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The Study of Defect of Structure by Using Vibration Technique

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Abstract— **Damage detection is a technique used in health monitoring in the damage detection, to ensure the serviceability and the durability of the structures. In this report defects analysis of the structures using low frequency technique is being done through experimental modal analysis and computational analysis software ANSYS 9.0 over structural elements beam and steel frame.In the Experimental Modal Analysis, investigation is carried over a 2m and 4m Reinforced concrete beam and rectangular hollow section steel frame.**

¾ Response of the structure is obtained through accelerometer, PZT and electric strain gauge

¾ Aglient Multimeter is used as data analyzer for data acquisition

¾ FFT analysis and FRF is carried out using MATLAB

In the computational Analysis using ANSYS 9.0 the Modal Analysis is done both in the 1D and 3D modeling. Damage induced analysis is carried in the ANSYS 9.0 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 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

Index Terms— Defect, Damage,
Sub area : Construction Technology
Broad Area : Construction Technology & Management

I. INTRODUCTION

Major civil engineering structures such as bridges, containment vessels, dams, off shore structures, buildings etc. constitute a significant portion of the national wealth. The maintenance costs of these structures is substantially high, and even a small percentage reduction in the maintenance cost amounts to significant saving. One of the most cost effective maintenance methods is structural health monitoring. Early detection of problems, such as, cracks at critical locations, delimitations, corrosion, spalling of concrete etc., can help in prevention of catastrophic failure and structural deterioration beyond repair.

Structural health monitoring has great potential for enhancing the functionality, serviceability and increased life span of structures and, as a result, could contribute significantly to the economy of the nation. The concept of long-term monitoring 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

II. IMPORTANCE OF DAMAGE DETECTION

Accurate **Damage detection** of civil engineering structures has become increasingly important. The need for quantitative global damage detection methods that can be applied to complex structures, has led to the development of methods that examine changes in vibration characteristics of the structure. Doebling et al (1996) provided an extensive overview of vibration-based detection methods. Those are non destructive methods based on the fact that structural damage usually causes a decrease in the structural stiffness, which produces changes in the vibration characteristics of the structure. Damage is determined through the comparison between the undamaged and the damaged states of the structure. The most common dynamic parameters used in damage detection are the natural frequencies and the mode shapes. But changes in natural frequencies alone cannot provide spatial information about structural damage. Therefore mode shape information is additionally needed to uniquely localize the damage.

III. OBJECTIVES AND SCOPE OF STUDY

The primary objective of this study is to identify the damage induced in the structures using low frequency techniques, to locate the damage location and determine the severity of the damage, so that the life span of the structures can be assessed and maintenance cost can be reduced.

In this study, the investigation was carried out on concrete beams of 2m and 4m length using low frequency techniques. The response of the beam was obtained from accelerometer, piezoelectric ceramic patch and electric strain gauge. Further, from the frequency response function, the modal frequencies were obtained and were compared with the finite element method analysis.Again, inducing damage in the beam, modal

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frequency has to be obtained, and from the experimental modal analysis using the change in flexibility method and the mode shape curvature method the condition assessment and damage detection has to be carried out.

Experimental mode shapes of the structural elements were obtained using the dynamic technique.

IV. FACTORS TO CONSIDER USING NATURAL FREQUENCIES FOR

DAMAGE DETECTION IN PROTOTYPES

Some factors to consider when using vibration testing for integrity assessment and for successful utilization of vibration data in assessing structural condition, measurements should be taken at points where represented. The simplest way of achieving this is to conduct a theoretical vibration analysis of the structure prior to testing. The best positions would be those points where the sum of the magnitudes of the mode shape vectors is maximized.

LOW FRQUENCY TECHNIQUE

Low frequency techniques are based on the analysis of structural dynamic response measurements, typically made by subjecting the structure to low frequency vibrations. By this analysis, a suitable set of parameters is identified, and any variation in these parameters is an indication of the changing state of the structures. Damage in a structure alters its modal parameters, namely the stiffness matrix and the damping matrix .In these techniques, the structure is excited by appropriate means and the response data is processed to obtain a quantitative index or a set of indices representative of the condition of the structure.

EXPERIMENTAL MODAL ANALYSIS

Experimental modal analysis (EMA) was used to identify the modal parameters of the structure: the resonant frequencies, modal damping ratios (MDR) and mode shapes.Linearity of the structural behavior is one of the basic assumptions of the method. EMA can be used to monitor damage. Variations of the resonant frequencies and mode shapes are mainly due to changes of the global and local linear stiffness properties, while the variations of the MDR's are associated with an increase of the internal energy dissipation or attenuation. Mode shapes are obtained by analysis of the vibration response at multiple locations. Their changes are valuable indicators for damage monitoring, since they provide local information.

MODAL ANALYSIS APPLICATION

Mode shapes and resonant frequencies of a structure (its modal response) can be predicted by using a mathematical model known as a Finite Element Model (FEM). An FEM uses points connected by elements possessing the mathematical properties of the structure's materials. Boundary conditions define how the structure is fixed to the ground and what force loads are applied. After defining the model, a mathematical algorithm computes the mode shapes and resonant frequencies. The practical benefit is that it is possible to predict the vibration response of a structure before it is even built.

After building the structure, it's good practice to verify the FEM using experimental modal analysis. This identifies errors in the model and leads to improvements in future designs. Professionals can also use experimental modal analysis without FEM models. In this case, the goal is to identify the modal response of an existing structure in order to resolve vibration problems.One of the common vibration problems identified by modal analysis is when a forcing function excites the resonant frequency of a structure. A forcing function is the mechanism that forces the structure to vibrate. Real world examples include rotating imbalance in an automobile engine, reciprocating motion in a machine, or broadband noise from wind or road conditions in a vehicle. The frequency of the forcing function is extracted from a frequency domain analysis of its signal. When a resonant frequency of the structure coincides with the frequency of the forcing function, the structure may exhibit large vibrations that lead to fatigue and failure.

In this case, the mode-shape information can be used to redesign or modify the structure to move the resonant frequencies away from the forcing function. Structural elements can be added to increase the structure's stiffness or simple changes made to increase or decrease the mass. These changes will act to change the structure's resonance frequency values.

DAMAGE IDENTIFICATION METHODS

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

- To identify the damage.
- To determine the location of the damage.
- To determine the severity of the damage.
- To determine the remaining useful life of the structure.

DAMAGE INDEX METHOD

The damage index method was developed by Stubbs and Kim (1994) to locate damage in structures given their characteristic mode shapes before and after damage.For a structure that can be represented as a beam, a damage index, β , is developed based on the change in strain energy stored in the structure when it deforms in its particular mode shape. For location jth on the beam this change in the i^{th} mode the damage index β_{ij} was defined as…

Where
$$\beta_{ij} = \frac{\left(\int_a^b [\Phi^{*''}_i(x)]^2\,dx + \int_0^L [\Phi^{*''}_i(x)]^2\,dx\right)\int_0^L [\Phi''_i(x)]^2\,dx}{\left(\int_a^b [\Phi''_i(x)]^2\,dx + \int_0^L [\Phi''_i(x)]^2\,dx\right)\int_0^L [\Phi^{*''}_i(x)]^2\,dx} \quad \ldots (3.1)$$

Where $\Phi''_i(x)$ and $\Phi^{*''}_i(x)$ are the second derivatives of the i^{th} mode shape corresponding to the undamaged and the damaged structures, respectively. Here, 'a' and 'b' are the limits of a segment of the beam where the damage is being evaluated. L is the length of the beam

For mode shapes obtained from ambient data, the modes are normalized such that

$$\{\psi_n\}^T\{M\}\{\psi_n\} = 1 \quad \ldots. (3.2)$$

MODE SHAPE CURVATURE METHOD

Pandey, Biswas and samman (1991) assume that structural damage only affects the structure's stiffness matrix and its mass distribution. The pre and post-damage mode shapes for the beam in its undamaged and damaged conditions can then be estimated numerically from the displacement mode shapes with a central difference approximation or other means of differentiation. Given the before and after mode shapes, the author consider a beam cross section at location' *x* 'along the length of the beam, $v''(x)$ is

$$v''(x)=M(x)/(EI)$$

Where E is the modulus of elasticity and I the moment of inertia of the section. From the equation, it is evident that the curvature is inversely proportional to the flexural stiffness, EI. Thus, a reduction of stiffness associated with damage will, in turn lead to an increase in curvature. Differences in the pre and post –damage curvature mode shapes will, in theory be in the damage curvature mode shapes will in theory be largest in the damaged region. For multiple modes the absolute values of changes in curvature associated with each mode are summed to yield a damage parameter for a particular location

CHANGE IN FLEXIBILTY METHOD

Pandey and Biswas (1994) show that for the undamaged and damaged structures, the flexibility matrix, [F], can be approximated from the unit –mass-normalized modal data as follows

$$[F] \approx \sum_{i=1}^{n} 1/\omega_i^2 \{\Phi_i\}\{\Phi_i\}^T \quad \ldots\ldots (3.3)$$

and

$$[F]^* \approx \sum_{i=1}^{n} 1/\omega_i^{*2} \{\Phi_i\}^*\{\Phi_i\}^{*T} \quad \ldots\ldots (3.4)$$

Where ω_I is the *i*th modal frequency, φ_i *i*th unit –mass-normalized mode, *n* the number of measured modes and the asterisks signify properties of the damaged structure. From the pre and post –damage flexibility matrices, a measure of the flexibility change caused by the damage can be obtained from the difference of the respective matrices as

$$[\Delta F] = [F] - [F]^* \quad \ldots\ldots (3.5)$$

Where $[\Delta F]$ represents the change in flexibility matrix. For each column of

this matrix$\bar{\delta}_j = \max 1 \delta_{ij} 1$, i =1…………..n. The column of the flexibility matrix

corresponding to the largest change is indicative of the degree of freedom where the damage is located.

CHANGE IN UNIFORM LOAD SURFACE CURVATURE

The coefficients of the *i*th column of the flexibility matrix represent the deflected shape assumed by the structure with a unit load applied at the *i*th degree of freedom. The sum of all columns of the flexibility matrix represents the deformed shape assume by the structure if a unit load is applied at each degree of freedom and this shape is to as the uniform load surface. Change in curvature of the uniform load surface can be used to determine the location of damage. In terms of the curvature of the uniform load surface, F", the curvature change at location *l* is evaluated as follows

$$\Delta F'' = \left| F_i^{*''} - F'' \right| \ldots\ldots (3.6)$$

Where Δ F" represents the absolute curvature change. The curvature of the uniform load surface can be obtained with a central difference operator.

CHANGE IN STIFFNESS METHOD

Zimmerman and Kaouk (1994) have developed a damage detection method
based on changes in the stiffness matrix that is derived from measured modal data.

The eigenvalue problem of an undamaged, undamped structure is

$$(\lambda i[M] + [K]\{\psi_i\} = \{0\} \quad \ldots\ldots (3.7)$$

The eigenvalue problem of the damaged structure is formulated by first replacing the pre-damaged eigenvectors and eigenvalues with a set of post-damaged modal parameters and second, subtracting the perturbations in the mass and stiffness matrices caused by damage from the original matrices. Letting ΔM_d and ΔK_d represents the perturbations to the original mass and stiffness matrices, the Eigen value equation becomes

$$[\lambda^*_i[M-\Delta M_d]+[K-\Delta K_d]]\{\psi_i\}^* = \{0\} \quad \ldots\ldots (3.8)$$

Two forms of a damage vector, $\{D_i\}$ for the ith mode are then obtained by

separating the terms containing the original matrices from those containing the

perturbation matrices. Hence,

$$\{D_i\} = (\lambda_i^*[M]+[K])\{\psi_i\}^* = (\lambda_i^*[\Delta M_d]+[\Delta K_d]]\{\psi_i\}^* \quad \ldots.. (3.9)$$

To simplify the investigation, damage is considered to alter only the stiffness of the structure of the structure (i.e. $\Delta M_d = [0]$). Therefore, the damage vector reduces to

$$\{D_i\} = [\Delta K_d]\{\psi_i\}^* \quad \ldots.. (3.10)$$

In a similar manner as the modal-based flexibility matrices previously defined, the stiffness matrices, before and after damage, can be approximated from incomplete mass-normalized modal data as

$$[K] \approx \sum \omega_i^2 \varphi_i \varphi_i^T \quad \ldots\ldots. (3.11)$$

And $$[K]^* \approx \sum \omega_i^{*2} \varphi_i^* \varphi_i^{*T} \quad \ldots\ldots. (3.12)$$

Equation (6) is subtracted from equation (14) to obtain$[\Delta K_d]$. This matrix is multiplied by the ith damaged mode shape vector to obtain the ith damage vector as shown in equation (4). A scaling procedure discussed by Zimmerman and kaouk was used to avoid spurious readings at stiff locations of the measured response is lower.

EXPERIMENTAL AND DATA PROCESSING TOOLS

This study has investigated the low frequency dynamic response technique utilizing accelerometer, electrical strain gauge and piezoceramic (PZT) patches.

HARDWARE REQUIREMENTS

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

EXPERIMENTAL APPROACH Build analytical models

- Determine theoretical sensitivity of method
- Address sensor placement
- Discuss the design of experiments

Experimental verification-

Test simple structural level specimens with various damage, work up through building block element. Assess feasibility of implementing method in SHM system

System architecture

- Sensor integration
- Test samples with realistic sensors
- Test method on representative structures

STRAIN GAUGE

A **strain gauge** is a device used to measure deformation (strain) of an object. The most common type of strain gauge consists of an insulating flexible backing which supports a metallic foil pattern. The gauge is attached to the object by a suitable adhesive. As the object is deformed, the foil is deformed, causing its electrical resistance to change. This resistance change, usually measured using a Wheatstone bridge, is related to the strain by the quantity known as the *gauge factor*.

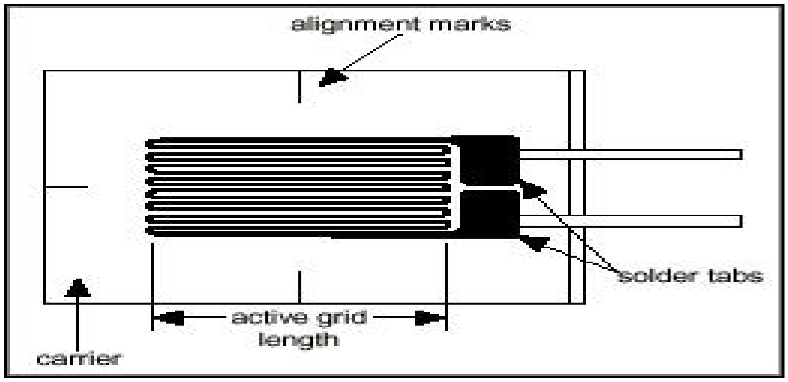
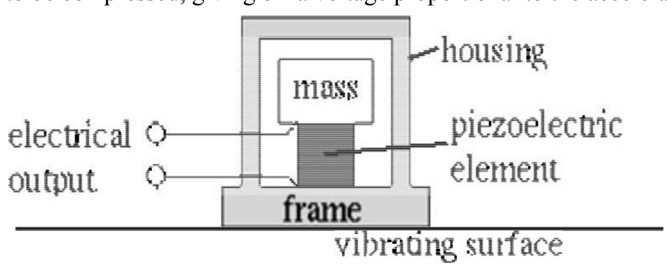


Fig: 4.1-Bonded Metallic Strain Gauge

In this project two 5mm strain gauge with a gauge factor of 2.09 are attached on the 4m steel beam. Both the gauges are attached at the centre parallel to the central axis of the steel beam as shown in the pictures below:
In this study, a reinforced concrete beam of 4m lengths, 0.15m widths, 0.2m heights were instrumented with electric strain gauge, peizoceramic patches and accelerometers. Fig shows the measurement set up, consisting of the test structure, digital multimeter, a personal computer and shaker machine. The structure was excited by the shaker machine and the vibration responses were measured using the Agilent 34411A digital multimeter. The multimeter records measurements from all the sensors one by one.In the case of ESG, the multimeter measures the resistance with time and was used to convert it into strain.

ACCLEROMETER

An accelerometer is a linear seismic transducer, which produces an electric charge proportional to the applied acceleration. A simple model of an accelerometer is shown in Figure. A mass is supported on a piece of piezoelectric ceramic crystal, which is fastened to the frame of the transducer body. Piezoelectric materials have the property that if they are compressed or sheared, they produce an electric potential between their extremities, and this electric potential is proportional to the amount of compression or shear. As the frame experiences an upward acceleration it also experiences a displacement. Because the mass is attached to the frame through the spring-like piezoelectric element, the resulting displacement it experiences is of different phase and amplitude than the displacement of the frame. This relative displacement between the frame and mass causes the piezoelectric crystal to be compressed, giving off a voltage proportional to the acceleration of the frame.



From the frequency response function, the first 3 modal frequencies were obtained from the Accelerometer, PZT and ESG
The equipment used in the data acquisition was AGILENT MULTIMETER, data was collected at an interval of 1millisecond and the duration of the data acquisition was kept to 20sec. Fig: 4.4 show the front and the rear views of the multimeter.

EXPERIMENTAL ANALYSIS

By 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 piezo transducers were attached 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:4.5. The response generated by the PZT patch and the region analyzed from the response patch was shown in the fig: 4.6.The response of the PZT from time domain to frequency domain through fast fourier transform and first three fundamental
l frequency is considered for the analysis was shown in the fig:4.7.

DAMAGE LOCATION AND IDENTIFICATION METHOD 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.
The governing equation of motion for dynamic system is

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{F(t)\} \quad \ldots. (5.1)$$

Where

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

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

$$\{\boldsymbol{\omega}\} = \{\omega_1, \omega_2, \omega_3, \omega_4 \ldots\ldots\} \quad \ldots. (5.2)$$

$$\{\boldsymbol{\Phi}\} = \{\Phi 1, \Phi_2, \Phi_3, \Phi_4 \ldots\ldots\} \quad \ldots. (5.3)$$

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

$$\{\mathbf{f}\} = \{f1, f_2, f_3, f_4 \ldots\} \quad \ldots. (5.4)$$

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

$$\{\Delta\mathbf{f}\}_m = \{\Delta f_1, \Delta f_2, \Delta f_3, \Delta f_4, \ldots\ldots\} \quad \ldots. (5.5)$$

Sorting the shift frequencies in the descending order we have

$$\{\Delta\mathbf{f}\}^m = \{\Delta f^1, \Delta f^2, \Delta f^3, \Delta f^4, \ldots\ldots\} \quad \ldots. (5.6)$$

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

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

Where m=number modes chosen

P=number elements in the structure

i=number chosen mode shapes

Δf =shift frequency

ΔE =element deformation parameter.

ΔE_{px}^{i} = longitudinal displacement of node $i+1$

ΔE_{py}^{i} = 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: 5.1 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 center and it is found that the bending cracks were found at the center and the shear cracks the support conditions as shown in the Fig:5.7 and Fig:5.9..From the figures shown below it was evident that the elemental damage propagation were taking place at the center 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.

CONCLUSIONS

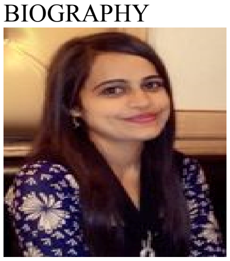
In this project experimental and computational modal analysis is carried over a 2m and 4m RC beams and experimental mode shapes have obtained for a rectangular hollow cross section steel frame. The modal frequencies were calculated both experimentally using MATLAB by Frequency Response Function and in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

- In 1D modelling using beam elements the modal frequencies obtained in ANSYS and analytically computed are in close approximation.
- 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 the isotropic consideration in the ANSYS and variability and deviation in elastic properties in the real structure.
- The modal frequencies obtained in1D and 3D differs considerably, this is due to torsion effect consideration in 3D Modal analysis, whereas in1D analysis it is not considered.
- In the data acquisition process it is found that PZT yields good results in comparison to that accelerometer and electric strain gauge.

ON 2m REINFORCED CONCRETE BEAM

- Damage detection and condition assessment carried over the 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.
- 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.

BIOGRAPHY



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