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Impedance based structural health monitoring using serially connected piezoelectric sensors

C. Bharathi Priya[a], N. Gopalakrishnan[a,*], A. Rama Mohan Rao[a]

[a]CSIR – Structural Engineering Research Centre, Chennai
*Corresponding author: ng@serc.res.in

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Abstract

The method of localised changes in Electro Mechanical Impedance (EMI) techniques with a cluster of piezoelectric (PZT) sensors, to detect damages is hastened in a serially connected LCR circuit under large-scale sensor deployment scenario. A heterogeneous material like concrete is utilised for technology demonstration of this novel scheme in structural health monitoring (SHM). Experiments are conducted on a concrete beam embedded with six PZT patches bonded on plates of increasing thickness by subjecting the beam to differential curing. 'Serial sensing' is used to in which the patches are connected in series and their admittance signatures are recorded from 10 kHz to 1000 kHz for different frequency ranges from day-2 to day-28. The frequency of admittance peaks of these patches are altered due to the plates of different thickness on which they are bonded. These frequency shifts are used to identify the contribution from individual patches from the serially obtained signatures. Using day-2 signature as baseline data, the variation in peak frequencies are observed and quantified using modified Root Mean Square Deviation (RMSD) as strength index. Results and observations from both serial sensing and individual recording indicate that serial sensing method using PZT is an efficient and quick method that has tremendous promising applications in SHM.

1 Introduction

The assessment of the performance of structures in terms of serviceability and ultimate limit states, durability and catastrophic failure has always been an important issue. Early detection of anomaly such as defects in a structure is necessary for condition monitoring of any structure, particularly, after a natural disaster, such as an earthquake. During these events, conventional monitoring of structures by visual inspection become a questionable health assessment method as it is highly unreliable. Inherent damages or defects in a structure developed at early-stage directly affects the strength gain process. Hence it is essential to monitor the health of concrete throughout, starting from the fresh state. This monitoring process can be continued after concrete attains its full strength after 28 days of curing. This process of monitoring a structure for any defect/damage using various techniques is popularly known as structural health monitoring (SHM). To ensure structural integrity and safety, structures have to be equipped with tools, instruments and techniques in SHM, which aims to develop automated systems for the continuous monitoring and damage detection of structures with minimum human involvement. The usage of piezoelectric sensors (PZT) is one of the smart sensing technologies of SHM. A PZT can serve as both sensor and actuator, when attached to a structure. When a PZT

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is driven by a fixed, alternating electric field of high frequency, a small deformation is produced in the PZT patch and this excites the attached structure. The response of this mechanical vibration is transferred back to the PZT patch in the form of an electrical response. When a crack or damage causes change in the mechanical dynamic response, it is manifested in the form of an electrical impedance response of the PZT patch. This principle can be widely exploited in smart SHM techniques. For continuous monitoring of a structures, they have to be equipped with several such patches and the response of each of the patch must be individually recorded and monitored. This is highly cumbersome and time consuming, if not automated. In order to overcome this, a 'serial sensing' method is utilized which allows monitoring of multiple patches with a single frequency sweep by connecting them together in series. The efficiency of this method is proved by conducting EMI based experimental investigation on a concrete beam equipped with PZT patches.

1.1 *Electro-mechanical Impedance (EMI) based damage detection strategy*

The EMI technique is widely accepted as a cost effective and highly sensitive technique for SHM and non-destructive evaluation (NDE) of a variety of engineering systems [Bhalla *et al.* 2005; Park *et al.* 2006a; Park *et al.* 2006b; Samman & Biswas 1994]. The structural component to be monitored is instrumented with a PZT patch on the surface, which is excited through an alternating voltage signal using an impedance analyzer/LCR meter, sweeping through a particular frequency range (of the order of tens to hundreds of Kilo-Hertz). At any particular frequency, the patch actuates the structure and the structural response is simultaneously sensed and measured by the patch in terms of electromechanical admittance '$Y(\omega)$'(a complex numbered reciprocal of impedance 'Z'), consisting of conductance 'G' (the real component), and susceptance 'B' (the imaginary component). The two dimensional governing equation for $Y(\omega)$ is expanded by Bhalla *et al.* [2005], which is given in Eq. 1.

$$Y(\omega) = \frac{1}{Z} = G + iB$$

$$Y(\omega) = \omega_j \frac{l^2}{h}\left[\begin{array}{c} \in^T{}_{33} - \dfrac{2d^2{}_{31}\bar{Y}^E}{1-\nu} + \dfrac{2d^2{}_{31}\bar{Y}^E}{1-\nu} \\ \left(\dfrac{Z_{a,eff}}{Z_{a,eff}+Z_{s,eff}}\right) d^2{}_{31}\bar{Y}^E(\bar{\mathrm{T}}) \end{array}\right] \tag{1}$$

where $\bar{Y}^E$ is the electrical admittance (inverse of electrical impedance) across the PZT terminals; w, l, and h represent the PZT patch's dimensions; ν is the Poisson's ratio of PZT patch; d_{31} = piezoelectric strain coefficient for the 1–3 axes; and ω= angular frequency. $\bar{Y}^E = Y^E(1+\eta j)$ = complex Young's modulus of the PZT patch (at constant electric field) and $\overline{\varepsilon^T{}_{33}} = \varepsilon^T{}_{33}(1 - \delta j)$ the complex electric permittivity (at constant stress), with the symbols η and δ denoting the mechanical loss factor and the dielectric loss factor respectively. $\bar{T}$ is the complex tangent ratio, which in an ideal situation would be equal to tan(κl)/κl. $Z_{s,eff}(\omega)$ and $Z_{a,eff}$ (ω) are the effective structural and mechanical impedances.

The sensitivity of EMI method is influenced by many factors like PZT excitation voltage, the distance between damage and sensor [Park *et al.* 2006a]. The real part of the EMI reflects the point wise mechanical impedance of the structure, and the EMI spectrum is equivalent to the point wise frequency response of the structure. As damage (a crack, corrosion, de-bonds) develops in the structure, the point wise impedance in the vicinity of damage changes. Piezoelectric active sensors placed at critical structural locations will be able to detect these near-field changes. The limitations of the EMI method reside in its sensing localization which limits its application to near field damages [Park *et al.* 2006b] and diminishes its ability to detect far field damage [Park *et al.* 2006a]. Tawie & Lee [2010] have used EMI technique for monitoring the strength development of concrete from day-3 to day-28. PZT patches coated with water-proof asphalt lacquer have been embedded in the concrete to study the changes in the real part of admittance (conductance) as an indicator of change in the strength and modulus [Wang 2011]. Same authors used metrics to investigate the effect of changes in the conductance signatures on the amount of damage inflicted on a concrete beam [Wang *et al.* 2013; Dong *et al.* 2014]. Effects of boundary conditions and low frequency loading (mass loading) have been investigated and quantified [Bharathi Priya *et al.* 2014; Wang *et al.* 2014].

2 Experimental investigations

In order for the serial sensing method to work, the patches that are connected in series must have different resonance frequency range. This is achieved by surface bonding the PZT patches with plates of different thickness using epoxy resin as shown in Figure 1. Seven PZT patches are taken and are surface bonded with stainless steel plates of increasing thickness (P1 to P7), minimum being 3 mm and maximum being 8 mm. To find the resonant frequencies, the patches with plates are excited at different frequency intervals and the admittance signature is recorded at each interval using an LCR meter connected to a laptop computer. The admittance signature is also obtained by connecting few and all of the patches in series. Among the seven patches, patch 1 is discarded due to improper bonding with plate. The real part of admittance of patch 3 and patch 7 measured individually and in series for a frequency range of 100–200 kHz are shown in Figure 2. From the series signature, the peaks due to different patches has to be identified in order to locate the damage. This is done by comparing the series signature with that of individual patch signatures. In the series signature, the individual peaks due to patch 3 and patch 7 are identified and are shown in circle and square respectively in Figure 2.

Figure 1. PZT patches bonded with plates of different thickness.

2.1 *Experimental studies on concrete beam*

Six PZT patches (P2 to P7) bonded on plates of increasing thickness, are placed at equal intervals in a concrete beam of 1.5 m span with cross section dimension 150 mm × 100 mm. One half of this beam is subjected to proper curing and the other half is left without any curing. Patches are placed at 240 mm centre to centre with 150 mm as edge distance. P2 to P7 are placed in a mixed up fashion so that peaks due to them can be differentiated easily from series signature. The arrangement is shown in Figure 3. Continuous monitoring of the beam is carried out by obtaining the admittance signatures for different frequency ranges on all days from day-2 (day immediately after casting) to day-28. The setup of concrete beam connected to an LCR meter and a computer is shown in Figure 4. All the tests are conducted at room temperature. To assess the efficiency of curing and subsequent strength gain, impedance signatures are compared for day 2, day 7, day 14 and day 21. Day 2 signatures are used as baseline measurement. In order to differentiate the peaks due to individual patches, individual signatures are obtained from the patches on day 2 alone. Rest of the days, signatures are obtained by connecting them in series for different frequencies and peaks are identified.

The admittance signatures are acquired for the patches connected in series on all days for various frequencies ranging from 10 kHz to 100 kHz in steps of 10 kHz and 100 kHz to 1000 kHz in steps of 500 kHz. The signatures were downloaded in the computer and graphs are plotted between frequency and conductance. Figure 5 presents a few of these plots for different days for selected frequency range of 300 kHz to 400 kHz.

From the plots shown in Figure 5, the peaks due to individual patches are identified using baseline data recorded for individual patches. The sub-ranges identified due to individual patches are used in calculating the RMSD values.

2.2 *Damage index – root mean square deviation (RMSD)*

In this impedance method for structural health monitoring, the key indicator of variation in

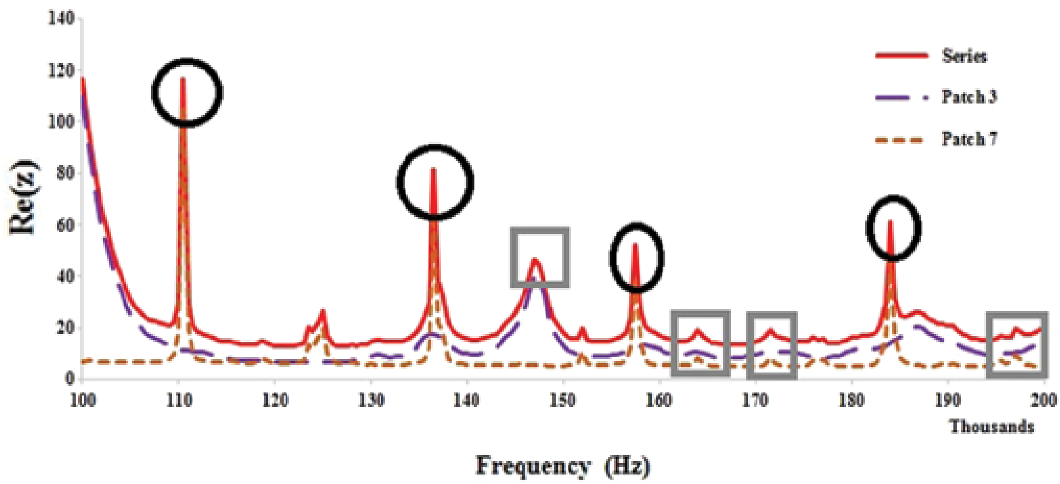

Figure 2. Frequency vs Re(z) plot for 100–200 kHz range.

signature is observed and quantified using statistical techniques. Giurgiutiu and Rogers [1998] used the root mean-square deviation (RMSD) between the signatures of the two states as the suitable damage index. Bhalla *et al.* [2005] in a detailed study on detection and characterization of damage in concrete cubes compared the above techniques and observed that the RMSD between the signatures was the most suitable damage index to characterize structural damage. In serial sensing, the conventional RMSD equation has to be modified suitably to highlight the variation in signatures. In our case, the numerator of RMSD is computed only for the sub-range of the individual patches, whereas the denominator is computed for the whole range of frequency. The RMSD expression used is given in Equation 2.

$$RMSD = \left[\frac{\{\sum (G^1_i - G^0_i)^2\}_{sub-range}}{\{\sum G^{0\,2}_i\}_{full-range}} \right]^{0.5} \qquad (2)$$

where,
G^1_i – conductance at the i-th measurement point on Day of interest
G^0_i – conductance at the i-th measurement point on Day 2 (baseline).

The computed RMSD values for 300–400 kHz range when patch 4 and patch 7 are in series, is presented in Table 1. The computed values are also compared against RMSD calculated from individual readings of patch 4 and patch 7. It is presented in Table 2.

From Table 1 and Table 2, it is observed that patch 4 has lesser RMSD value compared to patch 7, on day 21. It is inferred that, patch 4 which is in the portion of under-cured concrete gains its strength slowly compared to patch 7 which is cured properly.

This is also ensured by calculating RMSD values of all the patches from individual recordings. This is presented in Figure 6. The irregular value of RMSD for Patch 2 on day 21 is expected to have occurred due to erroneous recoding of the

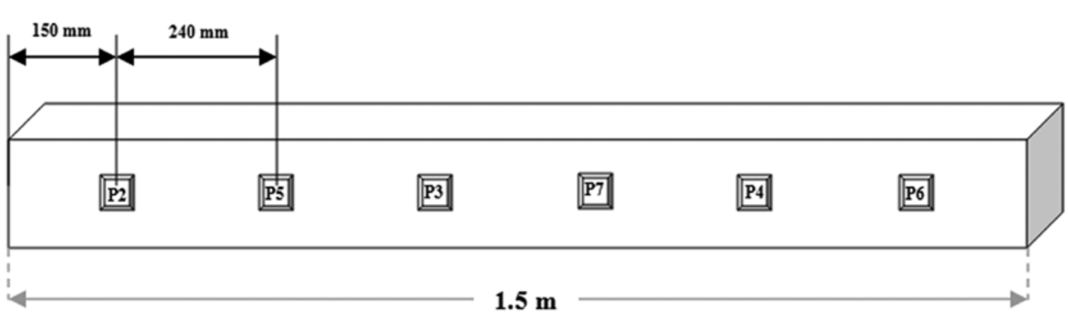

Figure 3. PZT patches in concrete beam.

Figure 4. Experimental setup of concrete beam.

data. Hence it is discarded. The patches 5, 3 and 7 located on good curing side show higher RMSD values compared to the patches 4 and 6 located on bad curing side. This trend can be attributed with the fact that good curing side has gained its strength faster resulting in higher conductance shift, increasing the RMSD compared to baseline. The patches in bad curing side has gained comparatively lesser strength resulting in less shifting of conductance signature. This has resulted in lesser RMSD values for these patches.

2.3 *Summary and inferences*

The application of smart piezoelectric sensors in structural health monitoring is experimentally investigated and presented in this paper. A simple approach to locate and also to quantify the health of the structure from the measured signatures of the PZT patches structures is demonstrated using serial sensing technique. This can be used to quickly assess the integrity of the critical parts of the structure after a disaster

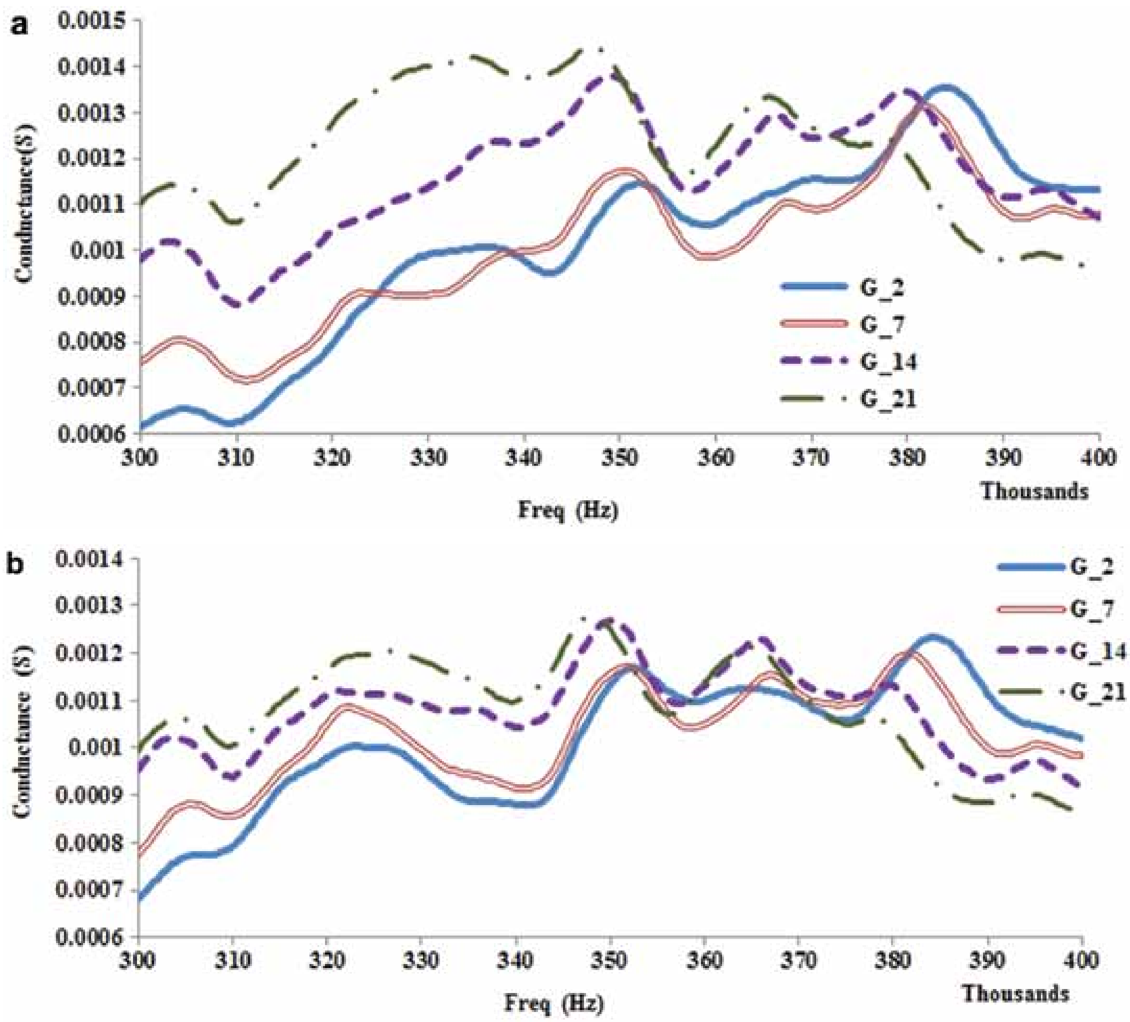

Figure 5. Conductance signature for (**a**) patches 3 and 7 in series (**b**) patches 4 and 7 in series.

Table 1. Percentage difference in RMSD values from patches 4 and 7 connected in series.

Patch	RMSD (%)		
	Day 7	Day 14	Day 21
4 (360–375 kHz)	1.10	2.52	2.01
7 (340–355 kHz)	1.28	5.54	7.31

Table 2. Percentage difference in RMSD values from patches 4 and 7 recorded individually.

Patch	RMSD (%)		
	Day 7	Day 14	Day 21
4 (360–375 kHz)	5.03	4.10	6.90
7 (340–355 kHz)	2.28	8.09	10.68

such as an earthquake; especially, the inaccessible parts of the structure, which are not exposed to visual check, can be easily monitored using the PZT patches. The studies conducted on a concrete beam embedded with six PZT patches bonded with plates of different thickness show that condition monitoring using conductance signatures and RMSD is found to be a reasonable index that can be used. The conventional RMSD equation is suitably modified in order to be used with serial sensing method. The modification of numerator of the RMSD equation is found to emphasize the contribution from any particular patch when connected in series with other patches. The pattern of computed RMSD values from individual patch recording is found to coincide with the RMSD values computed from serial sensing. These results indicate that serial sensing in impedance-based method is promising for quick and efficient condition monitoring of concrete structures in the field of SHM. The following points summarise the methodology and results:

- Initially individual EMI signatures have to be collected from each of the patch and the distinguishing peaks for each patch have to be identified. The common peaks, likely to occur in neighbourhood patches or surrounding plates of nearly same thickness have to be in different groups.
- The cluster of piezo patches for which serial recordings have to be taken can be decided based on the previous step. The collection of patches forming a single group need not be at neighbourhood locations. Only purpose is to maximise the difference in the peaks.
- The modal density of admittance peaks, which are less and more damped out in the case of quasi-brittle material like concrete shall result in reduced magnitudes of RMSD, accentuated by a further process of partial RMSD. A methodology to magnify the magnitude of these peaks have to be identified and resorted.
- Once the peaks are well separated and farther apart for individual patches forming a group, periodical data can be taken and strength gaining features or damage features can be identified.

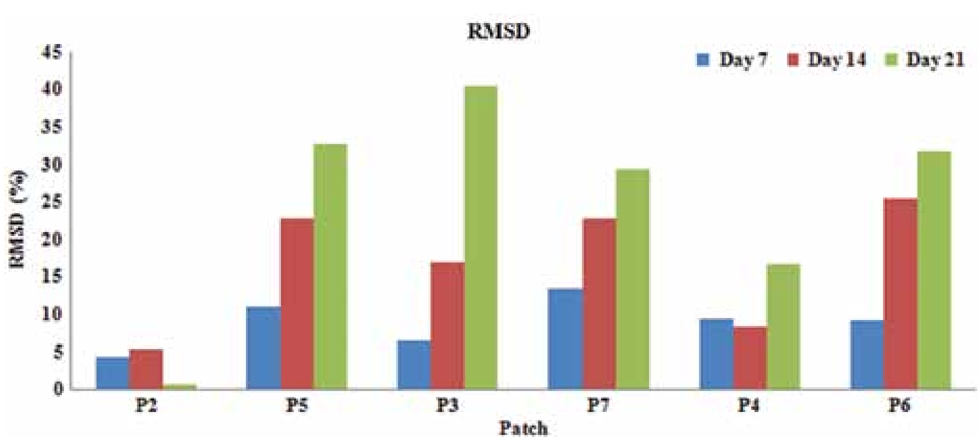

Figure 6. RMSD values recorded for individual patches.

3 Conclusions

The ability of the smart piezoelectric (PZT) sensors, using Electro Mechanical Impedance techniques (EMI) in concrete is studied for their utilization in structural health monitoring (SHM). Experiments are conducted on a concrete beam embedded with six PZT patches bonded on plates of increasing thickness by subjecting the beam to differential curing. A novel method called ‘serial sensing’ is used, in which the patches are connected in series and their admittance signatures are recorded from 10 kHz to 1000 kHz for different frequency ranges from day 2 to day 28. From the different ranges, 300 kHz to 400 kHz is found to be ideal with more number of peaks (increased modal density) observed. Hence it is selected as range of interest for the current study. The resonant frequency of the patches are altered due to the plates of different thickness on which they are bonded. This separation of peaks is ensured by recording the admittance signature before embedding the patches inside the concrete. From the signature of individual patches, the frequency peaks due to each patch is identified from the serially sensed signature. Using day 2 signature as baseline data, the variation in peak frequencies are observed for each of the patches. The conventional Root Mean Square Deviation (RMSD) equation is modified suitably in order to quantify the variation due to individual patches from the serial sensing signature. From the results, RMSD of the patches from serial sensing are found to follow the same trend as that of the RMSD calculated from individual patch data. It is also found that, patches located in good curing side have higher RMSD compared to patches in bad curing side. This can be attributed to faster strength gain of concrete which is cured properly compared to that of concrete subjected to improper curing. The same trend is observed from individually recorded values of all the patches. Results and observations from both serial sensing and individual recording indicate that serial sensing method using PZT is a simple, efficient and quick method that has tremendous promising applications in the field of SHM.

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Ms. C. Bharathi Priya is a scientist in Advanced Seismic Testing and Research Laboratory (ASTaR lab), CSIR-Structural Engineering Research Centre, CSIR Campus, Taramani, Chennai. She obtained her B.E

in Civil Engineering from College of Engineering, Guindy, Anna University and completed her masters in Engineering of Structures from AcSIR. She is currently pursuing her doctoral Research in the area of structural control at AcSIR. Her area of research includes Structural Dynamics, Structural Control and Structural Health Monitoring. She has published in various national and international peer reviewed journals and conferences.

Dr. N. Gopalakrishnan, Chief Scientist, Advanced Seismic Testing and Research Laboratory (ASTaR lab), CSIR-Structural Engineering Research Centre, CSIR Campus, Taramani, Chennai completed his bachelors in Civil engineering from College of Engineering, Guindy, Anna University and masters in structural engineering from Indian Institute of Technology, Madras. He obtained his Ph.D from Indian Institute of Science, Bangalore (With 12 International Journal Publications). He joined CSIR-SERC as Scientist B in 1987, after an year of service at Tata Consulting Engineers, Bangalore. His area of specialization include Structural Dynamics, Structural Health monitoring and Earthquake Engineering. He has published 61 papers in national and international publications.

Dr. A. Rama Mohan Rao is a chief scientist in CSIR-Structural Engineering Research Centre, CSIR Campus, Taramani, Chennai. His research interests include Computational Structural Mechanics, Structural System Identification, Health monitoring & Control, High-Performance Computing, Soft Computing Techniques for structural Engineering. He has several publications in SCI and other peer-reviewed journals and conferences.