Damage Detection of Structure using Vibration Characteristics

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Abstract— Structural Health Monitoring (SHM) and Damage Assessment (DA) based on measured data is one of the most important issues related to safety and reliability of engineering structure especially in the areas such as Civil, Mechanical and Aerospace engineering. Effective methods and tools developed for SHM and DA can help not only to prevent catastrophic failure but also to prolong the service life of the structure. However, the primary objective for SHM is to detect the state of the structure, either healthy or damaged, by comparing the vibration characteristics of healthy and damage structure. Damage changes the vibration characteristics such as natural frequency, frequency response and mode shapes. In this paper steel beam is modeled and analyzed for vibration characteristics using Finite Element Analysis (FEA) tool. The changes in the natural frequencies, mode shape and other associated vibration characteristic may be considered for interpreting an unhealthy structure with reference to a healthy one. The damages in the structure may be introduced as cut-outs, stiffness reduction. The outcome of this study is to detect and localize the damage in the structure using the vibration characteristics. The procedure is analyzed numerically and validated by introducing known location(s) of damage in the structure.

Key words: Structural Health Monitoring (SHM), Damage Assessment (DA), Dynamic Response, Natural Frequency, Frequency Response and Mode Shapes

I. INTRODUCTION

Increased downtime of the structure made the maintenance costlier, inconvenient and thereby it had made rehabilitation and retrofitting of the structure difficult. Catastrophic failure of the structure is mainly due to negligence and failure in early detection of damage. Lack of sophisticated data acquisition system and other supporting equipments have caused difficulty in capturing accurate results. This has led to the need for continuous monitoring of the structure with the advance technology. Structural Health Monitoring (SHM) is one such area which has made easier to monitor the structure during construction and service life.

Some of the important civil engineering structure like bridges, dams and tall buildings needs to be regularly monitored for damages employing SHM. Generally damages are due to poor workmanship and also misunderstanding while analyzing the drawing and detailing. Quality of construction and materials, effects of temperature, segregation and settlement leads to the damage and deterioration of the structural components.

In SHM, change in structural vibration properties can be observed in presence of damages such as cracks, reduction or addition of material area, as they alter the stiffness of the structure. These damages affect the working condition of the structural element that leads to failure of structure before the end of their service life. Among all the Non Destructive Tests (NDT), the one's which are dependent on vibration properties are set as standard and gives acceptable outcomes in the area of SHM [3, 8]. Vibration properties such as Natural Frequency (NF) and shift in the peaks of Frequency Response Function (FRF) are sensitive to the alterations in local stiffness in compression to the other parameters. The presence of damage and its location can be determined by comparing vibration properties of the healthy structure with that of damaged structure [2].

II. RELATED WORK

Batabyal et.al [1] , have studied on crack detection in cantilever beam by using first two natural frequencies. The damage assessment is done based on normalization of natural frequencies and the variation is considered for different crack depth and crack location ratios. Contour lines of the cracked beam frequencies have been plotted having crack location and crack depth as its axis to identify the crack. Esfandiari et.al, [2] have proposed the sensitivity of natural frequencies for the crack analysis of steel cantilever beam and is charecterized as a second order element function of the stiffness reduction. The proposed method is able to detect the damaged without an exact model of undamaged structure.

Eigen system realization algorithm and Mckelvey frequency domain subspace algorithms have proposed by Girsum [3] to determine the vibration properties used in the detection of local structural damage and deterioration in cantilever plate. The proposed method is able to predict NF and damping ratio with an average error of 3.2% and 2.8% respectively. Flexibility method, gapped smoothing method, damage index and weight coefficient are proposed by Lingling et.al, [4] to identify the damage in metallic sandwich panels with truss core. The proposed method is more efficiency in detecting single damage and multiple damage of same or different extent.

Loutridis and Douka [5] have adopted instantaneous frequency and empirical mode decomposition method to identify the cracks in cantilever beam and they concluded that instantaneous frequency is gives better results than Fourier analysis. Meholi et.al, [6] have worked on FRF used for damage detection in a beam. Independent component analysis (ICA) has been implemented in order to reduce dimension of the data. The efficiency of both methods is compared with numerical and experimental approach.

Nahvi et.al, [7] have presented an analytical as well as experimental approach to the crack detection in beam by vibration analysis. An experimental setup is designed in which cracked beam is excited by hammer and response is obtained using an accelerometer. Proposed method provides the useful information about the medium sized cracks. Yang et.al, [8] have proposed a distinct element model to simulate cracking in Reinforced Concrete beam and influence of cracking on natural frequency was analyzed. Experimental test were also conducted to verify the numerical simulation result. Cracking and yielding of longitudinal tensile reinforcement can be identified based on a continuously descending natural frequency.

III. OBJECTIVES

Following are the objectives of the proposed project:

1) To identify the damage based on vibration characteristics such as NF and FRF of the structure.
2) To locate and quantify the damage based on NF and FRF measures.

IV. METHODOLOGY

In this study steel beam is modeled and analyzed for vibration characteristics such as NF and FRF using FEA tool. The convergence study is carried out with NF and displacement to find the optimum size of the mesh. The changes in the NF and FRF are considered for interpreting an unhealthy structure with reference to a healthy one. The damages in the structure are introduced as cut-outs.

A. Natural Frequency (NF)

The equation for the free vibration without damping is given by ,

$$[M]\,[\ddot{X}] + [[K]- Q\,[K_g]]\,[X] = 0 \qquad (1)$$

where,
[M]= Consistent mass matrix
[K] = Bending stiffness matrix of the beam
[K g] = Geometric stiffness matrix
[X] = Displacement vector
Q = External excitation vector

For free vibration without damping, the equation (1) can be written as,

$$[M]\,[\ddot{X}]+ [K]\,[X] = 0 \qquad (2)$$

Where, the load function, Q = 0

The equation (2) represents an Eigen value problem and the solution for the above equation is in the form of angular frequency,

$$[K]-(\omega_n)^2\ [M] = 0 \qquad (3)$$

Therefore the first three NF's of the cantilever beam under free vibration condition is given by

$$\omega_1 = 1.875^2 * SQRT(EI/ML^4)\ ,\quad f_1 = \omega_1/2\Pi \qquad (4)$$
$$\omega_2 = 4.694^2 * SQRT(EI/ML^4),\quad f_2 = \omega_2/2\Pi \qquad (5)$$
$$\omega_3 = 7.855^2 * SQRT(EI/ML^4)\ ,\quad f_3 = \omega_3/2\Pi \qquad (6)$$

V. MODELLING

In this study a thin cantilever steel beam of following parameters are considered [3]. The modeling of the beam is done using ANSYS software. The element for modeling is considered as "shell 181" 4 nodded two dimensional elements. To find the optimum size of the mesh, the convergence study is carried out for both displacement and first three natural frequencies.

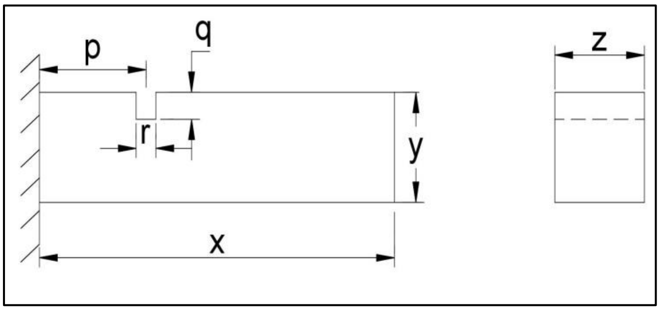

Fig. 5.1: Typical section of the damaged beam

The cantilever steel beam of cross-sectional dimension 25 * 4.4 mm and length of 260 mm is considered for modeling, the material properties taken are Young's modulus of beam material (E) = 210 * 10^3 N/mm^2 , Poisson's ratio (μ) = 0.3, Density (ρ) = 0.0785 N/mm^3.

Crack is introduced in the form of U shape cutout. The depth and location of the crack was changed at regular intervals.

- Width of the crack (r) = 0.26 mm
- Depth of crack (q) = 0.6 to 3 mm (interval of 0.6 mm)
- Location of crack (p) = 30 to 230 mm (interval of 20 mm)

Crack Depth Ratio (CDR) (q/y) is defined as the ratio of depth of the crack (q) to depth of the beam (y).

Crack Length Ratio (CLR) (p/x) is defined as the ratio of location of crack from the left support (p) to length of the beam (x).

VI. CONVERGENCE STUDY

In FEA, the accuracy of the results is directly proportional on the size of the element considered and also on the order of polynomial. Element size is taken from 0.052 mm to 0.0005 mm. Graph is plotted between no. of elements v/s frequencies such as First Natural Frequency (FNF), Second Natural Frequency (SNF) and Third Natural Frequency (TNF), and no. of elements v/s displacements as shown in Fig. 6.1 to Fig. 6.4. The mesh size is chosen based on convergence requirements.

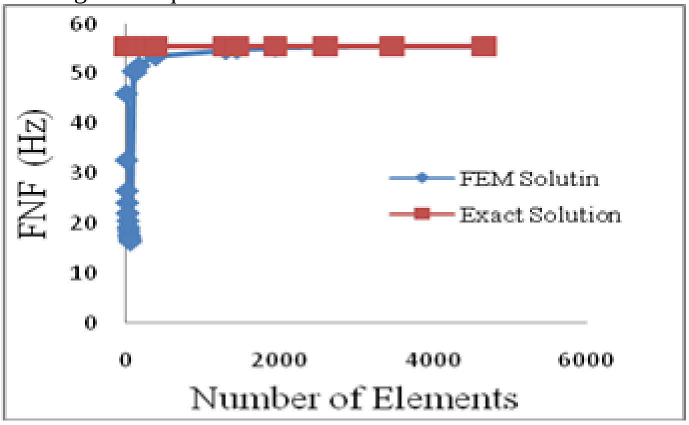

Fig. 6.1: FNF with number of elements for FEM and Exact solution.

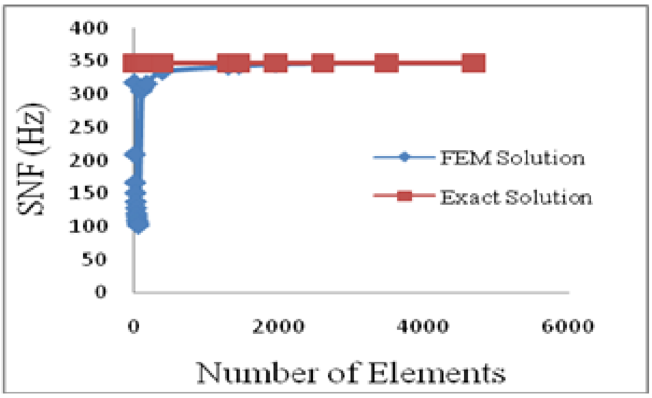

Fig. 6.2: SNF with number of elements for FEM and Exact solution

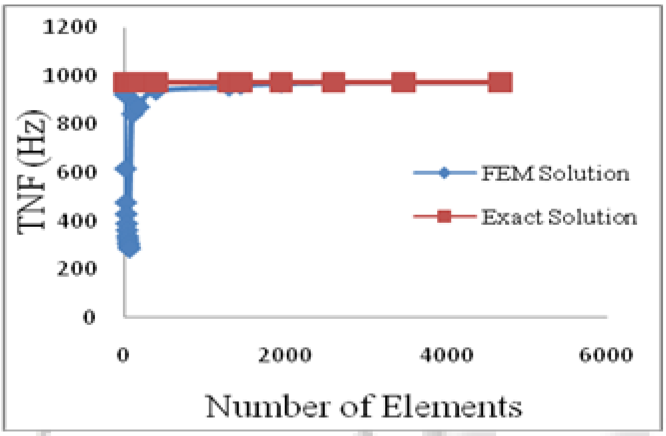

Fig. 6.3: TNF with number of elements for FEM and Exact solution

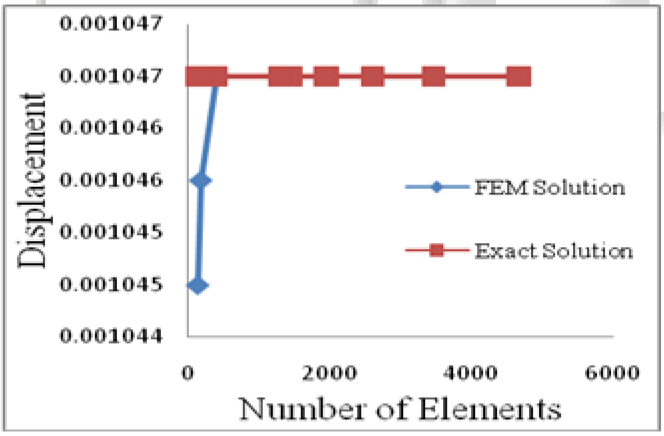

Fig. 6.3: Displacements with number of elements for FEM and Exact solution

From the above figures, it is observed that, all three natural frequencies of FEM solution converges with exact solution beyond 4000 elements (Fig. 2 to 4). The displacement of the FEM solution converges with exact solution beyond 1500 elements (Fig. 5). Comparing the convergence of displacement and frequencies, the mesh size chosen as 0.0005 m corresponding to the number of elements is equal to 4680.

VII. DAMAGE ANALYSIS

A. *Damage Detection Using Natural Frequency*

NF is more affected to damage when compared with other vibration characteristics and gives better information about the damage location and its intensity. The first three Normalized Natural Frequencies (NNF) are considered for damage assessment and graphs are plotted between frequencies with CDR for different CLR and vice versa.

Normalized frequency ratio is defined as ratio of NF of damaged beam to the NF of undamaged beam. NNF such as First Normalized Natural Frequency (FNNF), Second Normalized Natural Frequency (SNNF) and Third Normalized Natural Frequency (TNNF) provide better information about the damage state, because the NNF contains the frequencies of both healthy and unhealthy beams.

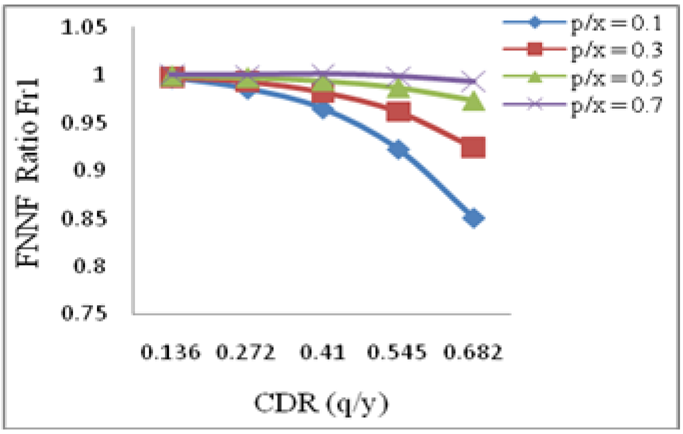

Fig. 7.1: FNNF ratio with CDR (q/y) for different CLR's (p/x).

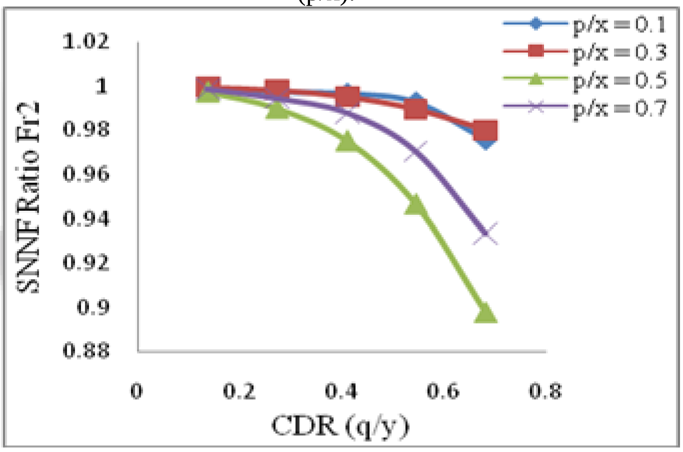

Fig. 7.2: SNNF ratio with CDR (q/y) for different CLR's (p/x).

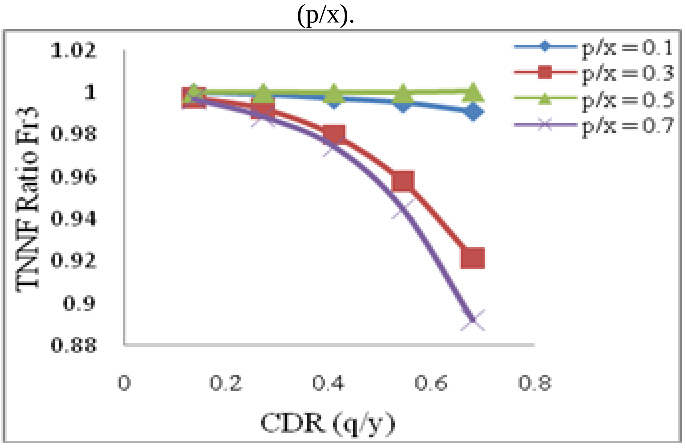

Fig. 7.3: TNNF ratio with CDR (q/y) for different CLR's (p/x).

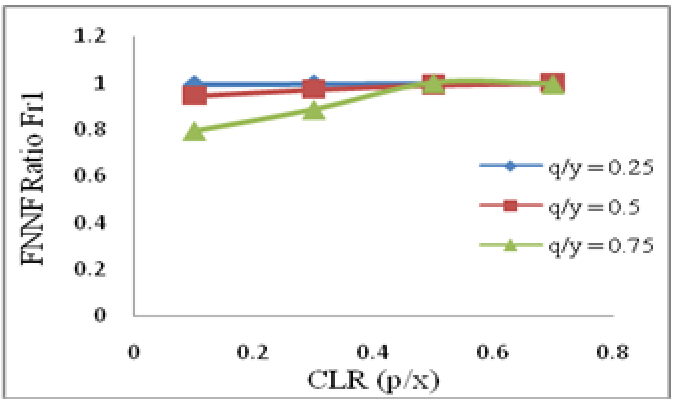

Fig. 7.4: FNNF ratio with CLR (p/x) for different CDR's (q/y).

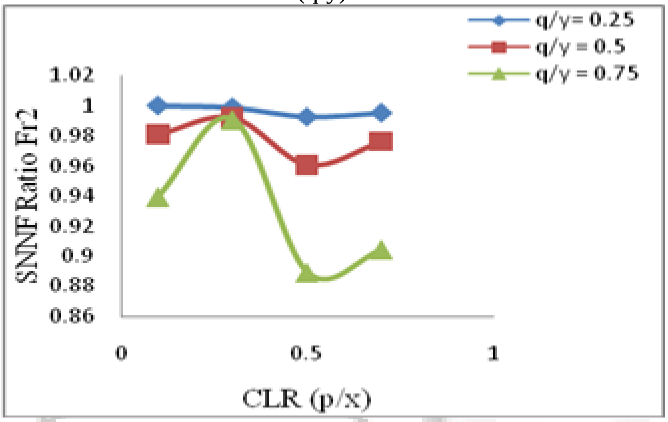

Figure 7.5 SNNF ratio with CLR (p/x) for different CDR's (q/y).

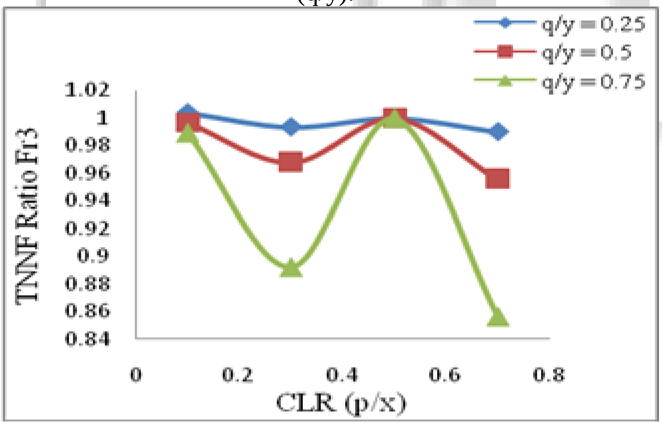

Figure 7.6 TNNF ratio with CLR (p/x) for different CDR's (q/y).

B. Damage Analysis by Frequency Response Function (FRF)

In FRF, the variation of amplitude is considered with the frequency and the variation is plotted by taking amplitude along y axis and frequency along x axis for different percentage of damping.

Frequency response function with zero percentage of damping ($\zeta = 0$)

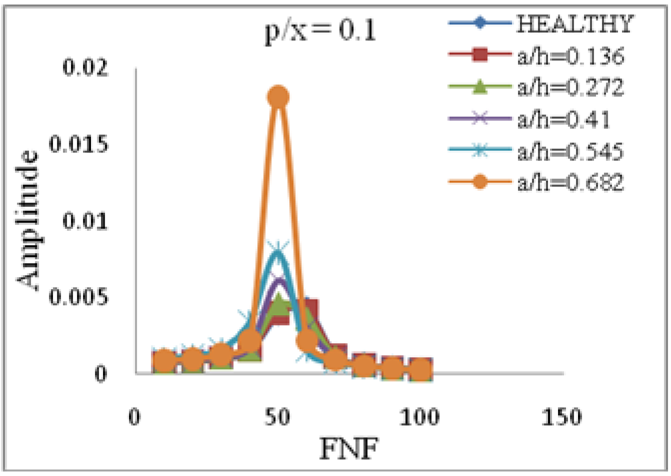

Fig. 7.7: Amplitude with FNF for different CDR at CLR = 0.1.

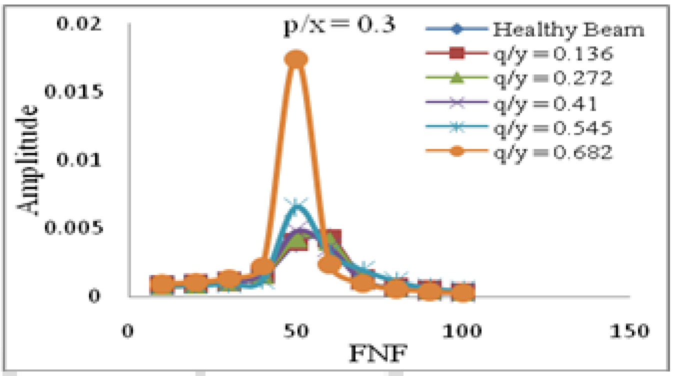

Fig. 7.8: Amplitude with FNF for different CDR at CLR = 0.3.

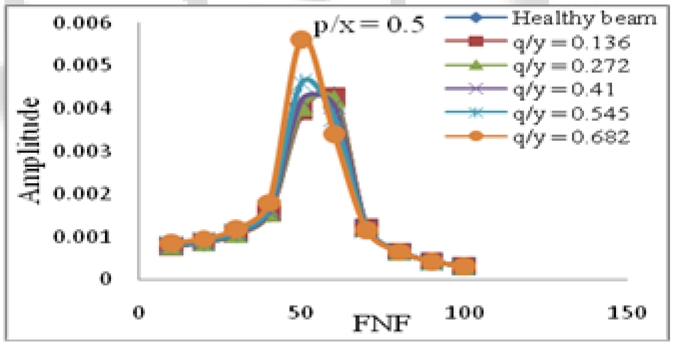

Fig. 7.9: Amplitude with FNF for different CDR at CLR = 0.5.

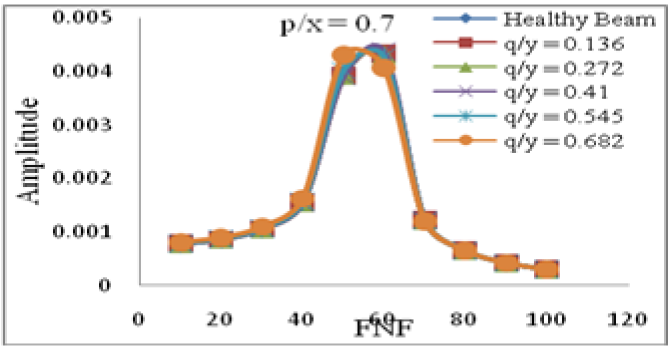

Fig. 7.10: Amplitude with FNF for different CDR at CLR = 0.7.

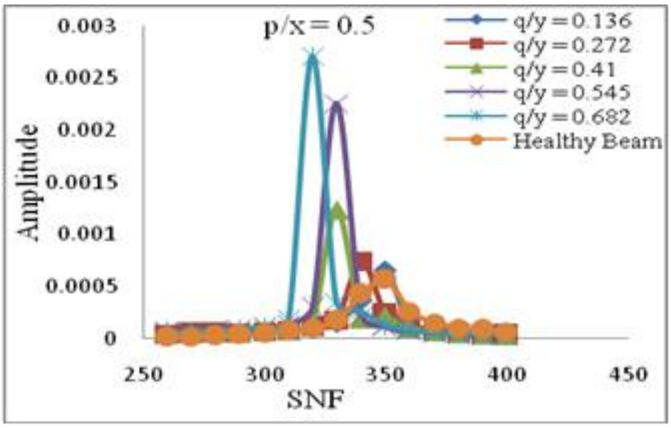

Fig. 7.11: Amplitude with SNF for different CDR at CLR = 0.5.

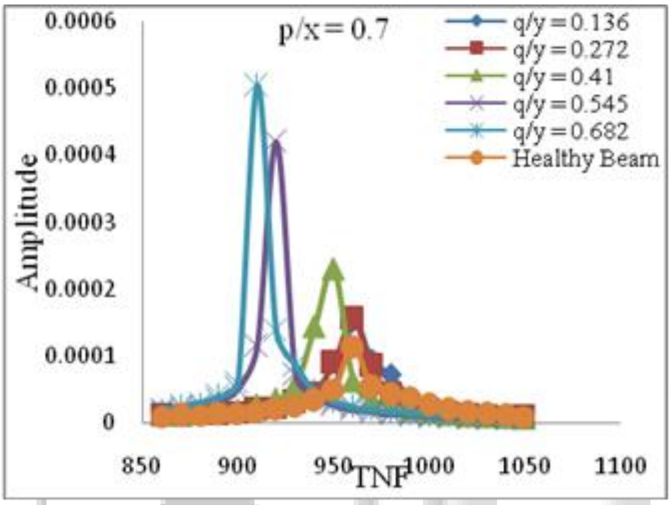

Fig. 7.12: Amplitude with TNF for different CDR at CLR = 0.7.

Frequency response function with different percentage of damping

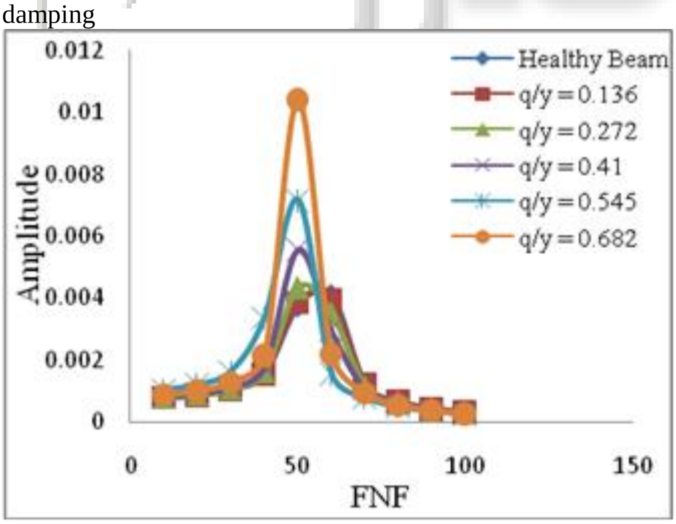

Fig. 7.13: Amplitude with FNF for ζ=0.02, p/x = 0.1.

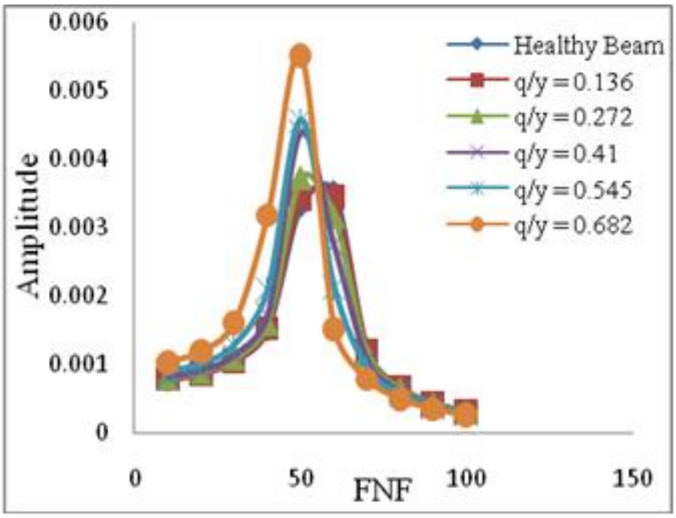

Fig. 7.14: Amplitude with FNF for ζ=0.04, p/x = 0.1.

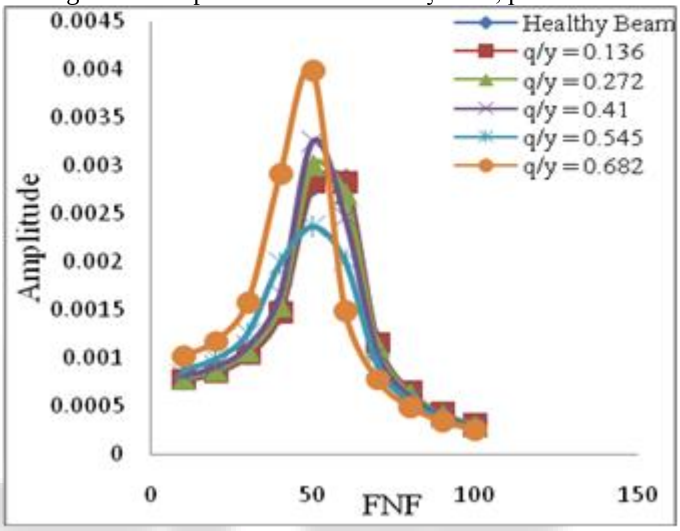

Fig. 7.15: Amplitude with FNF for ζ=0.06, p/x = 0.1.

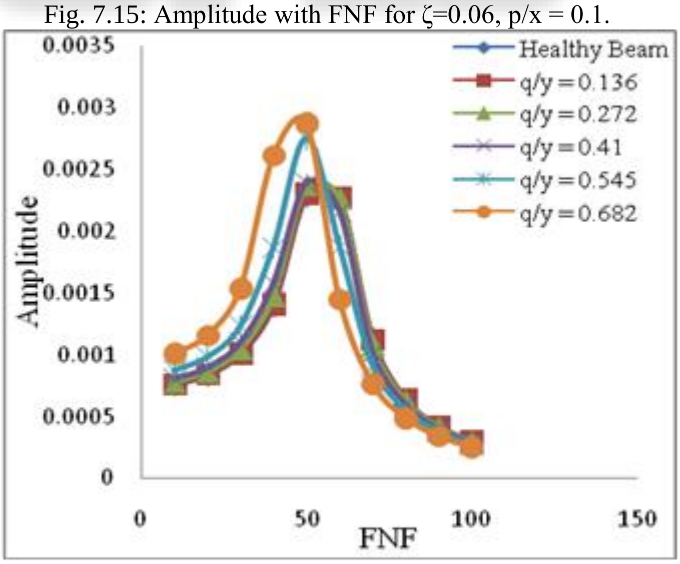

Fig. 7.16: Amplitude with FNF for ζ=0.08, p/x = 0.1.

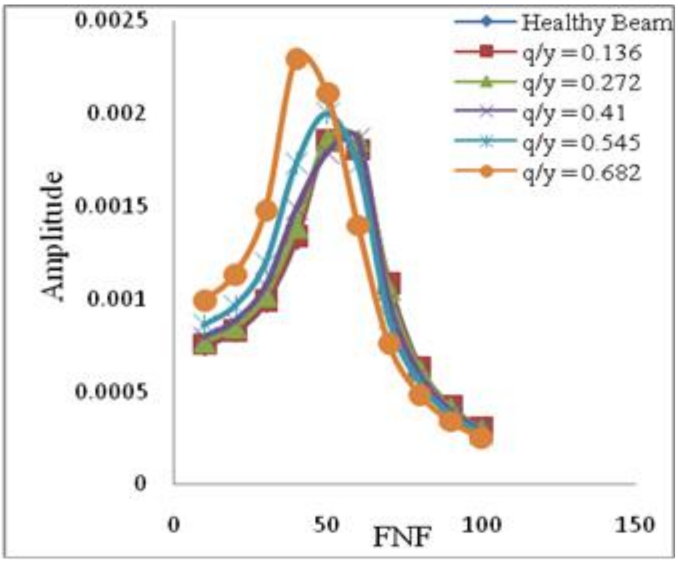

Fig. 7.17: Amplitude with FNF for ζ=0.1, p/x = 0.1.

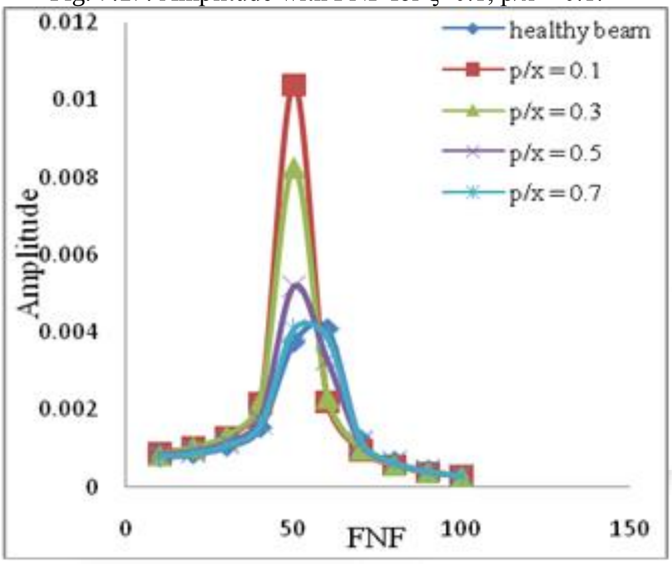

Fig. 7.18: Amplitude with FNF for ζ=0.02, q/y = 0.682.

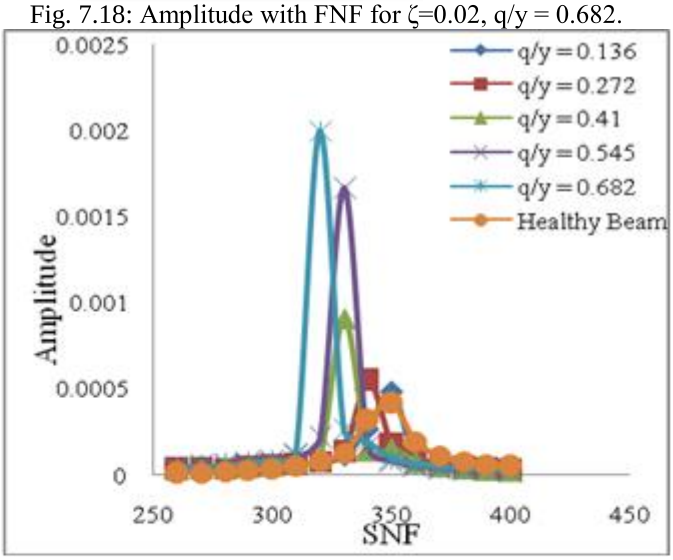

Fig. 7.17: Amplitude with SNF for ζ=0.02, p/x = 0.5.

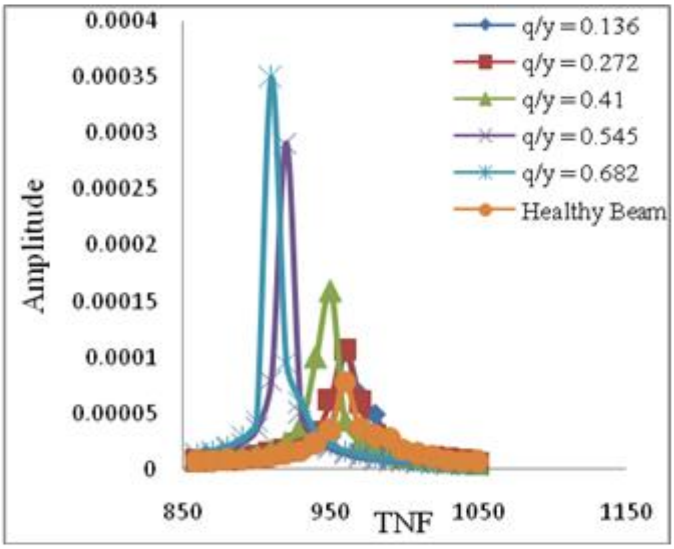

Fig. 7.17: Amplitude with TNF for ζ=0.02, p/x = 0.7.

VIII. Results & Discussions

From the graph, it is absorbed that the FNNF is higher sensitive when damage is present near the fixed end. The percentage change in FNNF is 15% for the corresponding crack length ratio 0.1 (i.e., crack is present at a distance of 26mm from the support) and crack depth ratio 0.682 (i.e., the depth of the crack is equal to 3mm) and it is also observed that the percentage change will increases as crack depth increases. The variation of fr1 is maximum for p/x ratio is equal to 0.1 and it decreases as p/x ratio shifts from 0.1 to 0.7.

It is observed that SNNF is more sensitive if the damage is present at the mid-span of the beam. The percentage change in SNNF is 12% for corresponding c/l ratio is equal to 0.5 and a/h ratio is equal to 0.682 and it is observed that the percentage change will increases as crack depth increases.

TNNF is more affected when the c/l ratio is equal to 0.7 and the maximum percentage change is 13% and it is also observed that the change in percentage will increases as crack depth increases.

It is observed that, the amplitude with FNF is maximum when the damage is present near the fixed end. As the damage location shifts from left to right support, the change in amplitude with FNF will decreases. It is observed that as the CDR increases, the amplitude will also increase. Damage analysis using amplitude with FNF will give more information when the crack present nears the fixed end. Amplitude with SNF and TNF will provide clear picture when the damage is present near the mid span and free end of the beam respectively.

The amplitude with FNF will decreases as CLR varies from 0.1 to 0.7 and it is also observed that as CDR increases, the change in amplitude is also increases. The amplitude with FNF is very small, as CLR and percentage of damping increases. In this method, at 2% damping will give clear information about the damage. The amplitude with SNF and TNF is more, when the cracks are present near the mid span and free end of the beam.

IX. CONCLUSION

Based on all the analytical investigations carried out in the study undertaken the following conclusions are drawn.

1) The strain accumulation is more near the fixed end, mid span and free end of the beam for first, second and third modes respectively.
2) The NF's corresponding to first, second and third modes are more sensitive at fixed end, mid span and free end of the beam.
3) In NF's, the FNF, SNF and TNF will give better knowledge about the crack when it present near the fixed end, mid span and free end of the beam respectively.
4) Normalization is considered for this three NF's for better damage analysis. The variation in this NF's will increases as the crack depth increases.
5) In FRF different percentages of damping is considered. The amplitude will decreases as the percentage of damping increases.
6) 2% damping will give the better idea about the crack analysis.
7) The variation of amplitude with FNF, SNF and TNF is more when the cracks present near the fixed end, mid span and free end of the beam respectively.

REFERENCES

[1] Batabyal A K, P Sankar, T K Paul, Crack detection in cantilever beam using vibration response, Springer proceedings on vibration problems ICOVP 2007, pp. 27 - 34.

[2] Esfandiari A, F Bakhtiari Nejad,Theoretical and experimental structural damage diagnosis method using natural frequency through an improved sensitivity equation, International journal of mechanical science 2013, Vol. 70, pp. 79-89.

[3] Girum S Urgessa, Vibration properties of the beam using frequency domain system identification method, SAGE JVC 2010, Vol. 17(9), pp. 1287-1294.

[4] Lingling Lu, Hongwei Song, Baseline – free damage identification of metallic sandwich panels with truss core based on vibration characteristic, SAGE SHM 2017, Vol. 16(1), pp. 24-38.

[5] Loutridis, Douka , Forced vibration behaviour and crack detection of cracked beams using instantaneous frequency, NDT&E Intrnational 2005, Vol. 38, pp. 411-419.

[6] Meholi Salehi, Saced Ziaei-Rad, A frequency response based structural damage location method using independent component analysis, Journal of mechanical science and Technology 2013, Vol. 27(3), pp. 609-619.

[7] Nahvi H and Jabbari M, Crack detection in beams using experimental modal data and finite element model, International journal of mechanical science 2005, Vol. 47, pp. 1477-1497.

[8] Rupika P Bandara, Tommy HT Chan and David P Thambirathnam, Structural damage detection method using frequency response function, SAGE SHM 2014, Vol. 13(4), pp. 418-429.

[9] Yang Gao, Yanliang Du, Research on cracking of RC beam and its influence on natural frequency by expanded distinct element method, Journal of Aerospace Engineering ASCE 2016, ISSN 0893-1321, pp. B4016015-1 B4016015-7.

