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Exact Damage Identification of Plate-Like Structure using Mode Shapes

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Abstract*: In this paper, Mode Shape Based Damaged Detection Technique (MSBDT) has been applied for plate-like structures to recognize the damage location and quantify the damage length. Two alternative approaches are exclusively used to extract damage indexes through mode shapes of undamaged plate (i.e. reference data) and damaged plate. The absolute difference of mode shapes used in first approach and mode shape curvatures used in second approach of undamaged and damaged plates. Healthy Aluminium plate was tested in the laboratory for accurate material properties and considered three different damage cases by changing the crack orientation and location for successfully implementation of above approaches. In order to make certain the sensitivity of the proposed approaches, natural frequencies and corresponding mode shapes for first six modes in transverse direction of a plate are obtained by Finite Element Modal Analysis (FEMA) in ANSYS 18.1 and validated by Experimental Modal Analysis (EMA) in virtual instrumentation environment using LabView software.

***Keywords* : Plate-Like Structures, Experimental Modal Analysis, Mode Shape, Damage Identification, Mode Shape Curvature**

I. INTRODUCTION

Majority of engineering structures like as engine parts, aero plane parts, civil structures etc. constitute a significant portion of the national prosperity. The maintenance budgets of industry-structures is significantly high and even a minute percentage of reduction is those budgets to significant saving for industrialists through damage detection in early stages. The Damage happened during working conditions as a result of the operational stacking conditions, maturing, chemical assault, mechanical vibration, shocks and changing of atmospheric conditions and stuns. Subsequently, early recognition of crack and its seriousness for damaged area of beams is a key point.

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The underlying method for damage discovery is to expel the structure from a help and check for its damage zones, anyway this is tedious and costly. Consequently online location of harm which means checking the structure while it is in-administration is liked. Therefore the online damage recognition of a structure called "Structural Health Monitoring (SHM)" has become a significant issue in different fields and industries. By and large, auxiliary wellbeing observing has 3 stages: energizing the structure, gathering reactions of the structure to excitation and building up the connection between these reactions and damage status (area and severity). Once damage is distinguished in the structure, the mechanical and dynamic properties of the structure change. In this manner reactions of the unblemished and harmed structures to the excitations are extraordinary.

These differences can be used to extract the damage status according to the method used for structural health monitoring such as vibration-based method may help in anticipation of sudden failures and structures deterioration beyond repair. SHM has vast potential for enhancing the serviceability, functionality and increased structure life span of structures. To ensure continued serviceability of structural parts, cyclic integrity assessments are necessary to observe the state of the parts. Number of assessment engineers prefers local damage techniques like Non-Destructive Test (NDT) methods since no damage, or limited surface damage is induced on the structure as a result of the testing. NDT methods that are not location dependent and involve the participation of the complete structure under investigation are more suitable for large engineering structures. One of such methods is vibration monitoring and relies on the fact that dynamic performance is sensitive to structural integrity. If the changes in the system parameters are known it should be possible to detect, locate and quantify, to some extent, the damage. In practice, the dynamic response of the structure is measured at a few easily accessible locations. The time histories are processed to yield response spectra from which modal and system parameters obtained. Many EMA based approaches developed for damage detection in structures. Some of these utilize shifts in the Eigen values and modal damping, modification of mode shapes or a combination of changes in all the modal parameters. Similarly, many model updating methods using experimental modal analysis have been suggested to validate predictions from theoretical models.

S. Rucevskis and M. W [1] created mode shape based crack recognition method for beam like structures as well as mode shapes and curvatures of mode shapes. Siva Sankar Chinka, BalaKrishna. A, Rao. P. S [2] observed the effect of damage on natural frequencies of cantilever beam using Finite element modal analysis (FEMA) and experimental modal analysis in NI Lab View environment.

Developed the Labview program to get frequency response functions and phase angle of real structures to observe the effect of crack on modal parameters mode shapes and resonant frequencies.

Numerous examinations have explored the effects of crack on modeshapes [3-5], then comparing modeshape of all modes and their corresponding curvatures [6, 7]. Many papers are showing that deflected shape curvatures are profoundly delicate to crack and could be utilized to confine it.

Be that as it may, the significant downside of those techniques is a requirement for the information of the healthy structure which in some cases could be complicated and time consuming to get or even incomprehensible.

To reduce these type problems, Gapped Smoothing Procedures [8-10] were offered by authors that permit the crack recognition in structures lacking earlier information on the healthy state.

The essential thought of strategies is that the modeshape curvatures of the undamaged structure have a soft surface; it very well may be estimated approximately by a polynomial. Siva Sankara babu Chinka, et al [11] developed a novel method to identify the damage for fixed-fixed beam with the help of normalized frequencies and also applied same type method for cantilever beam in [12].

From the existing literature, Majority of researchers are focused on frequency based detection methods for damage detection of beam like structures.

The paper main objective is to detect the damage of plate structures using modeshape damage identification techniques. Here mode shapes and mode shape curvatures are the main parameters to identify the damage exactly.

II. MATERIAL PROPERTIES

In order to evaluate the modal parameters such as mode shapes and natural frequencies, a numerical model was generated for the plate in finite element analysis package by setting exact material properties.

Density, modulus of elasticity and Poisson’s ratio are experimentally calculated by density, deflection and tensile tests and shown in fig. 1.

The experimentally calculated properties are slightly differing from manufacturer’s catalogue tabulated in table I. Further FEMA tests are applied by considering experimental values only.

The tests are conducted on a beam of same material where conducting the tests on plate is not possible.

The density of the material is calculated by following formula

ρ = weight of air/ loss of weight in water (1)

The poisson’s ratio of the material is given by

μ = lateral strain/ longitudinal strain (2)

Modulus of elasticity is given by

$E = (11/768) \times (Wl^3/\delta I)$ (3)

Where W= load applied, L= length of the specimen

δ= Deflection and I= Moment of Inertia

a) Density test

b) Deflection test

c) Tensometer and Tensile test specimens

Fig. 1. Experimental set up of a) Density test b) Deflection test c)Tensometer & Tensile test specimens for Aluminium material

Table I: Material properties

S.No.	Property	Actual Values	Experimental Values
1.	Young's modulus	71GPa	70GPa
2.	Density	2770kg/ m^3	2780kg/ m^3
3.	Poisson's Ratio	0.34	0.33

III. FINITE ELEMENT MODAL ANALYSIS (FEMA) OF PLATE LIKE STRUCTURES

To verify the validity of the proposed method and other reference methods, the numerical modal analysis was developed in ANSYS Workbench18.1. For this test, considered one undamaged Aluminium plate and three damaged plates has actual dimensions of length 400 mm, width 200 mm and thickness of 3 mm. Damaged plate dimensions are represented in schematic diagram of plate with three types of damages shown in fig. 2 as follows

Damaged Plate -1: Damage at middle of the plate and parallel to vertical direction with damage length = 20 mm, width = 1 mm and thickness = 3mm

Damaged Plate -2: Damage at 3/4th of the plate length, parallel to horizontal direction with damage length = 20 mm, width = 1 mm and thickness = 3mm

Damaged Plate -3: One damage at 1/4th of the plate length parallel to vertical direction and second damage at 3/4th of plate length parallel to horizontal direction with damage length = 20 mm, width = 1 mm and thickness = 3mm

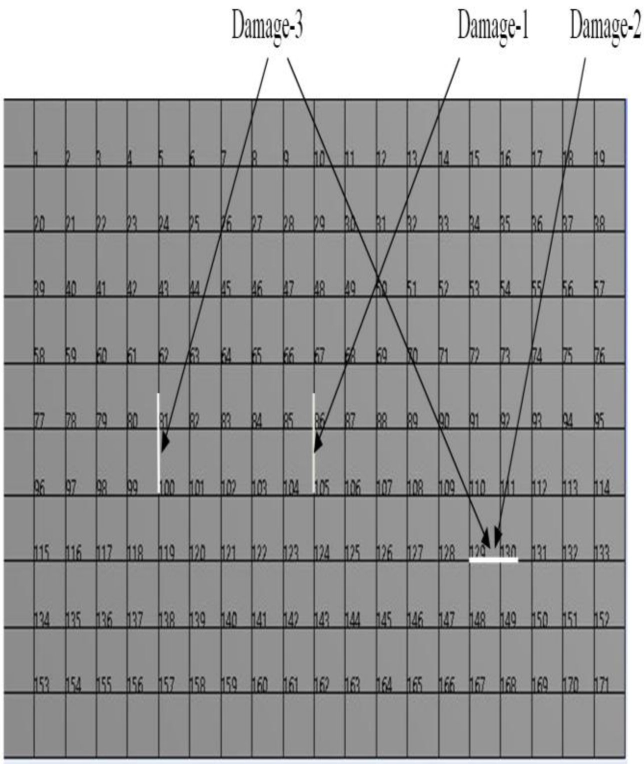


Fig. 2. Damaged plate schematic diagram with node numbers and damage locations

The geometry of the undamaged plate and three types of damaged plates are shown in fig. 3. Fine meshing is generated for all types of plates to get exact mode shapes and natural frequencies as shown in fig. 4. One side of the plate is fixed and other sides are free (C-F-F-F i.e. clamped-free-free-free) boundary support has been set on small side of the plate.

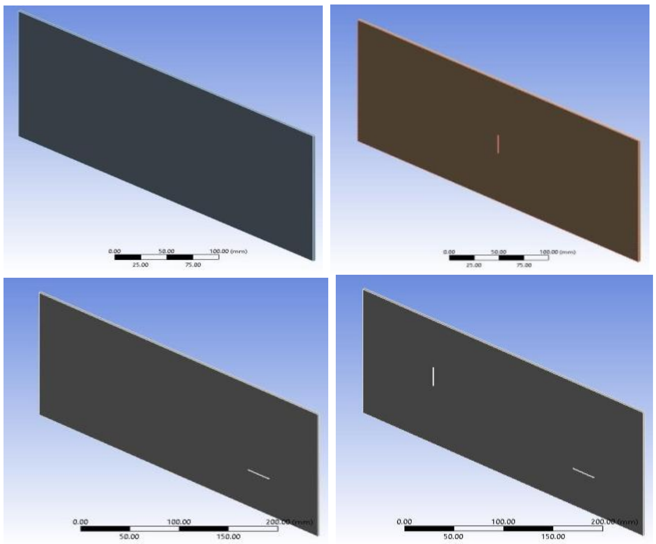


Fig. 3. Geometry of undamaged plate, damaged plate-1, damaged plate-2 and damaged plate-3 respectively

Natural frequencies and its modeshapes of C-F-F-F plate are taken for study the dynamic behavior and hence damage identification was done for first six transverse modes of undamaged and damaged plates. First six natural frequencies are tabulated in table II. By observing the frequencies, frequency is less for damaged plates when compared to undamaged plate. This is due to the change in stiffness of the plate which decreases the decrease in frequency.

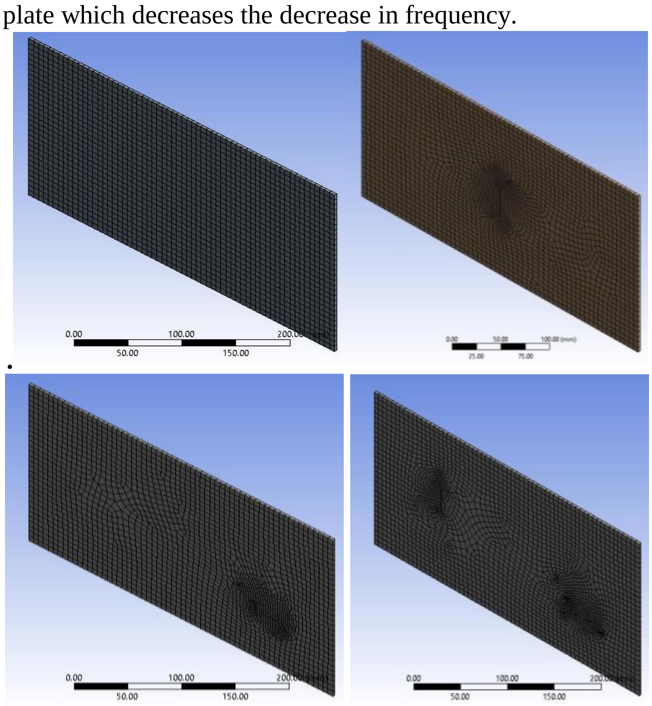


Fig. 4. Meshing of undamaged plate, damaged plate-1, damaged plate-2 and damaged plate-3 respectively

First six mode shapes of the undamaged plate are shown in fig. 5. In the first and second mode shapes, deflection are maximum at free end along the width of the plate, and the minimum at the fixed support of the plate and the deflection increases from fixed end to free end of the plate. The six vibration mode shapes are of transverse vibrations where plate vibrates perpendicular to the axis are shown in fig. 5.

First six mode shapes of the damaged plate-1, 2 and 3 are shown in figs 6, 7 and 8 respectively. In all cases the mode shapes are similar but there is small change in mode shape values at vicinity nodes of damaged area. This small change in mode shapes are extensively used for damaged detection of plate like structures in this paper as novel method.

Table II: Natural frequencies of C-F-F-F Plate by FEMA

S. No	Mode Number	Natural Frequencies (Hz)			
		Undamaged Plate	***Damaged Plate-1***	***Damaged Plate-2***	***Damaged Plate-3***
1.	1	15.873	15.838	15.89	15.746
2.	2	98.723	97.827	98.69	98.685
3.	3	276.99	276.94	276.78	275.2
4.	4	420.67	420.27	420.2	420.32
5.	5	545.06	543.11	544.34	539.5
6.	6	697.25	697.14	696.74	696.46

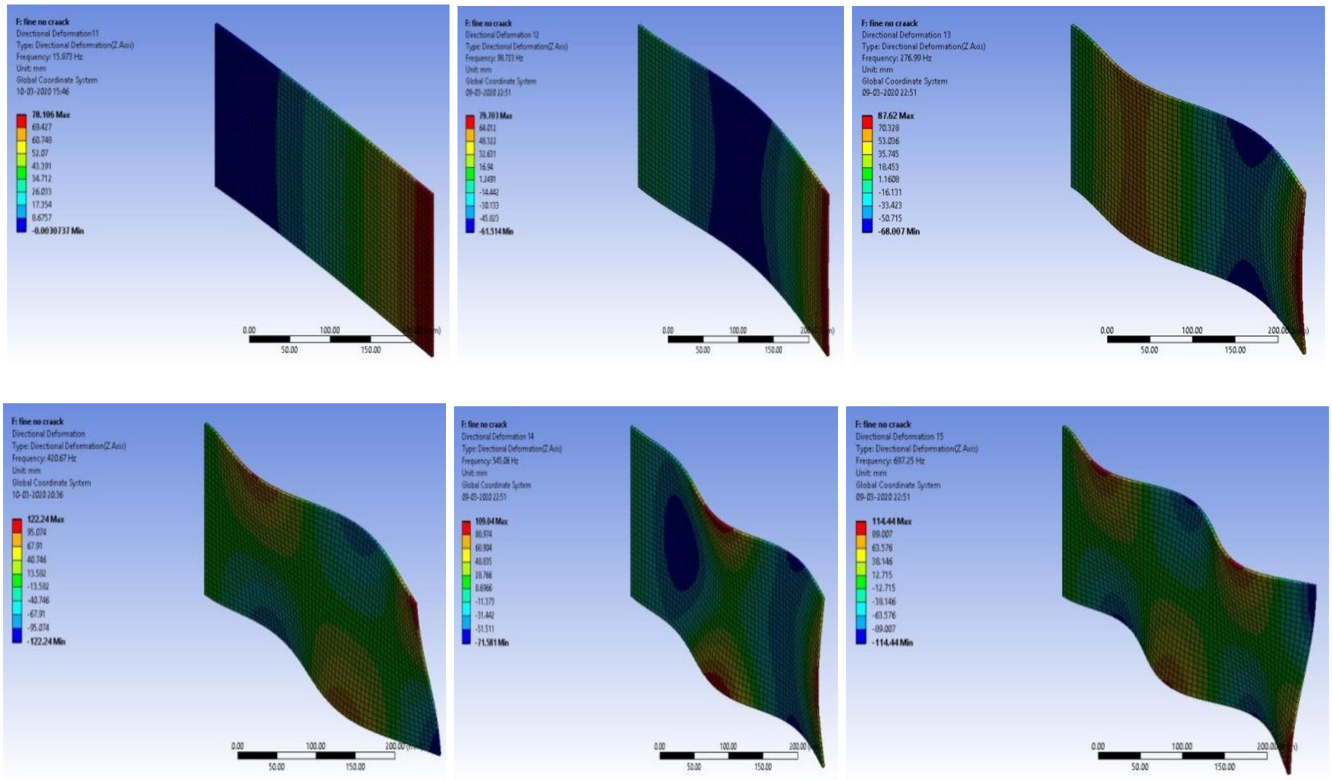
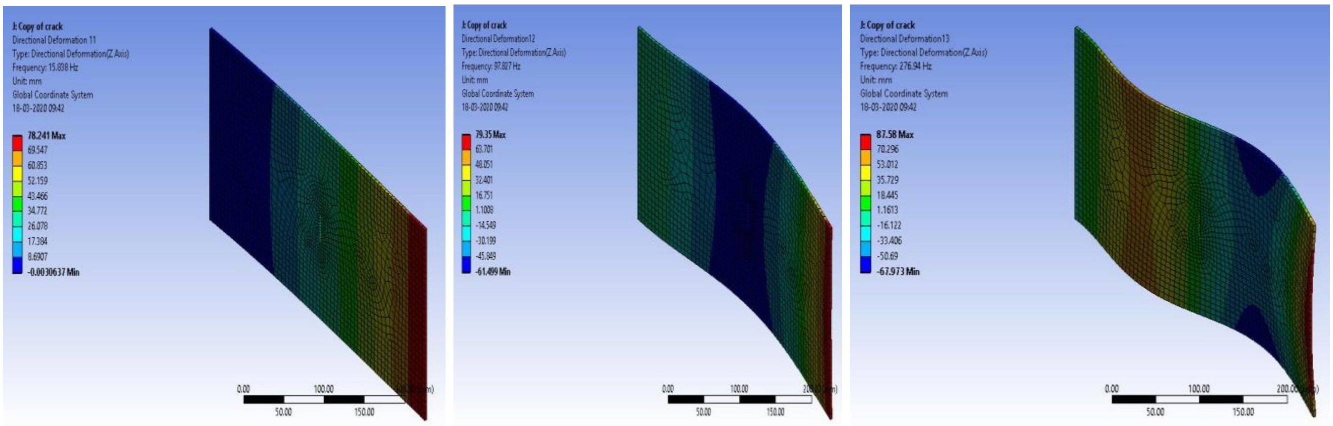


Fig. 5. First six mode shapes of the undamaged plate like structure.



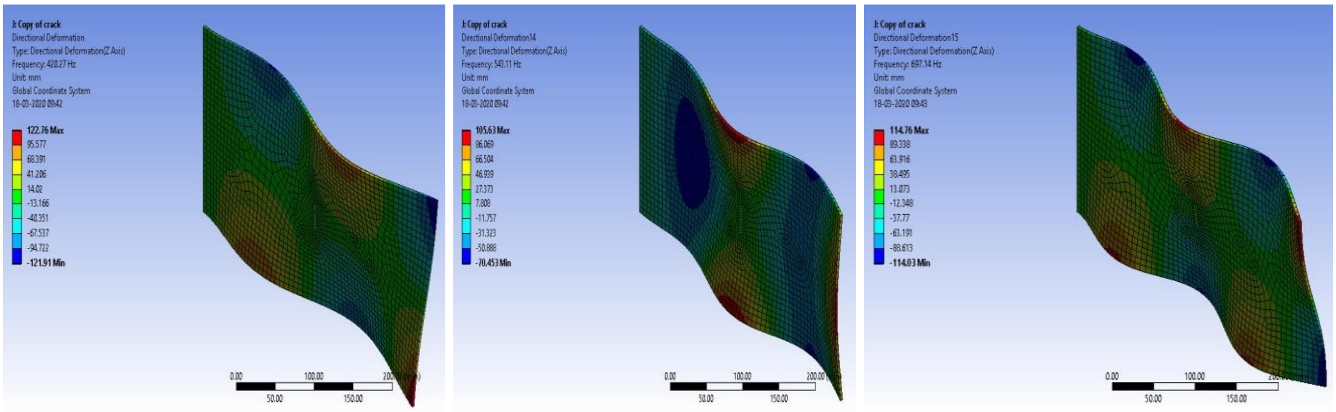


Fig. 6. First six mode shapes of the damaged plate-1

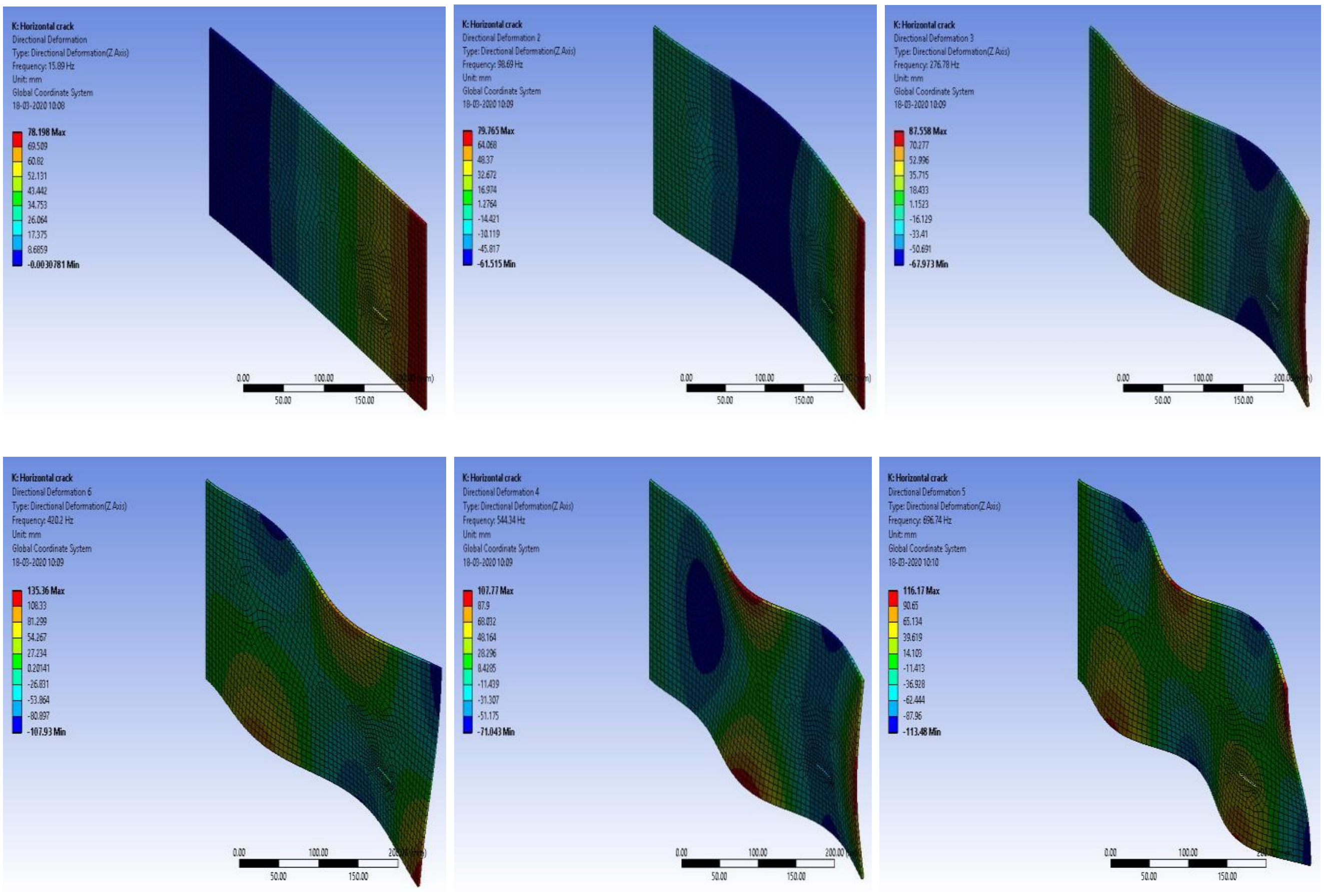
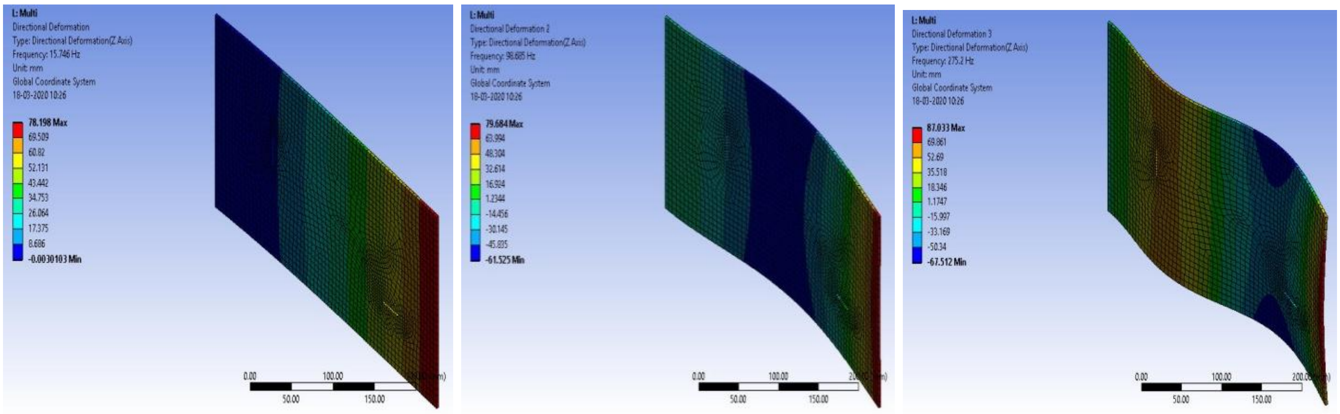


Fig. 7.First six mode shapes of the damaged plate-2



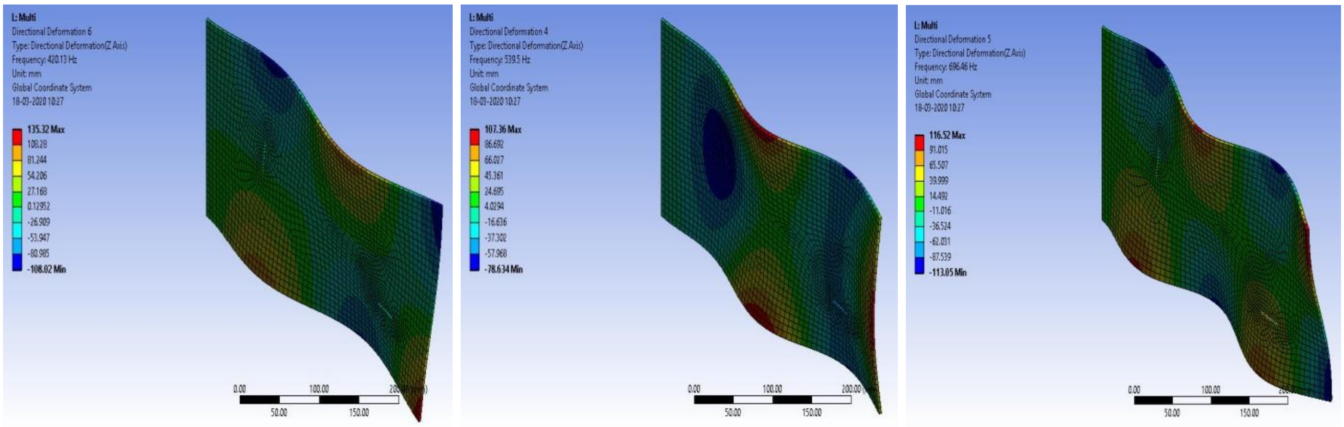


Fig. 8.First six mode shapes of the damaged plate-3

IV. EXPERIMENTAL MODAL ANALYS (EMA) OF PLATE LIKE STRUCTURES

To validate the Finite element analysis result, an experiment on Aluminium plate has been performed. Prepared an Aluminium damaged and undamaged plates with same dimensions mentioned in previous section. Before the experimental study the plate surface has been cleaned and organized for straightness. Subsequently damages are created by EDM for different damages. Experimental frame work has been developed which consists of Impact hammer, Accelerometer, Multi channel vibration analyzer, NI LabVIEW Software with advanced signal processing and sound & vibration tool kits as shown in fig. 9. During the experiment, the damaged and undamaged plates have been vibrated by impact hammer and signals are received in time response and frequency responses by accelerometer through 4-channel data acquisition system (DAQ). Time response signals are some more difficult when compared to frequency-response-functions (FRF's) to analyze for extracting the resonant frequencies and mode shapes. Mode shapes and Frequencies are access from FRF's by curve-fitting techniques. First six Natural frequencies are tabulated in table III. The experimental results are in close justification with Finite Element Modal Analysis results.

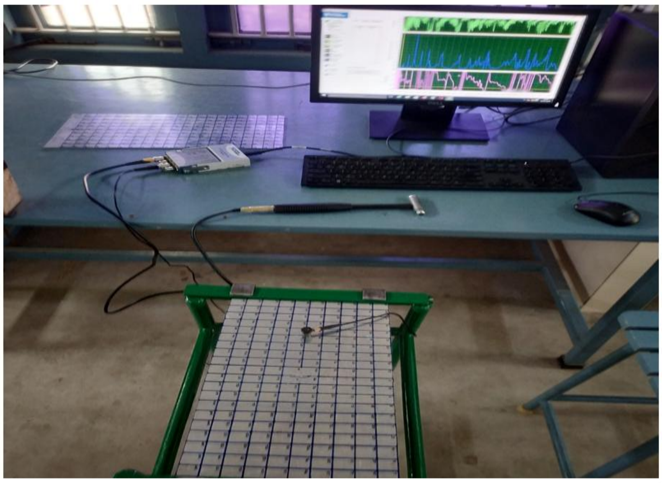


Fig. 9. Experimental setup

Table-III: Natural frequencies of C-F-F-F plate experimentally

S. No	Mode Number	Natural Frequencies (Hz)			
		Undamaged Plate	*Damaged Plate-1*	*Damaged Plate-2*	*Damaged Plate-3*
1.	1	14.93	14.838	14.89	14.746
2.	2	97.723	96.827	96.69	96.685
3.	3	275.99	275.94	275.78	275.2
4.	4	419.67	419.27	419.2	419.32
5.	5	543.06	542.11	542.34	539.5
6.	6	695.25	694.14	694.74	694.46

V. DAMAGE IDENTIFICATION TECHNIQUES FOR PLATE LIKE STRUCTURES

In this section, damage identification techniques are implemented and developed for the plate like structures based on mode shape information obtained from FEMA. Following methods are used to identify the damage exactly for plate like structures:

Damage detection using Mode Shapes (MS)

Damage detection using Mode Shape Curvatures (MSC)

A. Damage Detection Using Mode Shapes (MS)

If the mode shape deflection is ϕ, the absolute change in deflection is obtained as

$$\Delta\phi_i = |\phi^d{}_i - \phi_i| \quad (4)$$

where ϕ^d and ϕ are mode shape deflections of the damaged and undamaged beam respectively. i indicated the node number.

Due to noise in experimentation, measured mode shapes are certainly corrupted. This noise establishes perturbations in the modal information which leads to show major difference in change of modes shapes and its curvatures of damaged and undamaged plate as peaks. These peaks may wrongly interpret the damage location or peaks may mask the actual damage location in the beam and guide to false damage identification. To conquer this type of situation, it is planned to calculate the average damage indices of all modes. The modes shape damage index (MSDI) is proposed as

$$MSDI_{\ i} = \frac{1}{N}\sum_{n=1}^{N}(\Delta\phi_i)_n \quad (5)$$

B. Damage Detection Using Mode Shape Curvatures (MSC)

The curvature of mode shape can be obtained from the deflection shape by numerical differentiation (central difference approximation). Since the crack/flaws causes a change in local stiffness, there will be a significant difference in the modeshape-curvatures of the un-damaged structure & the damaged structure at the location of damage. Either the two curvatures or the difference between them along the length of the beam or over the surface of the structure can be plotted and the location of crack can be determined by the variation in the position of the maximum difference in the curvatures.

The mode shape curvature (MSC) of the damaged and the healthy structures is given by

$$\Delta\phi_i'' = \left|\phi_i''^{d} - \phi_i''\right| \tag{6}$$

The curvatures of mode shape are calculated by central difference approximation

$$\phi_i'' = \frac{\phi_{i-1} - 2\phi_i + \phi_i}{a^2} \tag{7}$$

where 'a' is the space between two measured points or consecutive nodes.

The Average of MSC damage index (MSCDI) is given by

$$MSCDI_{\,i} = \frac{1}{N}\sum_{n=1}^{N}(\Delta\phi_i'')_n \tag{8}$$

The above mentioned two methods used to evaluate the crack location of the crack on the structure by the major absolute difference between the modeshapes of the damaged and undamaged state of the plates.

VI. RESULTS AND DISCUSSIONS

First six transverse natural frequencies are calculated using FEMA and EMA and both values are approximately same. Mode shapes (directional deformations) are calculated using FEMA for every 10 mm interval distance of plate width from one end to other end along the length by path scooping method. For example one of the path model at location point-1(0, 60) and point-2(400, 60) for damaged plate is represented in fig.10. Fig. 11 represents the first four mode shapes of plate type-1 using damage identification approach -1. By observing the four mode shapes, peaks appeared at damage location exactly, but in some mode shapes other peaks are developed due to vibration nodes of the plate. To avoid such problem determine the damage indexes which are calculated by using equations (5) and (8) in both approaches.

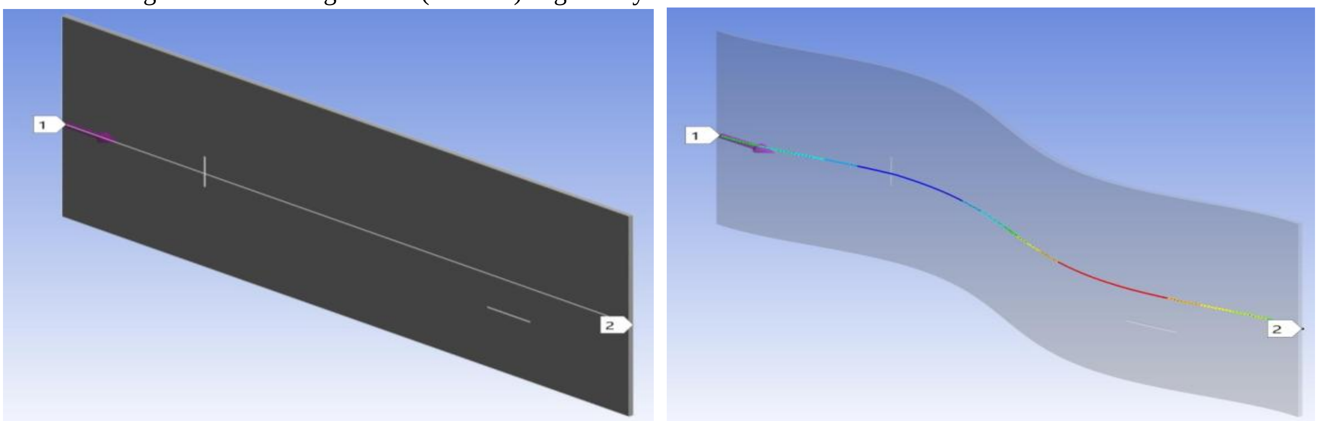
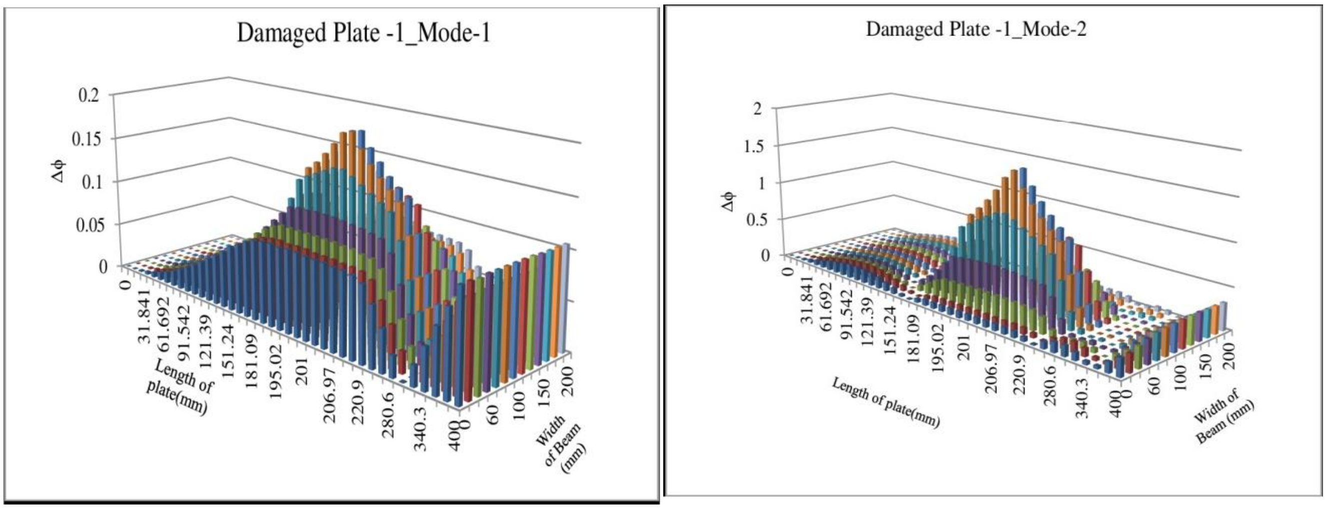


Fig. 10. Directional deformations on path location point-1(0, 90) and 2(400, 60)



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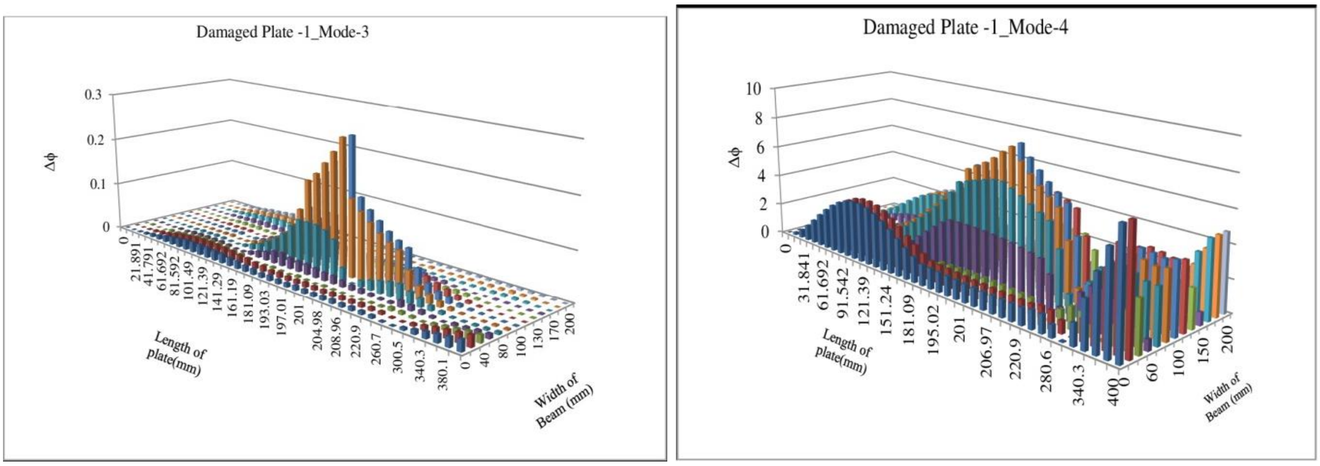

Fig. 11. Damage detection using first four mode shape difference for damaged plate-1

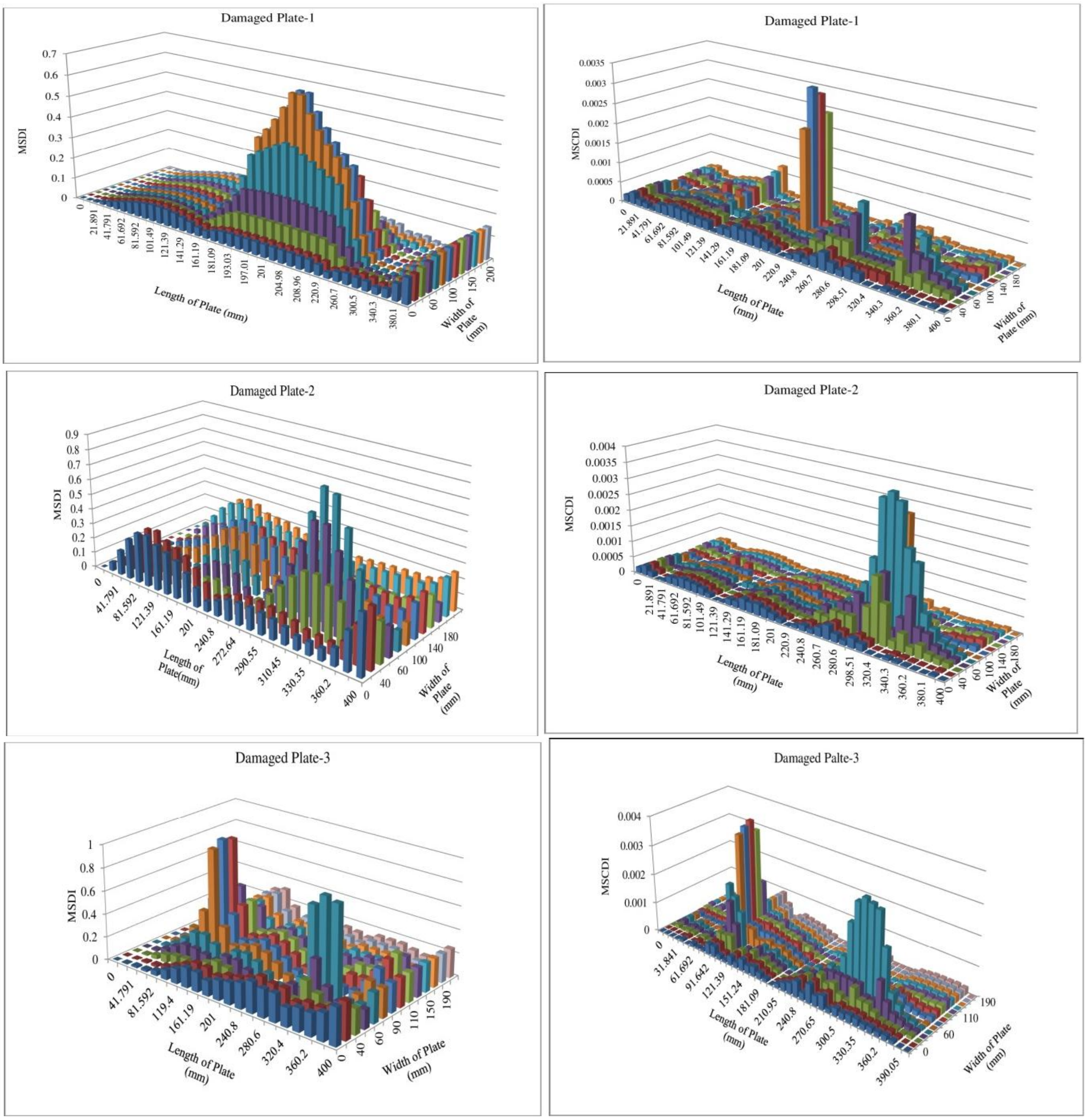

Fig. 12. Damage detection using MSDI(left side) and MSCDI (right side) for damaged plates-1, 2 and 3

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In figure 12, left side diagrams are representing the damage identification of three different damaged plates using MSDI and right side diagrams are representing damage locations using MSCDI. It is observed from the figure 12 is that, the damage detection for plate like structures using mode shape curvatures approach is highly precise when compared to mode shapes MSDI approach.

VII. CONCLUSION

Material properties are determined using conventional tests such as density, tensile and deflection tests, the reason is that to get exact vibration parameters through FEMA by setting experimental material properties. The properties are slightly differs from manufacturer's catalogue. Verified the natural frequencies of FEMA with EMA and observed that there is very less difference due to noise during EMA. Through measured mode shapes, the damage detection techniques are conducted using two approaches for exact damage location identification by considered three different damaged plates. The damages are identified through some of the modes and not possible for some other modes due to fake peaks developed due to vibration nodes. That is overcome by evaluating the indexes such as MSDI and MSCDI for getting exact damage size. Finally MSCDI approach provides exact damage dimensions when compared to MSDI approach very accurately for plate-like structures.

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