

Studies on Vibration-Based Damage Detection Methodologies for Structural Health Monitoring

D.K. Jayashree^{1,a}, B. Arun Sundaram², S. Parivallal³, D. Sivakumar⁴

M.E Student, K.S.Rangasamy College of Technology, Tiruchengode, Namakkal, Tamil Nadu, India¹

Scientist, CSIR-Structural Engineering Research Centre, Chennai, Tamil Nadu, India²

Principal Scientist, CSIR-Structural Engineering Research Centre, Chennai, Tamil Nadu, India³

Assistant Professor, K.S.Rangasamy College of Technology, Tiruchengode, Namakkal, Tamil Nadu, India⁴

ABSTRACT: Early detection of damage is important for upgrading, assessment and maintenance of our ageing infrastructure like bridges. A recent development in the health monitoring of structures is Vibration-Based Damage Detection (VBDD). It has been represented as the process to typically monitor changes both in modal frequency and mode shapes. This paper presents the studies carried out on various modal parameters that are influenced by damage. Finite element studies were carried out on a truss model for extracting the modal parameters. In this study the truss structure was subjected to three damage cases by reducing the cross sectional area of a single element. Modal Analysis was performed and the frequency and mode shapes were extracted for both the healthy and unhealthy states of the truss structure. Using these parameters, the other parameters namely Frequency change, Damage Location Assurance Criterion (DLAC), Mode shape Curvature and Curvature Damage Factor (CDF) were studied. These parameter changes are useful to predict damage information, such as the presence and location of damage in a structure.

KEYWORDS: Vibration-based damage detection, Truss structure, Modal analysis, Damage detection

I. INTRODUCTION

Structural health monitoring (SHM) is a new safety and management tool that aims to provide quantitative and reliable data on the real conditions of the structure, observe its evolution and detect the appearance of degradations. The primary objective of Structural Health Monitoring (SHM) is to determine if a structure is performing as expected or it has anomaly in its behavior as compared to the normal condition.

Vibration Based Damage Detection (VBDD) applied to structural health monitoring is very useful in interpreting the global vibration response of a structure to identify local changes (e.g. damages) in it. VBDD depends on the change of dynamic characteristics of the structures. These characteristics are natural frequencies, mode shapes and damping properties. These directly depend on material properties, geometry and support condition which contributes to the stiffness and also the distribution of mass. Damage can cause change to any of these dynamic characteristics. Therefore, the VBDD method uses any change to dynamic or modal parameters of structures to identify, locate and detect the severity of the damage. T. Siebel et al (2011) [1] analyzed the application of vibration-based damage detection methods to a wind turbine in this paper. The target was to develop a system that detects and locates damage on a structure subjected to wind excitation.

The present work is to study the various modal parameters by requiring measurements of the changes in a few of the structure's natural frequencies and mode shapes between the undamaged and damaged states. It is observed to provide good predictions of both the detection of damage.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Special Issue 6, May 2015

II. NUMERICAL MODELLING AND ANALYSIS

Analytical evaluations were performed with the commercial, general-purpose finite element code ABAQUS, which can effectively depict the nonlinear behavior of structures. A specific objective of the analytical evaluation included the development of a finite element model that could correctly represent global bridge behavior and accurately predict damage.

A two-dimensional truss model was developed to determine the overall structural response of the structure. The geometrical and material properties of the model are listed below.

- Span - 6m
- Height - 1m
- Young's modulus (E) - $2 \times 10^{11} \text{ N/m}^2$
- Density (ρ) - 7850 kg/m^3
- Poisson ratio (μ) - 0.3

The analysis was carried out by considering both the undamaged and damaged cases. Modal analysis was performed to extract the first five frequencies and mode shapes. The model of a 2D Howe truss structure which consists of 13 elements is shown in figure 1.

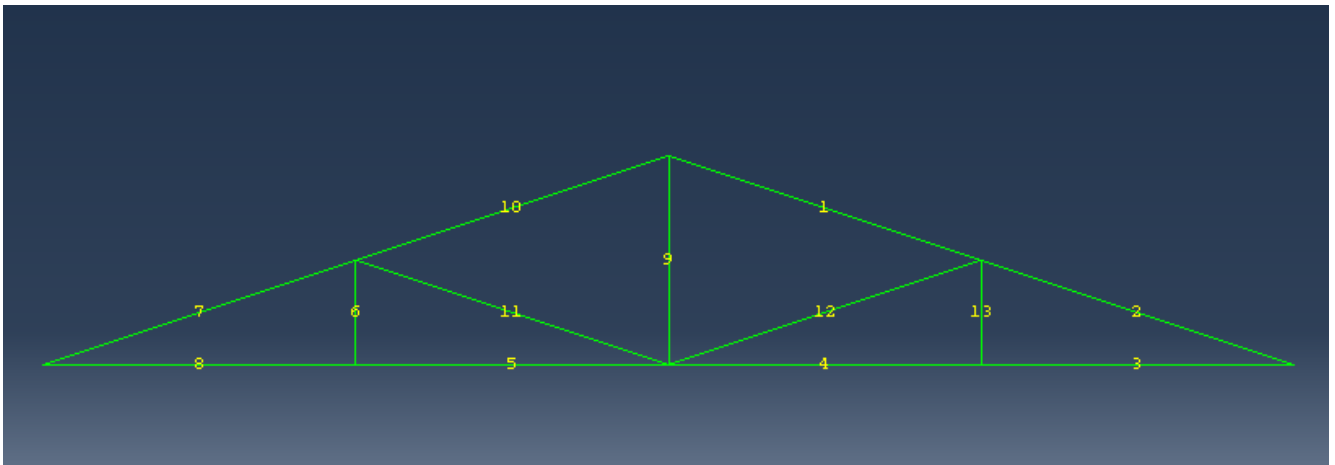


Figure 1: Finite Element Model Of Truss

Initially the modal parameters were extracted for the undamaged state in which the angle section is considered as $100 \text{ mm} \times 100 \text{ mm} \times 12 \text{ mm}$ (2259 mm^2). Then damage is induced by reducing the cross-sectional area of a single element (element 11) of the structure. Three damage cases are specifically studied where the cross sectional area reduction is achieved by changing the angle section considered. All damage types considered are summarized in table 1 and the mode shapes for damage case 1 is shown in figure 2.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Special Issue 6, May 2015

Table 1: Considered Damage Cases

Damage Cases	Cross- Sectional Area (mm ²)	Angle section (mm)
1	1402	75 × 75 × 10
2	1002	45 × 45 × 10
3	2250	25 × 25 × 5

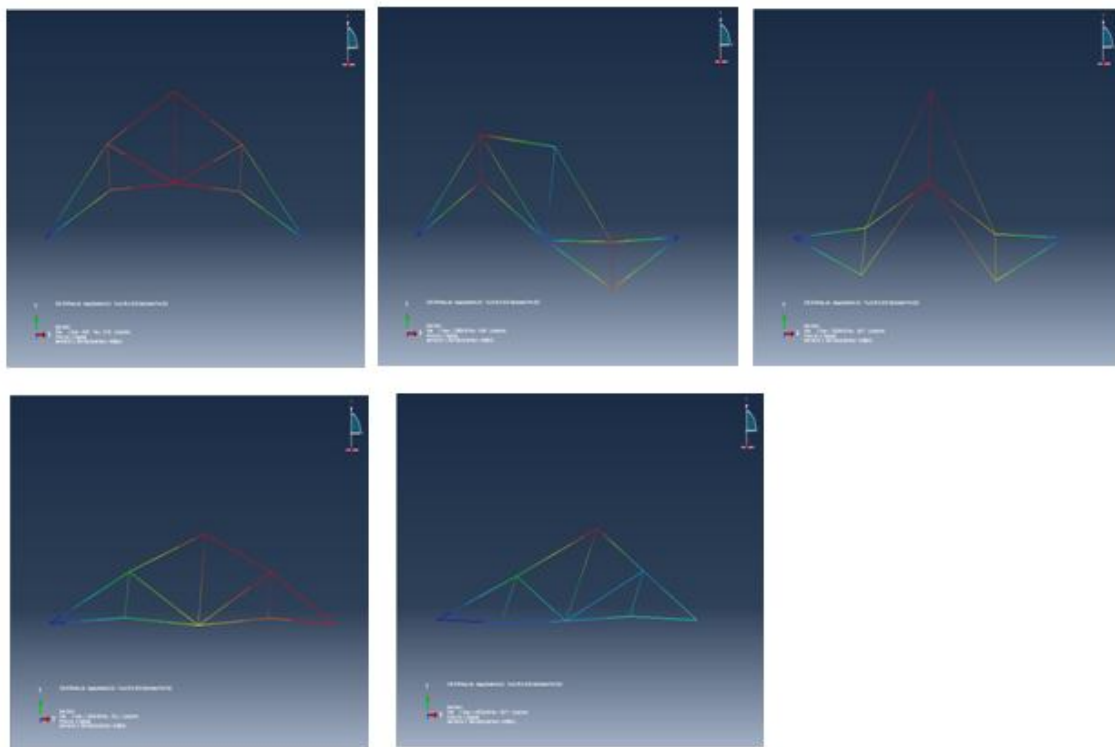


Figure 2: First Five Mode Shapes Of Damage Case 1

III. STUDY ON MODAL PARAMETERS

Structural damage often causes a loss of stiffness in one or more members of a structure that affects its modal frequencies and mode shapes. Based on these changes many methods have been developed to detect the location and size of damage. In this study, damage was predicted noting the change in natural frequencies and mode shapes. For localization of damage other dynamic parameters such as Damage Location Assurance Criterion, Curvature of the mode shape and Curvature Damage Factor have also been studied. The results of this study were generated using MATLAB which are discussed below.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Special Issue 6, May 2015

A.FREQUENCY CHANGES

The use of natural frequency as a diagnostic parameter in structural assessment procedures using vibration monitoring is based on the fact that natural frequencies are sensitive indicators of structural integrity. Thus, an analysis of periodical frequency measurements can be used to monitor structural condition. The presence of damage or deterioration in a structure causes changes in the natural frequencies of the structure. The most useful damage location methods are probably those using changes in frequencies because frequency measurements can be quickly conducted and are often reliable [2].The frequency values obtained from numerical analysis are tabulated in table 2.

Table 2: Natural Frequencies Of The Truss Structure

Mode number	Undamaged state	Damage case 1	Damage case 2	Damage case 3
1	32.841	32.752	32.730	25.643
2	78.880	74.634	70.647	65.269
3	142.62	136.77	129.64	125.59
4	178.31	178.26	178.11	170.68
5	340.06	320.97	320.97	314.28

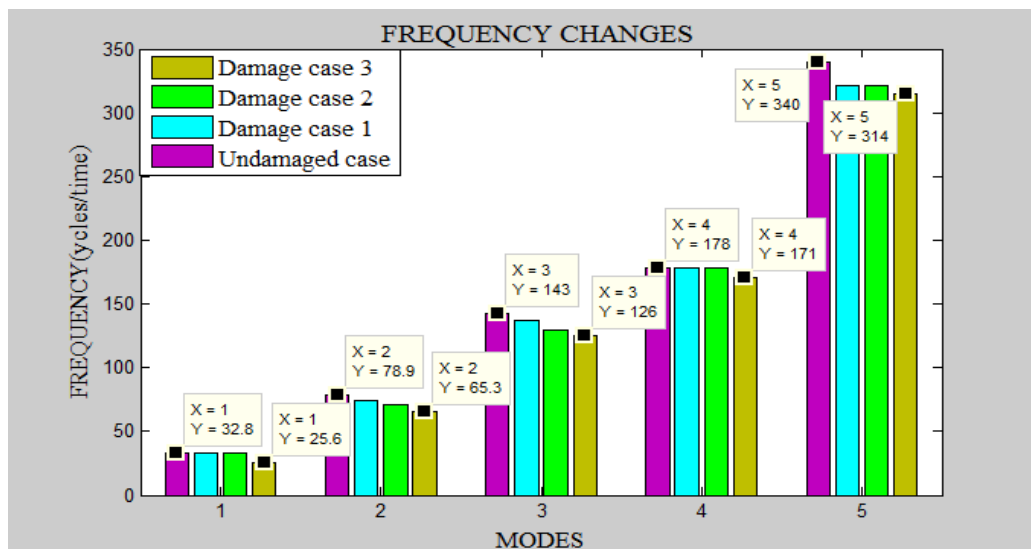


Figure 3: Changes In Natural Frequency

Figure 3 summarizes the natural frequency obtained during each undamaged and damaged cases. No change in the dynamic properties can be observed until the final level of damage is introduced. At the final level of damage the natural frequencies for the all the modes have decreased. This indicates the presence of damage in the structure.

B. DAMAGE LOCATION ASSURANCE CRITERION (DLAC)

The Damage Location Assurance Criterion can be defined using a correlation approach. DLAC approach identifies damage by evaluating the linear correlation between frequency change vectors obtained by numerical measurements.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Special Issue 6, May 2015

The final estimation for the linear correlation between frequency change vectors is accomplished by the DLAC equation which is restricted to positive values between 0 and 1. DLAC values close to unity indicate a strong correlation and therefore a potential damage location.

$$DLAC = \left| \frac{(\Delta F^T \Delta f)^2}{(\Delta F^T \Delta F)(\Delta f^T \Delta f)} \right|$$

Where as,

ΔF = undamaged state frequency

Δf = damaged state frequency

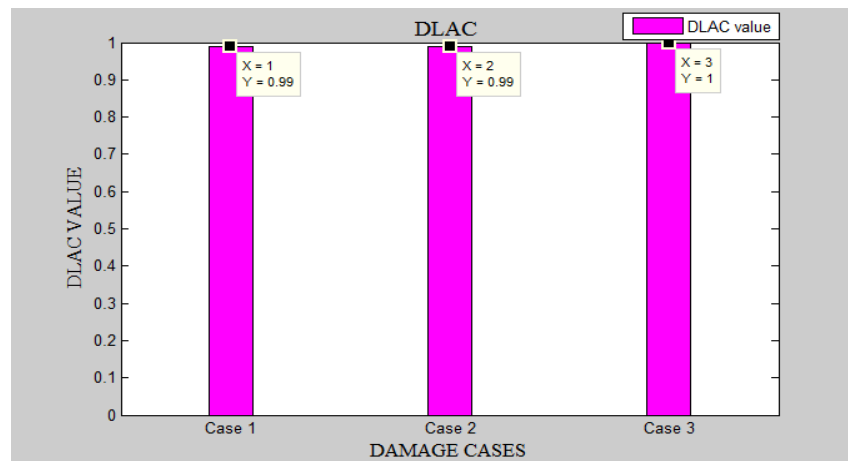


Figure 4: Dlac

DLAC values lies in the range of 0 to 1 with 0 indicating no correlation and 1 indicating an exact match between the patterns of frequency changes[3].

DLAC value for 3 cases are,

- Case 1: 0.99
- Case 2: 0.99
- Case 3: 1.00

This indicates that the DLAC value for the three damage cases were nearing 1, which assures the damage in the element no.11. The DLAC value for case 1 and 2 approximately specify the damage. But, the DLAC value for the case 3 accurately signifies the damage. It was found that more accurate damage identification can be obtained, if the frequency of the damaged state decreases with respect to the undamaged state frequency.

C. MODE SHAPE CURVATURE

This method is based on direct consequence of damage, as reduction of flexural stiffness of a structure in correspondence with the damaged regions. This increases the amplitude of curvature at damaged region and so can be used to detect and locate damage.

The curvature mode shapes are derived using a central difference approximation as follows

$$K_i = (w_{i+1} + w_{i-1} - 2w_i) / h^2$$

where w is the modal displacement at i^{th} point, h is the length of the specimen.[4]

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Special Issue 6, May 2015

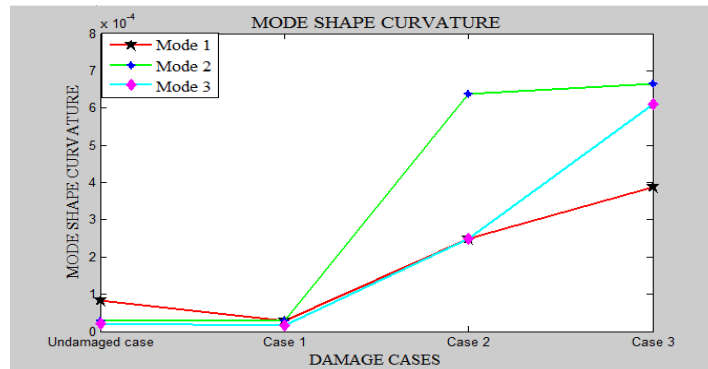


Figure 5: Mode Shape Curvature For Three Modes

From figure 5 it is observed that the maximum curvature mode shape is highest in case 3 subjected to heavier damage. Thus results showed that the study of displacement mode shape can be a good indicator of damage location.

D. CURVATURE DAMAGE FACTOR (CDF)

Curvature Damage factor can be derived as the differences in modal curvature averaged over all modes which give a clear identification of damage locations. Hence the method can be adopted with confidence for accurate modal parameter evaluation and subsequent application for damage identification. To summarize the results for all the modes, the curvature damage factor as proposed by Wahab and Roeck is calculated, which can be written as [5]

$$CDF = \frac{1}{N} \sum_{i=1}^N |u_{und} - u_d|$$

Where,

- N = the total number of modes to be considered,
- u_{und} = the curvature mode shape of the intact structure
- u_d = curvature mode shape of the damaged structure

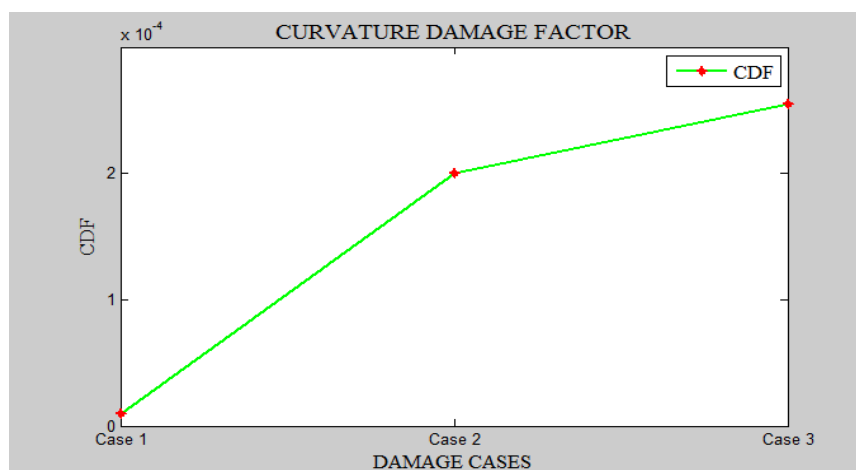


Figure 6: Cdf

The CDF value is highest at the location of severe damage case 3. Using this parameter the location of crack can be precisely identified.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Special Issue 6, May 2015

IV. SUMMARY AND CONCLUSIONS

The intention of this paper is to detect damage by extracting the modal parameters of structures. Numerical studies were carried out on a truss structure using ABAQUS software for undamaged and damaged states. Frequency and mode shapes were extracted as a result of modal analysis. Using these parameters the various damage indicating methods were studied. The results of this study were generated using MATLAB.

Based on the results of various methods, it can be concluded as,

- A gradual decrease in frequency occurs correspondingly as the cross sectional area decreases.
- Natural frequency changes alone may not be sufficient for a unique identification of the location of structural damage
- A new correlation coefficient termed the Damage Location Assurance Criterion has been studied to provide reliable information about the detection and location of damage.
- The maximum mode shape curvature is highest in region of severe damage.
- A better localization of damage could be done by curvature damage factor which shows more sensitivity than the mode shape curvature.

ACKNOWLEDGEMENT

The paper is published with the permission of the Director, CSIR-Structural Engineering Research Centre Chennai.

REFERENCES

- [1] T. Siebel, A. Friedmann, M. Koch and D. Mayer, "Assessment of mode shape-based damage detection methods under real operational conditions", 6th European Workshop on Structural Health Monitoring.
- [2] O. S. Salawu, "Detection of structural damage through changes in frequency: a review", Engineering Structures, Vol 19, No. 9, pp 718-723, 1997.
- [3] A. Messina, E.J. Williams, and T. Contursi, "structural damage detection by a sensitivity and statistical-based method", Journal of Sound and Vibration", 216(5), 791-808, 1998.
- [4] Wei Fan and Pizhong Qiao, "Vibration-based damage identification methods: A review and comparative study", Structural Health Monitoring, Vol 10(1): 83-29, 2010.
- [5] Anjan Dutta and S. Talukdar, "Damage detection in bridges using accurate modal parameters", Finite Elements in Analysis and Design, Vol 40, 287-304, 2004.