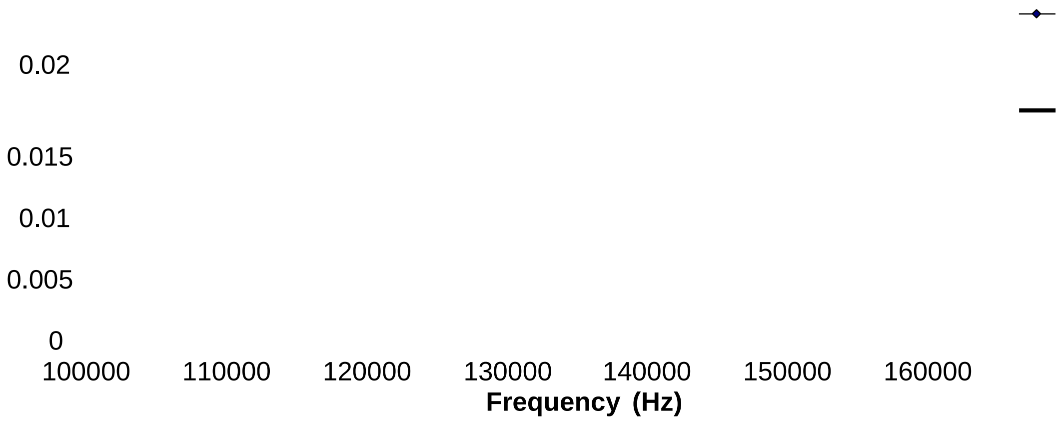


Fig 4.5 Conductance signatures using 10mm, 5mm and 3mm size of the elements.

From the figure 4.5 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 theexperimental signature shown in Fig 4.7(Bhalla& Soh, 2004)

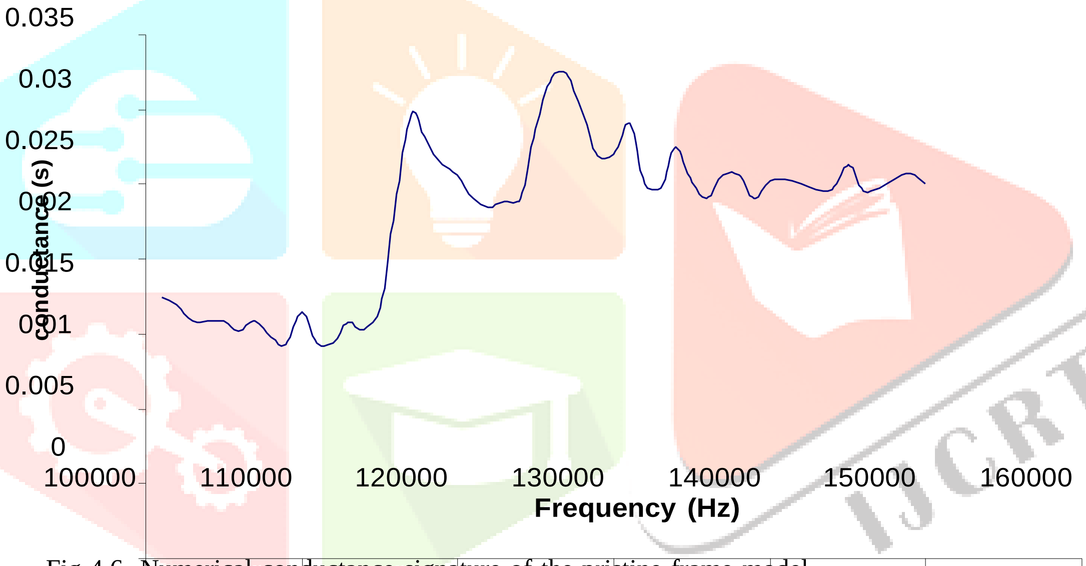


Fig 4.6 Numerical conductance signature of the pristine frame model.

Experimental Healthy conductance signature

Signature obtained by Bhalla (2003) is shown in fig. 4.7.

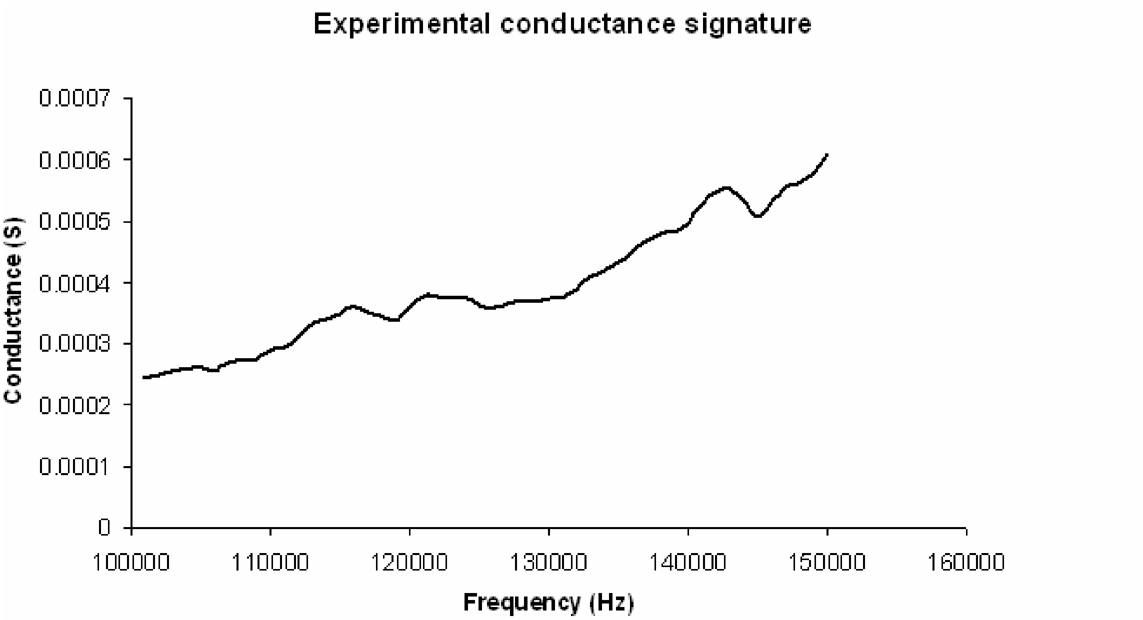


Fig 4.7 Experimental conductance signature of the pristine frame model.(Bhalla and Soh2003).

COMPARATIVE STUDY

Discussions:

It is observed from the Fig 4.6& 4.7 that simulated and experimental signatures are more are less similar in nature. Peak conductance in the both signatures occurs at quite close at same frequencies (117 and 127kHz). Although the magnitudes aredifferent, the results show much improvement than Tseng(2004) and Giurgiutiu & Zagrai (2002) results. In case of Tseng (2004), peak conductance in experimental and simulationcurves did not coincide at same frequency. In the case of Giurgiutiu & Zagrai(2002), the conductance varied by nearly 100 times. But in the present study, conductance varied by 65 times only. The variation is due to high frequency effects which could not be included in the analysis and variation of damping of concrete. From dynamic analysis point of view, the damping of concrete might varied from 2% to 6%.

DEVIATION IN CONDUCTANCE SIGNATURE WITH FLEXURAL DAMAGE

Healthy conductance signature has been compared with signature obtained byintroducing small vertical flexural crack at PZT location. This is shown in Fig 4.8. Fromit 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.

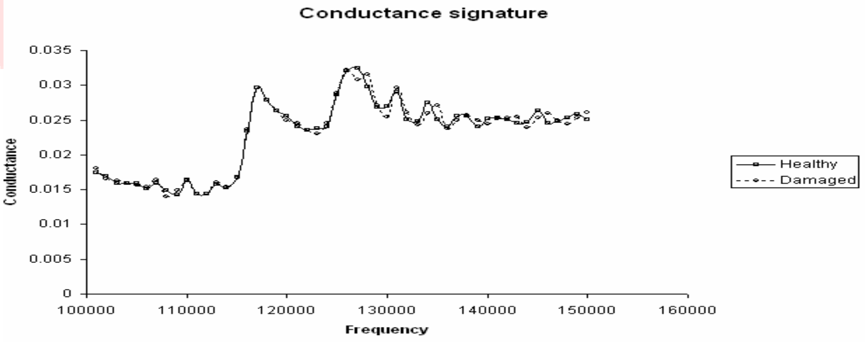


Fig 4.8 simulated conductance signature of healthy and damaged state.

CONCLUSIONS AND RECOMMENDATIOS.

CONCLUSIONS

(1) On this project, 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 patterns 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 effectof different types of cracks was introduced. And again procedure was repeated andconductance 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 experimentals. But in the present research, the deviation t was around 20 times only. Hence, this is the better simulation compared to earlier researchs.

(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 resourcse. According to Tseng and Wang (2004) detectionof damage by a PZT patch limited to 500 mm from the PZT patch. Therefore for large 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 patternscan be studied with out subjecting the structure to any cracks.

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