Comparative Study on the Modal Parameter of Cracked Beams

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Abstract Crack occurrence is a crucial factor that affects the lifespan of civil structures. Cracks present on the surface of the structural element like beams, accounts changes in stiffness, flexibility and consequently their static and dynamic behaviour is affected. The influence of natural frequencies and modes of vibration of structures have been the subject of many investigations. The damage detection studies contain forward approach and inverse approach. The forward approach involves the determination of dynamic characteristics while inverse approach deals with detecting damage with the help of those characteristics. Forward approach is used in this study. The effect of crack location, crack depth, material and fixity conditions on the changes in natural frequencies of the beam are studied. The finite element analysis of different cases of cracked beam is done using the software Ansys Workbench and the results obtained are compared.

Keywords Damage detection · Mode shape · Modal analysis · Natural frequency

1 Introduction

Nowadays structural health monitoring has high importance for damage assessment and safety evaluation of structures. The objective of structural health monitoring is to detect structural damage at earlier stage to avoid catastrophic failures. Engineering structures when subjected to repeated loading conditions undergoes cracks or damages in overstressed regions. Cracks can be described as unintended discontinuities in structural components [1]. They may occur due to various reasons. Cracks present on the surface of the structural element like beam, causes changes in stiffness, significantly depending upon the characteristics of cracks. Since the behavior of the structures are affected by cracks, it is necessary to detect them.

As the presence of cracks affects the vibration parameters like modal natural frequencies, mode shapes, etc., vibration based crack detection approaches [4] has

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been discovered by a lot of investigators. The advantages of vibration based technique over other methods are they are quick, non-destructive, economical, identifies more cracks and also detects internal cracks which are not visible to naked eye. Basically crack detection consists of forward problem and backward problem. The forward problem involves determination of various vibrational characteristics while the backward problem focuses on detection of cracks using these vibrational characteristics. So by identifying the changes in natural frequency and mode shapes of structure having cracks, it is possible to detect the cracks in a structure.

Modal analysis refers to the study of the dynamic properties of structures subjected to vibration. The natural frequency and mode shape of a beam like structure is determined by modal analysis. When the structures are subjected to vibration loads, the dynamic response of structures like natural frequencies, mode shape and damping are affected.

The main objective is to study and compare the changes in natural frequency of beams with cracks at different locations, depth, materials and fixity conditions. The study is limited to mode 1 vibration.

2 Validation

Natural Frequencies (NF) and mode shapes of a slender steel beam in healthy condition and beam with cracks at different location and depth were determined by modal analysis. Modal Analysis of Cracked Cantilever Beam was carried out using the software Abaqus by Mia et al. The validation was done using the finite element analysis software Ansys Workbench R19.2. The validation was conducted for 6 cases of beam without crack and beams with crack at different locations and depths. The crack was modelled as a triangular shape. The opening width of the crack provided was 2 mm. Crack was given at the top surface throughout along the width of the beam. The mesh size given for the study was 30 mm. The mode 1 Natural Frequencies of different cases were obtained. These values were compared with the values from Mia et al. and percentage error was also calculated. Table 1 gives the properties of beam used for the validation. Table 2 shows the different cases considered for validation, values of NF of mode 1 obtained from the analysis and from Mia et al. and percentage error for all the 6 cases. The percentage error obtained was comparatively less for all the cases considered for validation.

Table 1 Properties of specimen used for validation [1]

Property	Value
Length (L)	3 m
Width (w)	0.25 m
Depth (t)	0.2 m
Material	Mild steel
Elastic modulus (E)	210×10^6 N/m^2
Density	7860 kg/m^3
Poisson's ratio	0.3

Table 2 Summary of validation

Cases	Location of crack (m)	Depth of crack (m)	Obtained values of NF	Values of NF from Mia et al. [1]	% Error
Case 1	0	0	18.561	18.622	0.328
Case 2	1	0.1	16.621	16.936	1.86
Case 3	1	0.075	17.587	17.733	0.823
Case 4	1	0.125	14.983	15.471	3.154
Case 5	1.5	0.1	17.73	17.917	1.044
Case 6	2	0.1	18.353	18.437	0.456

3 Numerical Study on Different Types of Beams

3.1 General

The NF of Reinforced Cement Concrete (RCC) beams, Plain Cement Concrete (PCC) beams and Steel–Concrete (SC) Composite beams with and without cracks for both cantilever and fixed end boundary conditions were determined by modal analysis. Crack was provided at different locations of 0.2L, 0.4L, 0.6L and 0.8L from the fixed end of cantilever beam and left end of fixed end beams, where L is the total length of beam and for each of these locations the crack depth varied by 5, 10, 20 and 40 mm. Table 3 shows different cases considered for the study. The study was conducted using the finite element analysis software Ansys Workbench R19.2. For all the cases the crack was modelled as a triangular notch with an opening size of 5 mm extending throughout the width of beam considered.

Table 3 Different cases considered for modal analysis

Cases	Location	Depth (mm)	Cases	Location	Depth (mm)
Case 1	0	0	Case 10	0.6L	5
Case 2	0.2L	5	Case 11	0.6L	10
Case 3	0.2L	10	Case 12	0.6L	20
Case 4	0.2L	20	Case 13	0.6L	40
Case 5	0.2L	40	Case 14	0.8L	5
Case 6	0.4L	5	Case 15	0.8L	10
Case 7	0.4L	10	Case 16	0.8L	20
Case 8	0.4L	20	Case 17	0.8L	40
Case 9	0.4L	40			

3.2 Modal Analysis of Different Types of Beams for Different Cases

Modal analysis was conducted on RCC, PCC and SC Composite beams for 17 cases. The beams were modelled in Ansys Workbench R19.2. For RCC, the concrete was modelled by SOLID 65 and reinforcement by Link 180 finite elements and for PCC, the concrete was modelled by solid element. For SC Composite beam also, the materials were modelled by solid elements and different materials added with the help of modelling feature 'Add Frozen'. The study was conducted on 2 boundary conditions, cantilever and fixed end conditions. The analysis was done under the loading condition of self weight only. The mesh sizing given was 25 mm for RCC and PCC beams while for SC Composite beams it was given as 20 mm. For RCC and PCC beams, the crack locations given were 0.2, 0.4. 0.6 and 0.8 m and they were provided at top surface. For SC Composite beams, crack was given at 0.1, 0.2, 0.3 and 0.4 m at bottom surface. For all the cases, the depth varied as 5, 10, 20 and 40 mm. The specimen details of RCC, PCC and SC Composite beams are given in Tables 4, 5 and 6 respectively. Figure 1 shows the model of SC Composite beam.

3.3 Natural Frequencies Obtained for Different Cases

Natural Frequencies of different modes of vibration were obtained by modal analysis. Modal analysis was conducted on RCC, PCC and SC Composite beams for both cantilever and fixed end boundary conditions. For each type, a total of 17 cases were considered on the basis of location and depth of cracks. The mode 1 NF obtained for all the cases for all types of beams for both cantilever and fixed conditions are given in Table 7. Figures 2 and 3 shows the mode shape of mode 1 vibration of RCC cantilever beam of case 9 and PCC fixed beam of case 12 respectively.

Table 4 Details of RCC beam [2]

Particulars	Property	Value
Dimension	Length	1 m
	Width	0.25 m
	Depth	0.4 m
Reinforcement	Top bar	2# 20 mm dia
	Bottom bar	2# 8 mm dia
	Stirrups	8 mm dia @ 83.33 mm c/c
Concrete cover	Cover to reinforcement	40 mm
Concrete properties	Strength	25 MPa
	Young's modulus	3×10^7 kN/m^2
	Poisson's ratio	0.2
Reinforcement steel properties	Strength	500 N/mm^2
	Young's modulus	2×10^8 kN/m^2
	Poisson's ratio	0.3

Table 5 Details of PCC beam

Particulars	Property	Value
Dimension	Length	1 m
	Width	0.15 m
	Depth	0.15 m
Concrete properties	Density	2348.65 kg/m^3
	Young's modulus	2.58×10^7 kN/m^2
	Poisson's ratio	0.3

Table 6 Details of SC composite beam [3]

Property	Steel	Adhesive	Concrete
Length	500 mm	500 mm	500 mm
Width	100 mm	100 mm	100 mm
Depth	6 mm	2 mm	100 mm
Density	7579.0 kg/m^3	1611.8 kg/m^3	2364.4 kg/m^3
Young's modulus	12.5 GPa	200.3 GPa	48 GPa
Poisson's ratio	0.16	0.3	0.3

4 Results and Discussions

The NF obtained for different cases of all types of beams were compared. The comparison study was done for mode 1 vibration. The variation of NF keeping the

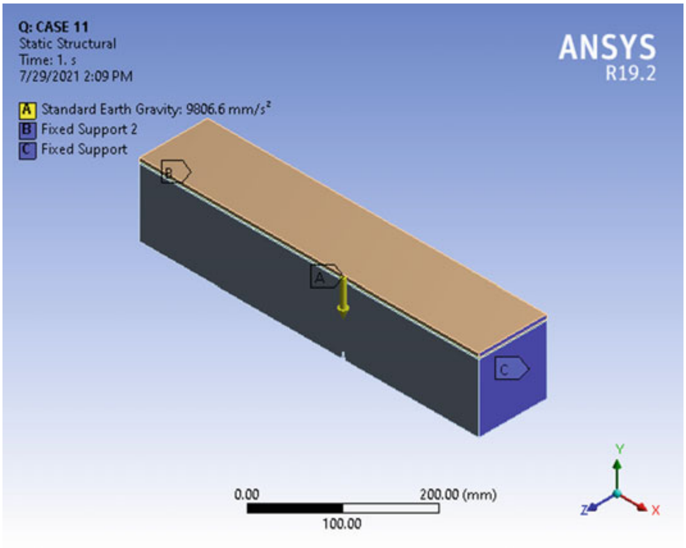

Fig. 1 Geometry of SC composite fixed beam with crack at 0.6 m and 10 mm depth (case 11)

Table 7 NF obtained for different cases

Cases	RCC beam		PCC beam		SC composite beam	
	Cantilever	Fixed	Cantilever	Fixed	Cantilever	Fixed
Case 1	139.09	697.67	79.245	453.88	282.45	1530.4
Case 2	139.08	697.66	79.127	453.86	282.13	1530.2
Case 3	139.02	697.61	78.787	453.80	281.16	1529.4
Case 4	138.80	697.44	77.400	453.53	277.15	1525.9
Case 5	137.73	696.31	71.882	452.22	255.59	1507.8
Case 6	139.08	697.68	79.191	453.58	282.33	1530.0
Case 7	139.06	697.60	79.062	452.85	281.91	1528.0
Case 8	138.96	697.27	78.515	449.75	280.36	1520.4
Case 9	138.48	695.50	76.111	437.84	274.81	1493.1
Case 10	139.09	697.69	79.233	453.58	282.44	1530.0
Case 11	139.08	697.62	79.204	452.81	282.36	1528.4
Case 12	139.06	697.29	79.064	449.56	281.97	1520.8
Case 13	138.93	695.51	78.421	437.44	280.43	1494.5
Case 14	139.09	697.66	79.250	453.86	282.51	1530.2
Case 15	139.10	697.63	79.255	453.80	282.55	1529.4
Case 16	139.10	697.43	79.257	453.54	282.63	1525.9
Case 17	139.10	696.31	79.233	452.29	282.67	1508.6

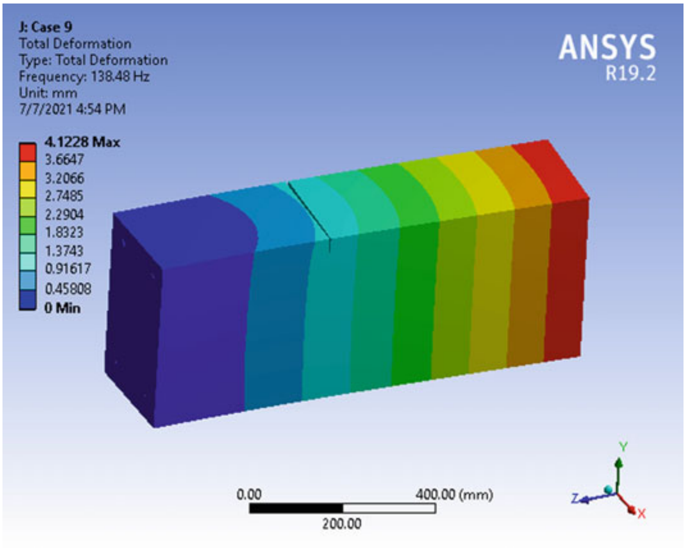

Fig. 2 Mode shape of mode 1 vibration of RCC cantilever beam of case 9

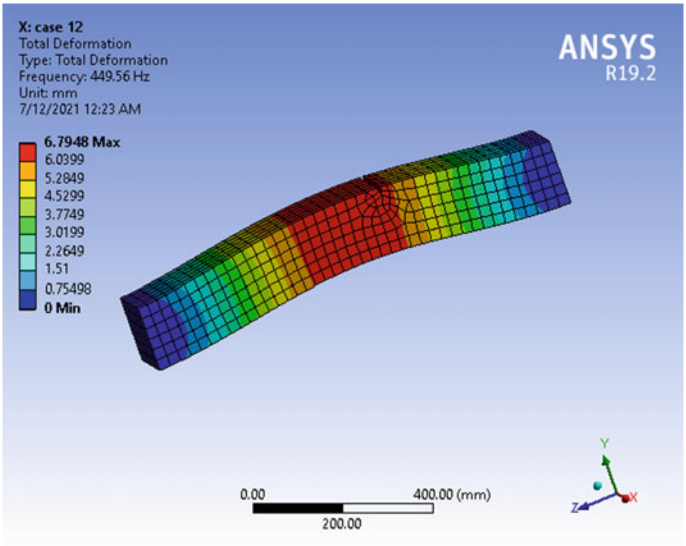

Fig. 3 Mode shape of mode 1 vibration of PCC fixed beam of case 12

location of crack as constant and varying the depth of crack as well as variation of NF keeping the depth of crack as constant and varying the location of cracks were found out. Comparison study was carried out by creating comparison charts in which crack depth or crack location is plotted along x- axis while NF is plotted along y-axis. Figure 4a and b shows the graph depicting variation in NF of RCC cantilever beam for mode 1 vibration with respect to location and depth of crack respectively. Figure 5a and b shows the graph depicting variation in NF of RCC fixed beam with respect to location and depth respectively.

From the study of cantilever beams, it is found that NF decreases as crack depth increases. The variation in NF is more for cracks having higher depths. For a constant depth, the variation reduces as the crack position moves from fixed end to free end of the beam. NF increases as crack position moves to free end at constant depths for mode 1 vibration. From the study of fixed beams, it is also found that NF decreases as crack depth increases. The variation in NF is more for cracks having higher depths. The variation in NF shows a symmetric pattern. The reduction in NF is more at the

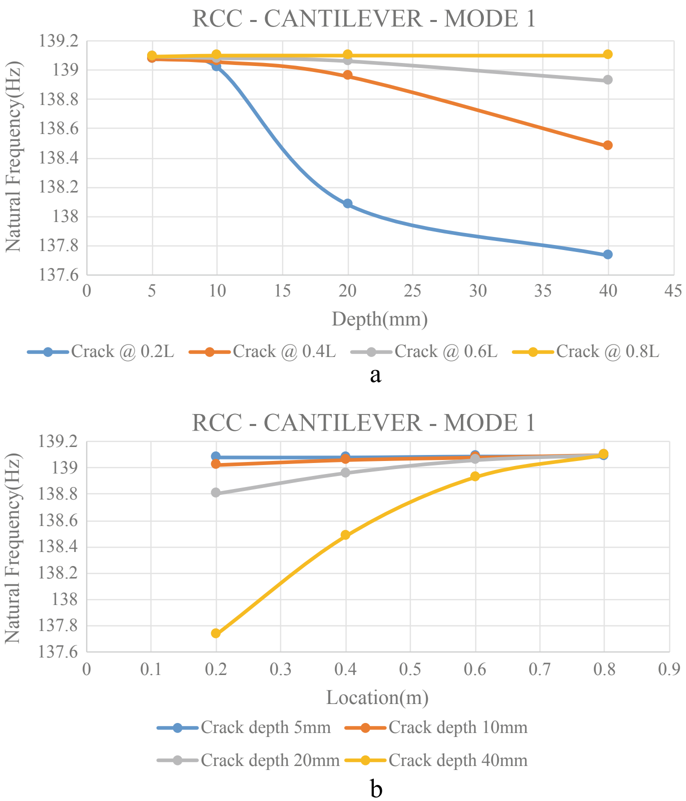

Fig. 4 **a** Variation in NF of RCC Cantilever beam with respect to location **b** Variation in NF of RCC Cantilever beam with respect to depth

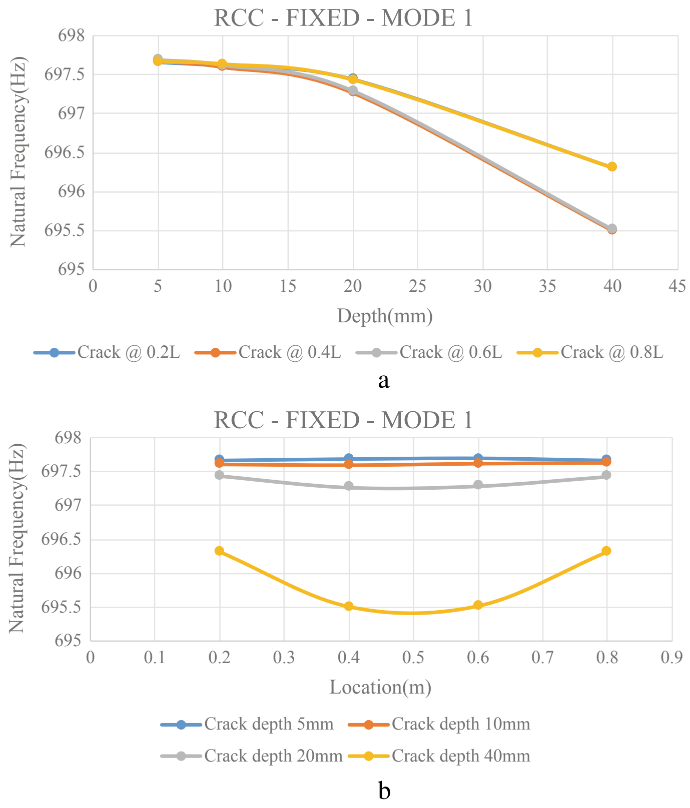

Fig. 5 **a**. Variation in NF of RCC Fixed beam with respect to location. **b.** Variation in NF of RCC Fixed beam with respect to depth

mid span than far ends i.e., NF decreases as crack position moves towards center and then increases. For both cantilever and fixed cases all the three types of beams i.e., RCC, PCC and SC Composite beams showed similar results.

5 Conclusion

The forward approach of crack detection is focused in this study. The study was conducted on different types of concrete beams. Beams with and without cracks were modelled in Ansys Workbench and modal analysis was done to obtain Natural Frequency and Mode Shapes. The Natural Frequencies of different cases were compared to identify the pattern of variation in Natural Frequency in the presence of cracks. From the study the following conclusions are made.

1. In all types of concrete beams considered, for both cantilever and fixed beams, as depth of crack increases, the Natural Frequency decreases.
2. In cantilever beams, the effect of crack is more at cantilever end.
3. In fixed beams, the effect of crack is more at mid spans for mode 1 vibration.
4. There is much greater difference in the values of Natural Frequency between cantilever and fixed beams for each cases.
5. The variations in Natural Frequency is very less for lower depth cracks.

So it is clear that the modal parameters can be used for the purpose of damage identification. By measuring these modal parameters, we can detect and quantify the damages in a structural member with the help of suitable crack detection strategies.

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