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Structure Health Monitoring using Vibration-based Technique

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Abstract: SHM holds the Promise for improving the structural performance with an excellent cost /benefit ratio. Condition assessment is a technique use7d in behavior monitoring in the damage detection, to ensure the serviceability and the durability of the structures.In this report condition assessment of the structures using low frequency technique is being done through experimental modal analysis and computational analysis is done by using software ANSYS over structural elements beam.In the Experimental Modal Analysis, investigation is carried over a 2m and 4m Reinforced concrete beam.

1) Response of the structure is obtained through accelerometer, PZT and electric strain gauge
2) Aglient Multimeter is used as data analyzer for data acquisition

In the computational analysis using ANSYS software, the Modal analysis is done both in the 1D and 3D modeling. Damage induced analysis is carried in the ANSYS software and the difference in the modal frequency is noted, which was compared in the experimental modal analysis of the damage induced analysis of the beam.

In 1D and 3D modal analysis experimentally and analytically the results were found in close agreement with small error. Damage induced Analysis is done in 3D modeling in computational analysis it has to be checked with the experimental modal analysis.

Damage detection and Condition assessment of the beams were carried out with Mode shape curvature and Flexibility method, changes in the beam element were compared with the real time experimental specimen and damage detection was found in very close approximation.

Keywords: Structure Health Monitoring (SHM), Analysis Software(ANSYS), Piezoceramic Patches (PZT)

I. INTRODUCTION

SHM is a broad concept that encompasses various techniques to assess and measure the on-going in-service performance of the structure, symptoms of the incipient damage and health of the structure during and after extreme natural calamities.

SHM is basically a continuous diagnosis of the health of the structure involving measurement of the loads, the performance and the critical response of the structural system and its components. [1]

This type of monitoring is also a non-destructive in-situ evaluation of damage, but the technique and methodology involved in SHM is different in many ways from non-destructive testing methods.[1] The subject and technology involved in SHM is kind of bridge between the field of civil engineering and application of electronics system in civil engineering that has set the foundation for a new field with the name rightly coined as *Civionics.*

[2] Many civil engineering structures such as dams, bridges, ports & harbours, marine structures, nuclear containment vessels, multi-storeyed buildings etc. constitute major aspects towards the national wealth. Practically, the maintenance costs of these structures are very high, so even a small reduction in the maintenance cost leads to significant saving. Hence, structural health monitoring is one of the most cost effective method for maintenance of these super structures.

Hence, detection of problems at early age, such as, failure cracks at critical locations, corrosion, delaminations, spalling of concrete etc., can help in prevention of catastrophic failure and deterioration of structure, which can also help to reduce the major repair works.

SHM has great abilities for enhancing the performance, serviceability and increased life span of the structures and, as a result, could contribute notably to the economy of the nation. The concept of long-term surveillance of civil engineering structures is evolving as a result of the requirement of cost-effective maintenance of complex structures and the development of new sensor technologies & methods.

II. IMPORTANCE OF STRUCTURAL CONDITION ASSESSMENT

Nowdays, it has become very important to perform **Structural Condition Assessment** with more accuracy & more precision.[3]The conventional way of detecting damge is by visual inspection but due to increased size & complexity of structures this assesssment is not very effective. Moreover, when damage is inevitable inside the finish materials and fire proofing, removal of facing material is necessary and that may be too costly & time consuming.

With improvement in measuring apparatuses and technology, various new damage detection technique have been developed through experiments and measurements. [3] Such nondestructive damage evaluation methods as ultrasonic, acoustic emission and x-ray inspections are techniques which indirectly investigate structural defects without tempering with the structure. Slight damage which cannot be seen by the human eye, can be detected with these techniques, but only the local damage not the gobal structural damage condition. So, there is a need for quantitative global damage detection methods that can perform assessment of complex structures, which can also examine changes in vibration characteristics of the structure.

Doebling et al (1996), [4] broadly elaborated vibration-based detection methods.Vibration-based damage detection methods that evaluates the global structural condition. [4] It is based on the fact that structural damage usually causes a decrease in structural stiffness and an increase in structural damping, thereby producing change in vibration characteristics. These methods are non-destructive methods. Hence, damage detection is done by comparing the undamaged and the damaged states of the structure.

Vibration data used to detect structural damage fall into two categories; modal data and the frequency response function (FRF). Modal data include the natural frequency, mode shape, mode shape curvature, modal flexibility and modal strain energy. The most common dynamic parameters used for damage detection are the natural frequencies and the mode shapes. But changes in natural frequencies alone cannot provide geographic data about structural damage. Therefore, mode shape information is additionally required to localize the damage.

III. DAMAGE IDENTIFICATION METHOD

Based on the vibration features,the damage identification methods are classified into four major categories: natural frequency-based methods, mode shape-based methods, curvature mode shape-based methods, and methods using both mode shapes and frequencies.

[5] Based on the amount of information provided regarding the damage state, Farrar and Jauregui (1998) defined four distinct objectives of damage detection are :

A. To identify the damage.
B. Determination of the geometric location of the damage.
C. Quantification of the severity of the damage.
D. Prediction of the remaining service life of the structure.

IV. EXPERIMENTAL AND DATA PROCESSING TOOLS

In this study of work, we examine the low frequency dynamic response technique by using electrical strain gauge, accelerometer and piezoceramic (PZT) patches.

A. Tool Requirements

For practical application, the following hardware components are required.

1) Electrical strain gauge, accelerometer and piezoceramic (PZT) patches are bonded to the structures, which acts as integrated sensors.
2) Data analyzer, for structural frequency response function acquisition. In this study **34411A Agilent multimeter** was used.
3) A personal computer, for graphic control and display.
4) Electro Dynamic Shaker machine with its Function generator.

B. Experimental Approach

1) *Firstly* : Creation of analytical models.
a) Determination of theoretical sensitivity of the method.
b) Mark the placement of the sensor.
c) Discuss the model of the experiment.

2) *Secondly* : Experimental verification
a) Test simple structural level specimens with various damage, work up through building block element.
b) Check the feasibility of implementing method in SHM system.
3) *Thirdly* : Architecture layout of the system
a) Sensor integration.
b) Test samples with realistic sensors.
c) Test method on representative structures.

C. *Experimental Analysis*

The experimental setup is done for conducting random vibration analysis on the Beam with the help of impact hammer, resistance is measured through electronic strain gauge and voltage through accelerometer and peizoceramic patches. The data obtained is transformed into frequency response function. From the plot modal frequencies of the first 3 modes is noted.
The smart piezoelectric transducers were fixed to the surface using CNX adhesive and were soldered through wires to the multimeter. Multimeter was appropriately calibrated to get the readings for time duration of 20 seconds with small time interval of 1 milliseconds in order to capture the first few nodal frequencies Two strikes were given by the hammer in order to generate sufficient response for time duration of 20 seconds. These two strikes can be seen in the form of two peaks in the *Fig.2*. The response generated by the PZT patch and the region analyzed from the response patch was shown in the *Fig.3*.The response of the PZT from time domain to frequency domain through fast fourier transform and first three fundamental frequency is considered for the analysis was shown in the *Fig.4*.

1) *Experiment on 2m concrete Beam:* Experiment on 2m RC beam was carried out on a symmetric support condition for the condition assessment as shown below. A simply supported overhanging 20cm on both sides is taken into consideration which is shown below in *Fig.1*.

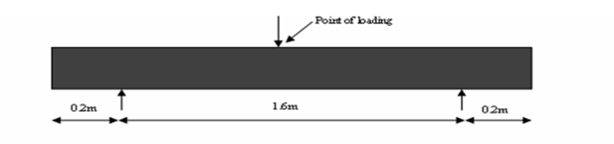

Fig.1. Simply supported overhanging 20cm on both sides.

Due to some uncontrolled noise, the damping nature is shown in the Response of the PZT, in analysis it is eliminated by Filtering technique and the Frequency Response.

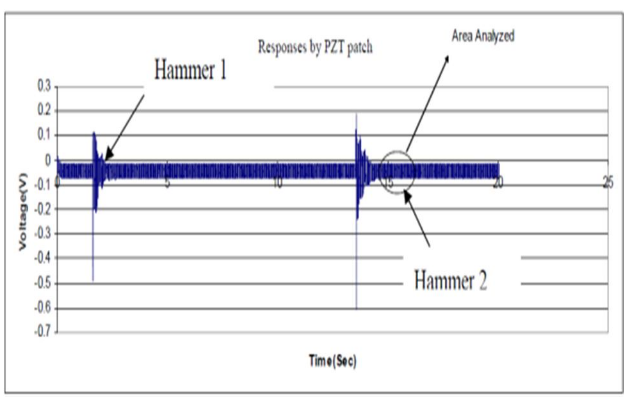

Fig.2. Responses by PZT Patch

The following region was analyzed for frequency response to obtain the experimental values of modal frequencies for the longer span of 2 m concrete beam.

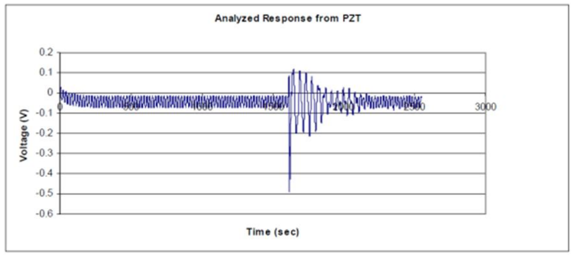

Fig.3. Graph showing Regions analysed for PZT Patch

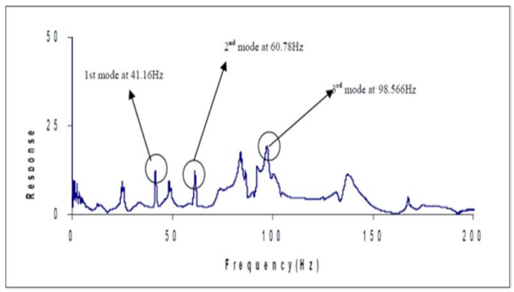

Fig.4. FFT analyses for PZT Patch

2) *Experiment on 4m Concrete Beam:* On 4m RC beam experiment was carried out in 2 support conditions as shown below. *Fig.7* shows the FFT analysis for the PZT patch response and the first 3 fundamental frequencies under the symmetric support condition. *Fig.8.* shows the FFT analysis of the accelerometer generated response and first four fundamental frequencies under the asymmetric condition.

Supported condition-1: Overhanging of 50cm on either side (Symmetric).

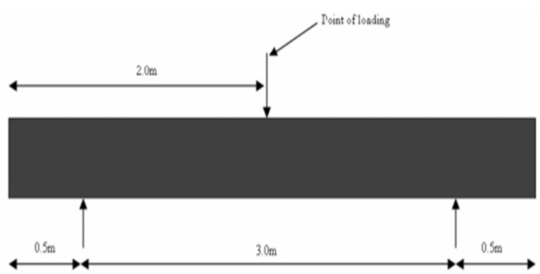

Fig.5. Symmetric 4m long span over-hanging beam

Similarly, the experiment is repeated after inducing the damage in the RC beam under the same support conditions. The fundamental frequencies of the damaged RC beam were noted and condition assessments of the structures were carried out.

Supported condition-2: Overhanging of 50cm and 100cm on either side (Asymmetric).

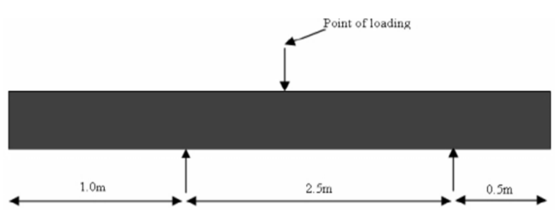

Fig.6. Asymmetric 4m long span over-hanging beam

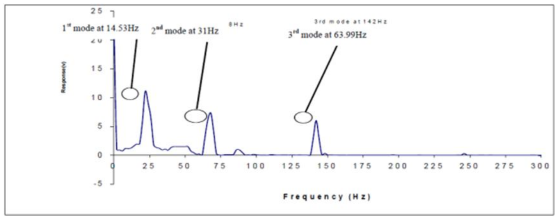

Fig.7. FFT Analyses for PZT Patch Response (Support condition-1)

The first three distinct peaks in the FRF are seen at 14.53 Hz, 31Hz and 63.99Hz indicating them to be the first three modes of vibration for the 4-meter concrete beam.

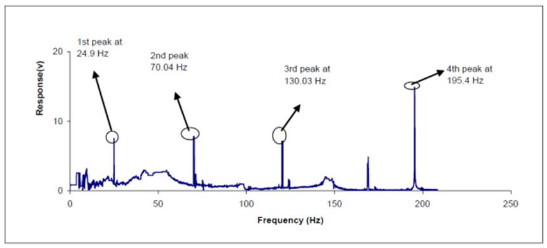

Fig.8. FFT Analyses for Accelerometer generated response (Supported condition-2)

The peaks obtained using the PZT are obtained at 24.90 Hz, 70.04 Hz, 130.03 Hz and 195.40 Hz.

V. CONDITION ASSESSMENT OF BEAMS

In this chapter, the condition assessment of the concrete beams was carried out using Change in Flexibility Method and the Mode shape curvature method.

A. Damage Location & Identification Method ON 2m Beam

This method requires only the information of the natural frequency changes of the damaged structure and the mode shapes of the undamaged structure. The basic framework of this work has been presented in Naidu et al., 2002.

[6] The governing equation of motion for dynamic system is

$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{F(t)\}$ ……...(1)

Where

[M]=Mass matrix; [C] =Damping matrix; [K] =stiffness matrix.

The Eigen frequencies and mode shape vectors of the dynamic system is given by

$\{\boldsymbol{\omega}\} = \{\omega 1, \omega 2, \omega 3, \omega 4......\}$ ……...(2)

$\{\boldsymbol{\Phi}\} = \{\Phi 1, \Phi 2, \Phi 3, \Phi 4 ......\}$ ..…….(3)

The angular frequency can be replaced by cyclic frequency, *f,* and as such set of natural frequencies in Hertz is given by

$\{\mathbf{f}\} = \{f1, f2, f3, f4 ...\}$ ..…….(4)

After the structure is damaged, the shift in frequency is given by,

$\{\boldsymbol{\Delta f}\}m = \{\Delta f1, \Delta f2, \Delta f3, \Delta f4, ...\}$ ……...(5)

Sorting the shift frequencies in the descending order we have

$\{\boldsymbol{\Delta f}\}m = \{\Delta f1, \Delta f2, \Delta f3, \Delta f4, ...\}$ ………(6)

The Damage indicator or Damage metric, DI for each element is given by

$$DI_x = \frac{\sum_{i=1}^{m} I\Delta E^i_{px} I\Delta f^i}{\sum_{i=1}^{m} \Delta f^i} ; \quad DIy = \frac{\sum_{i=1}^{m} I\Delta E^i_{py} I\Delta f^i}{\sum_{i=1}^{m} \Delta f^i} ; \quad DIz = \frac{\sum_{i=1}^{m} I\Delta E^i_{pz} I\Delta f^i}{\sum_{i=1}^{m} \Delta f^i}$$

Where,

m = number modes chosen

P = number elements in the structure

i = number chosen mode shapes

Δf = shift frequency

ΔE = element deformation parameter.
ΔE^{i}_{px} = longitudinal displacement of node $i+1$
ΔE^{i}_{py} = ½*{curvature value of node $i+1$ + curvature value of node i)
ΔE^{i}_{pz} = rotation of node $i+1$ – rotation i)

The damage metric index computed for the damaged beam elements of the 2m and 4m beam were shown below. *Fig.9* shows the elemental damage at various loads over the 2m beam in the symmetric condition. In the figures a threshold damage metric index of 70% were taken. The beam was divided in 50 elements so that each element was of 4cm in length.

During experiment the loads were applied at the centre and it is found that the bending cracks were found at the centre and the shear cracks the support conditions. From the figures shown below it was evident that the elemental damage propagation were taking place at the centre and support condition.

In the 2m beam numerical analysis only the modal displacement were used, hence the damage location were found to be in close approximation with the experiment but the severity of the damage location were not in much correlation.

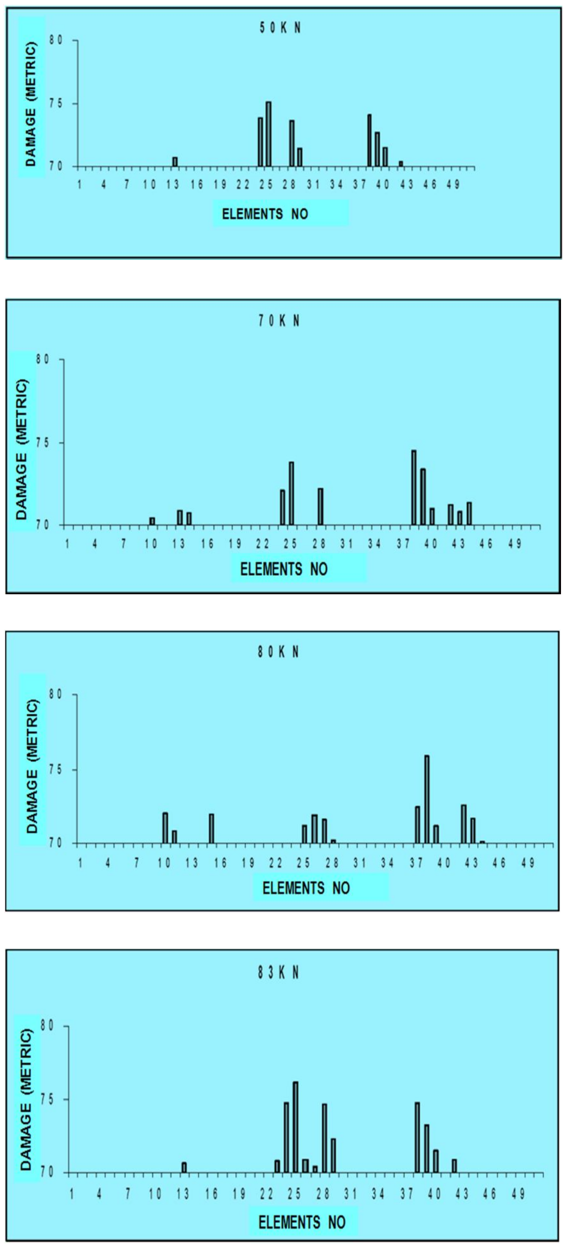

Fig.9. ELEMENTAL DAMAGE AT VARIOUS LOADS

B. Change in Flexibility OF 2m Beam

In this method the change in flexibility of the beam was calculated using [7] the Pandey and Biswas and the change in elemental flexibility was plotted. *Fig.10* shows the change in elemental flexibility of the 2m beam. From the figures it is clear that the bending and the shear crack development at the centre and support was in correlation with the high flexibility change in the plots at the centre and support elements as shown below.

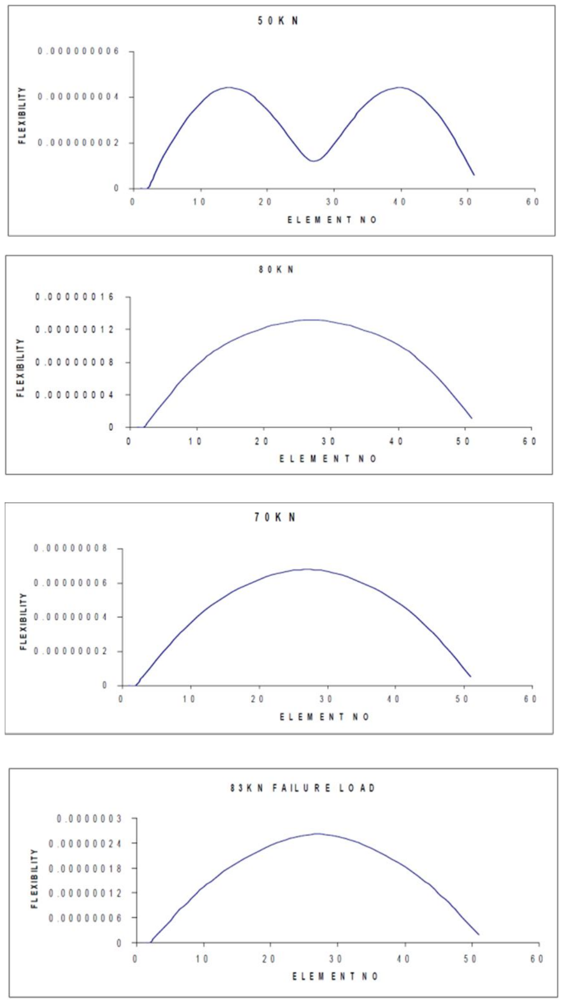

Fig.10. Change in flexibility of the beam element

C. Damage Location & Identification Of4m Beam

Damage metric index were computed on the 4m beam under the symmetric and asymmetric conditions .In the symmetric condition only the final damage inspection was done, whereas in the asymmetric condition damage assessment at various load levels were carried out.

In the asymmetric condition the bending cracks at the centre and shear cracks at the unsupported condition found in experiment was in correlation with the elemental damage at the corresponding element numbers.

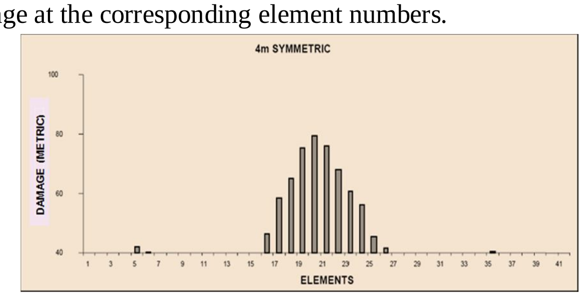

Fig.11. Elemental Damage in Symmetric Condition

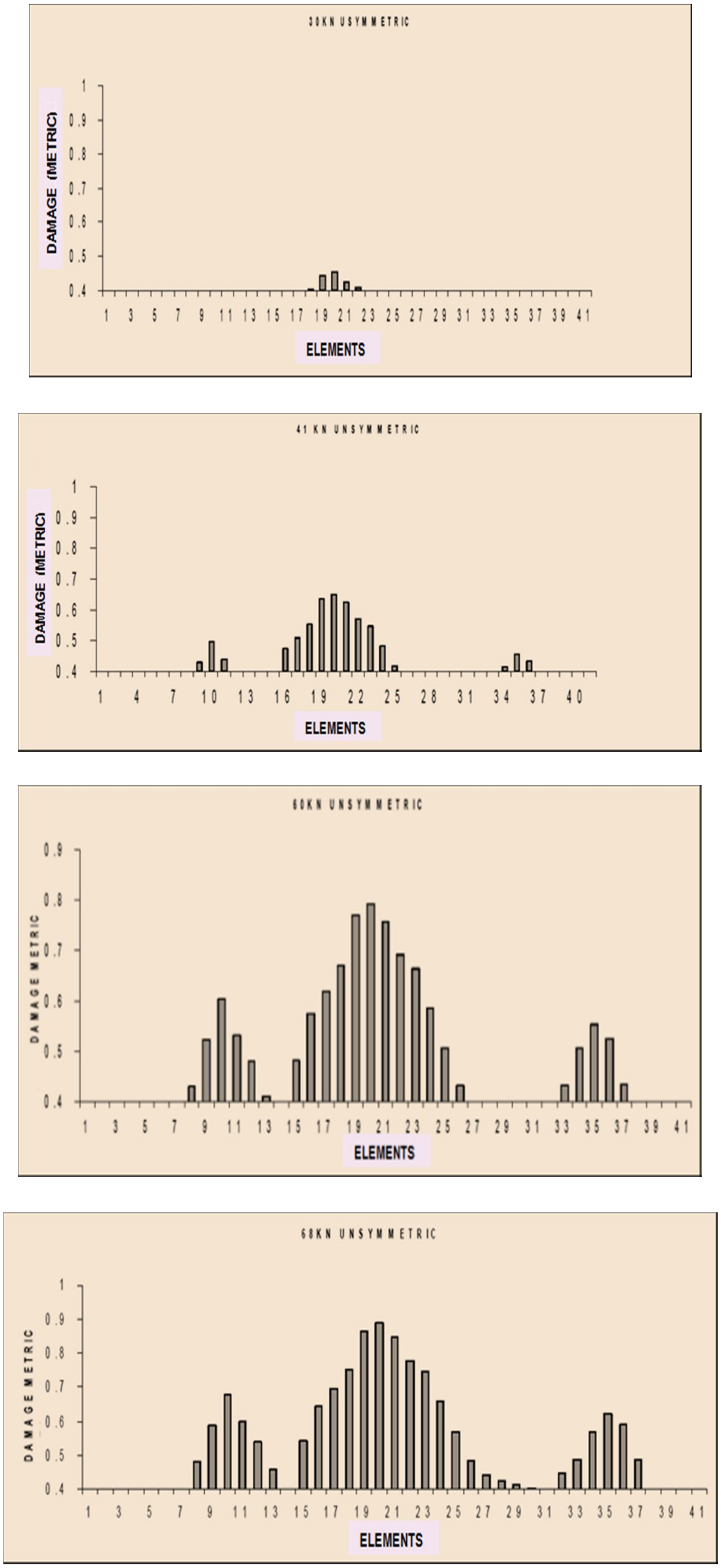

Fig.12. Elemental damage in unsymmetric condition

D. Change in Flexibility Method ON 4m Beam

Change in flexibility of the 4m beam was computed accordingly. The beam was divided into 40 elements hence the overhanging of the beam was up to 10th element and from the 35th element at the other end.

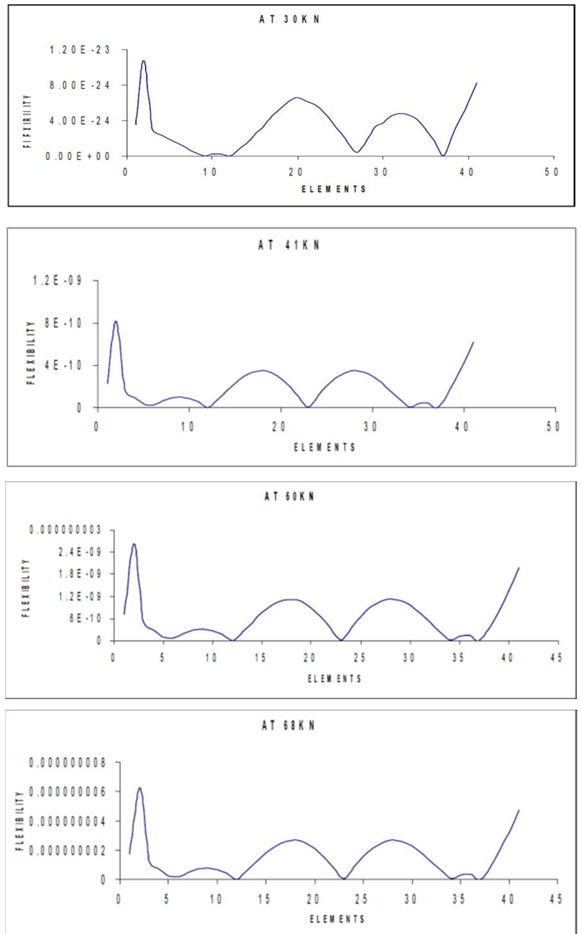

Fig.13. Flexibility Change in Elements of 4m Beam Unsymmetric Condition

VI. FINITE ELEMENT ANALYSIS

In this study, analytical detail of the experiments was described through the modelling software [8] ANSYS. Elements used in analysis for 1D and 3D, computational results of the analysis and the mode shapes were given. The modelling software ANSYS is used to model the beam with different beam elements in 1D and 3D modelling.

A. Description Of Elements

In 1D analysis the beam is modelled using BEAM4 element (i.e. 3D Elastic 4)

1) Specification of BEAM4

a) Nodes

b) I, J, K (K orientation node is optional)

2) Degrees of Freedom

a) UX, UY, UZ, ROTX, ROTY, ROTZ

b) In 3D analysis the beam is modelled using SOLID45 element (i.e. Brick 8 node45)

3) Specification of SOLID45

a) Nodes

b) I, J, K, L, M, N, O, P

4) Degrees of Freedom

UX, UY, UZ

B. Computational Results

By using ANSYS analysis software, computational analysis is performed on 4m span beam both in 1-Dimensional and 3-Dimensional modelling. In 1D analysis the [8] ANSYS output is compared with the analytical value. *Table.1.* shows the ANSYS 1-Dimensional frequencies of the 2m beam

1) 1-D ANALYSIS (2m Concrete Beam)

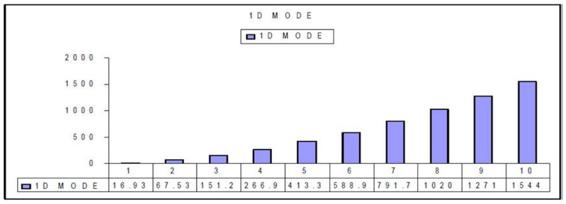

Table.1: 1D ANSYS Output

2) *3D Analysis: Table.2.* and *Fig.14.* shows the ANSYS output of the 3D analysis and the element modelling of the 2m beam at the various load level.

3D Analysis: ANSYS Output (2m Concrete Beam)

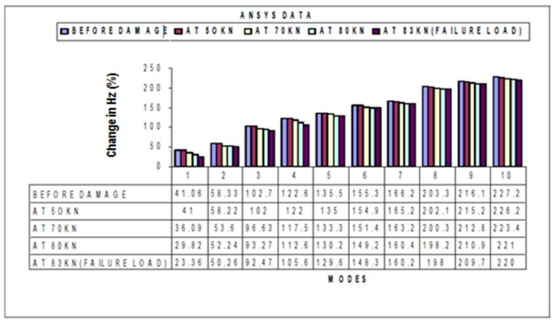

Table.2. 3D ANSYS Output

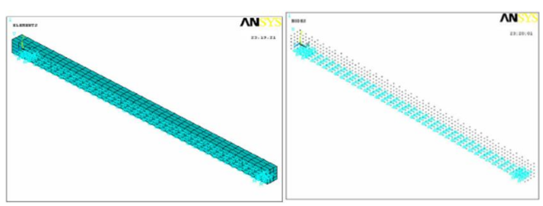

Fig.14. The Beam Modelling and Nodal Points in ANSYS.

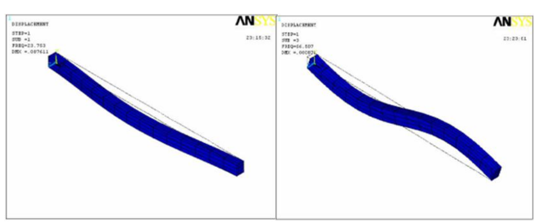

Fig.15. 3-Dimensional Mode Shapes

In 3-Dimensional analysis, the beam is modelled into block volume, Using solid45, and brick element. The block is meshed into hexagonally of dimensions (0.1× .05× .05) m^3. In order to eliminate the longitudinal mode shapes the beam is supported as pinned-pinned condition. As in experimental setup the beam is over hanged by 0.2m at both the ends.

The torsional effect can be seen in the 3D analysis, which can be compared with the experimental data.

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3) *Damage Induced Analysis in Concrete Beam:* To stimulate the cracks in the Beam, the Beam is modelled in three sub beams in which the propagation of the crack is varied by varying the width and the height of the crack between the sub beams. The beams are analysed in the [8] ANSYS software so that it behaves as a monolithic beam with the crack propagation.

Damaged Induced 3d Analysis: Ansys Output (2m Concrete Beam)

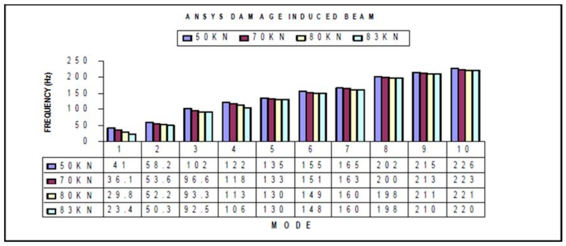

Table.3. 3D ANSYS Output of Damaged Beam

Mode Shapes of 2m Concrete Beam After Damage Induced

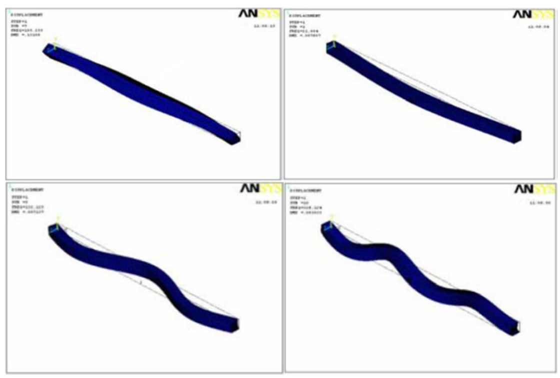

Fig.16. 3D Mode shapes of the Damaged Beam

4) *ANSYS Analysis Of 4 Metre Concrete Beam*

One Dimensional ANSYS Analysis (4m Symmetric)

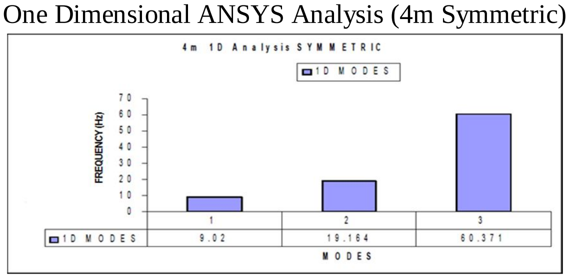

Table.4. 4m Beam 1D Analysis symmetric

One Dimensional Ansys Analysis (4m Asymmetric)

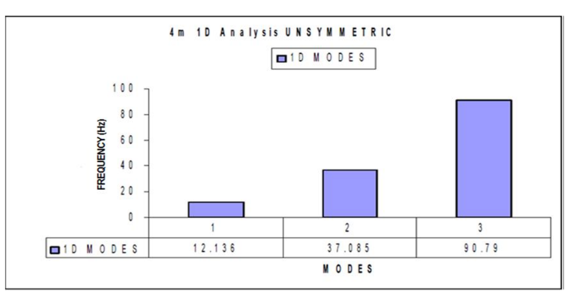

Table.5: 4m Beam 1D Analysis Asymmetric

3D ANSYS Analysis (4m Symmetric)

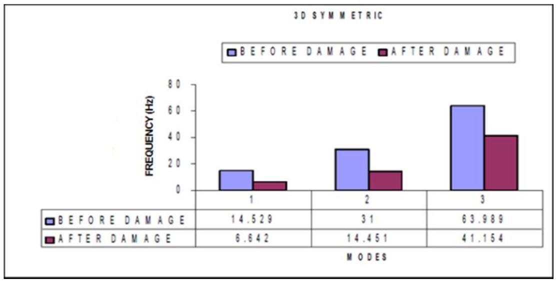

Table.6: 4m Beam 3D Analysis symmetric

3D ANSYS Analysis (4m Asymmetric)

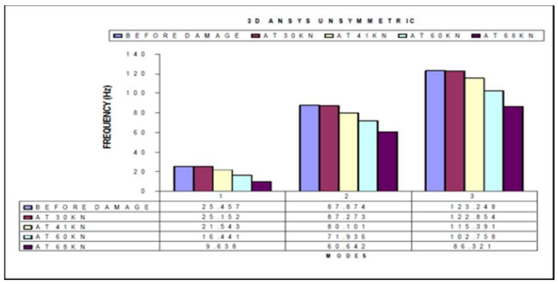

Table.7. 4m Beam 3D Analysis Asymmetric

VII. COMPARISION OF RESULTS

The experimental and analytical results were compared. The three sensors that are Electric Strain Gauge, PZT and Accelerometer performance were also interpreted in the experiment.

A. *One Dimensional Analysis*

In One Dimensional analysis, analytically modal frequency of the simply supported beam can be obtained by

$$f_n = \frac{\pi n^2}{2L^2}\sqrt{\frac{EI}{M}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

Where,

L = Length of the beam

E = Young's modulus of concrete (i.e. $5000\sqrt{f_{ck}}$)

I = Moment of inertia

M = Mass of the concrete block

N = Mode number

For the beam under consideration, the numerical values are

L = 4*m*, $\sqrt{f_{ck}}$ = 20 N/mm^2, E = $2.236E^{10}$ N/mm^2, I = 10^{-4} mm^4, M = 75kg/m^2

MODES	ANALITICAL (Hz)	ANSYS (Hz)	% ERROR
1^{st}	16.95	16.934	0.09
2^{nd}	67.80	67.528	0.40
3^{rd}	152.55	151.17	0.90
4^{th}	271.20	266.87	1.60
5^{th}	423.75	413.30	2.47
6^{th}	610.20	588.85	3.50
7^{th}	830.55	791.69	4.68
8^{th}	1084.80	1019.90	5.98
9^{th}	1372.95	1271.30	7.40
10^{th}	1695.00	1543.80	8.92

Table 8: Comparison of 1D Analysis

The Modal Frequency that is obtained by ANSYS and Analytical are compared and the Percentage of error is given above.

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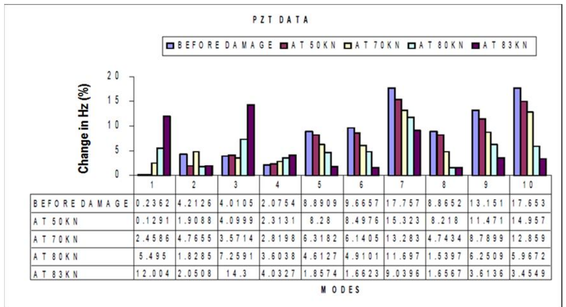
B. Experimental Data

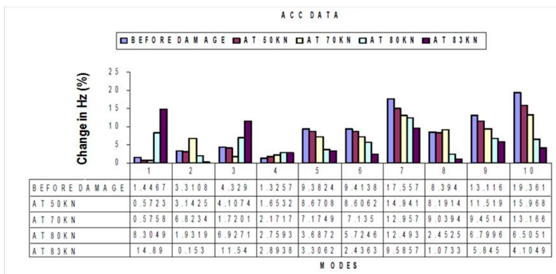
In 3D analysis, the ANSYS modal frequency obtained was compared with the first 3 modal frequency obtained from the accelerometer, PZT and ESG was compared below it is found that the accelerometer and PZT were giving close value. Table *9*, Table *10*, Table *11* gives the experimental values obtained by the sensors at various damaged location.

Damaged Induced ON 2m Concrete Beam



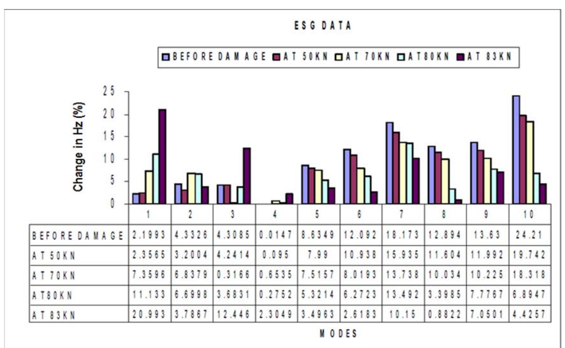
	1	2	3	4	5	6	7	8	9	10
BEFORE DAMAGE	0.2362	4.2126	4.0105	2.0754	8.8909	9.6657	17.757	8.8652	13.151	17.653
AT 50KN	0.1291	1.9088	4.0999	2.3131	8.28	8.4976	15.323	8.218	11.471	14.957
AT 70KN	2.4586	4.7655	3.5714	2.8198	6.3182	6.1405	13.283	4.7434	8.7899	12.859
AT 80KN	5.495	1.8285	7.2591	3.6038	4.6127	4.9101	11.697	1.5397	6.2509	5.9672
AT 83KN	12.004	2.0508	14.3	4.0327	1.8574	1.6623	9.0396	1.6567	3.6136	3.4549

Table 9: 2m Beam Experimental frequencies with PZT.



	1	2	3	4	5	6	7	8	9	10
BEFORE DAMAGE	1.4467	3.3108	4.329	1.3257	9.3824	9.4138	17.557	8.394	13.116	19.361
AT 50KN	0.5723	3.1425	4.1074	1.6532	8.6708	8.6062	14.941	8.1914	11.519	15.968
AT 70KN	0.5758	6.8234	1.7201	2.1717	7.1749	7.135	12.957	9.0394	9.4514	13.166
AT 80KN	8.3049	1.9319	6.9271	2.7593	3.6872	5.7246	12.493	2.4525	6.7996	6.5051
AT 83KN	14.89	0.153	11.54	2.8938	3.3062	2.4363	9.5857	1.0733	5.845	4.1049

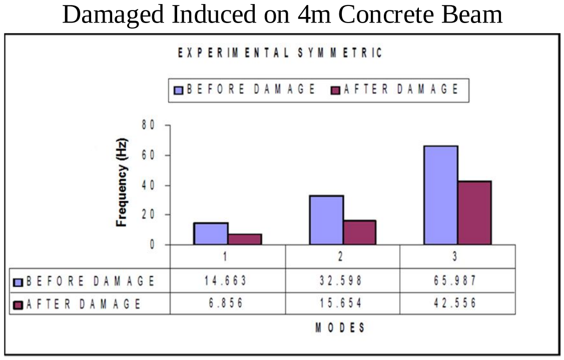
Table 10: 2m Beam Experimental frequencies with Accelerometer.



	1	2	3	4	5	6	7	8	9	10
BEFORE DAMAGE	2.1993	4.3326	4.3085	0.0147	8.6349	12.092	18.173	12.894	13.63	24.21
AT 50KN	2.3565	3.2004	4.2414	0.095	7.99	10.938	15.935	11.604	11.992	19.742
AT 70KN	7.3596	6.8379	0.3166	0.6535	7.5157	8.0193	13.738	10.034	10.225	18.318
AT80KN	11.133	6.6998	3.6831	0.2752	5.3214	6.2723	13.492	3.3985	7.7767	6.8947
AT 83KN	20.993	3.7867	12.446	2.3049	3.4963	2.6183	10.15	0.8822	7.0501	4.4257

Table 11: 2m Beam Experimental frequencies with ESG

Damaged Induced on 4m Concrete Beam



	1	2	3
BEFORE DAMAGE	14.663	32.598	65.987
AFTER DAMAGE	6.856	15.654	42.556

Table 12: 4m Beam Experimental frequencies in symmetric condition

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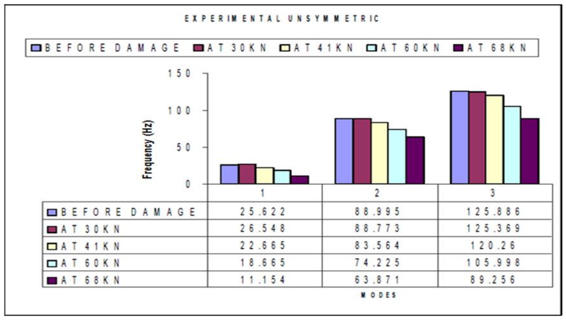

	1	2	3
BEFORE DAMAGE	25.622	88.995	125.886
AT 30KN	26.548	88.773	125.369
AT 41KN	22.665	83.564	120.26
AT 60KN	18.665	74.225	105.998
AT 68KN	11.154	63.871	89.256

Table 13: 4m Beam Experimental frequencies in asymmetric condition

There is considerable change in frequency, due to the damage induced in the structure, this experimental change in frequency and modal displacement is used in the condition assessment of the structure.

VIII. CONCLUSIONS & RECOMMENDATIONS

In this project, the experimental and computational modal analysis is carried on a 2m and 4m reinforced concrete beams and experimental mode shapes have obtained for a rectangular hollow cross section steel frame. The modal frequencies were calculated both experimentally by Frequency Response Function using ANSYS in 1D and 3D modelling.

1) In 1D modelling using beam elements the modal frequencies obtained in ANSYS and analytically computed are in close approximation.
2) In 3D modelling using solid elements the modal frequencies obtained in ANSYS and experimentally obtained through accelerometer, the PZT patch, the ESG are varying by a small margin. This may be due to the isotropic consideration in the ANSYS and variability and deviation in elastic properties in the real structure.
3) The modal frequencies obtained in 1D and 3D differs considerably, this is due to torsion effect consideration in 3D Modal analysis, whereas in 1D analysis it is not considered.
4) In the data acquisition process, it is found that the PZT yields good results in comparison to that accelerometer and electric strain gauge.

A. Remarks ON 2m Reinforced Concrete Beam

1) Damage detection and condition assessment carried on 2m beam using only modal displacements instead of curvature and it has been found that the damage location can be detected conveniently but the severity of the damage is not properly quantified.
2) Change in flexibility of the beam element has been found to be in close approximation to locate the damage and the intensity of the flexibility gives the severity of the damage occurred.

B. Remarks on 4m Reinforced Concrete Beam

1) In the 4m RC beam, the curvature of the nodes of the beam elements was used and the damage location and the severity of the damage in the beam were found to be well correlated with the actual observation.
2) Change in flexibility of the beam element under different support condition was found according to the damage location which is checked through experimental pictures available**.**

C. Recommendations

1) Further work can carry out in structural elements by considering various boundary conditions and structured frames with will stimulate real time analysis.
2) Assessment of different structures taking time history analysis real time data of any earthquake can be done which will stimulate the actual scenario.
3) Wireless network for data acquisition for the experiments and monitoring the structures can be done, so as to make it more feasible to the structural behaviour monitoring.
4) Further, the condition assessment work can be carried out to plates, steel frames, composites fibres etc.
5) Monitoring of the structures with the embedded sensors, data acquisition has to be done over the structural elements which is more useful in the wireless network system and a compatibility study can be done over the structural behaviour monitoring.

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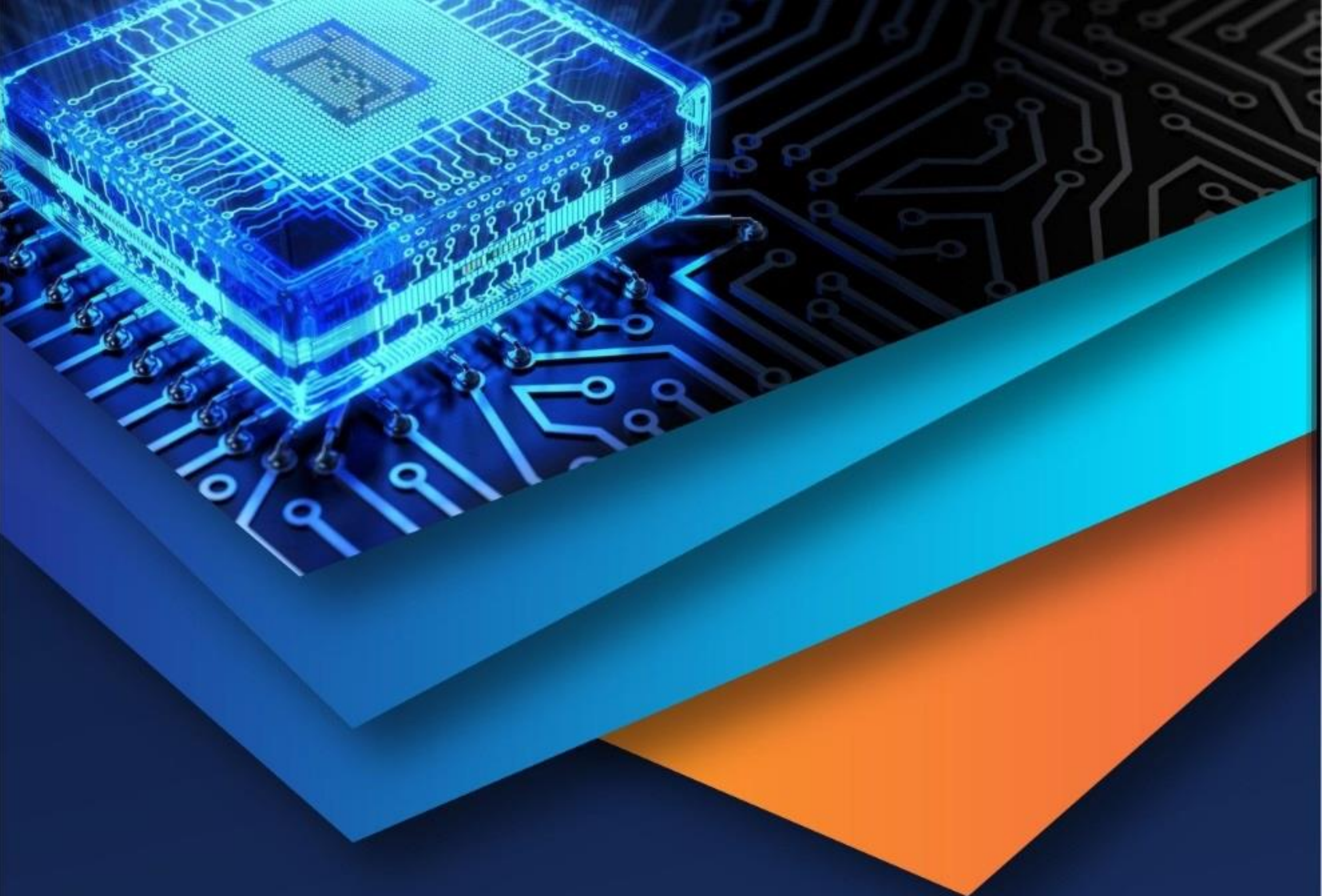

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