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Technical Note

STUDY ON CHANGE IN MODAL PARAMETERS OF RC BEAMS DUE TO FATIGUE TYPE DAMAGE

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ABSTRACT

Vibration monitoring of civil engineering structures has gained a lot of interest over the past few years, due to the relative ease of instrumentation and the development of new powerful system identification techniques. The damage assessment consists of relating the dynamic characteristics to a damage pattern of the structures. This paper presents experimental results obtained within the framework of the development of a health monitoring system for civil engineering structures, based on the changes of dynamic characteristics. As a part of this research, Reinforced concrete beams subjected to cyclic loading to introduce damage. After each loading phase, an experimental modal analysis is performed on the beams with the impact hammer to obtain dynamic characteristics. Beams were excited with the impact hammer over a frequency range of interest 0-4000Hz. Frequency response functions (FRFs) were obtained using OROS Dynamic vibration analyzer. The FRFs were processed using NV Solutions modal analysis software to identify natural frequencies, Damping ratios and the corresponding mode shapes of the beams. A characteristic decrease of natural frequencies and an increase of structural damping were observed.

Keywords: Modal parameters; frequency response function; natural frequency; damping; mode shape; and fatigue load

1. INTRODUCTION

Most of the Civil engineering structures are often subjected to cyclic loads, in which strength of the structures reduced due to fatigue, which is a process of progressive and permanent internal damage in a material subjected to repeated loading. This is attributed to the propagation of internal micro cracking, which results in a significant increase in irrecoverable strain [1].

Regular inspection and condition assessment of engineering structures subjected to cyclic loads are necessary in order to assess its serviceability and reliability. Also early damage

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detection and damage location allows maintenance and repair works to be properly programmed and thereby minimizing costs. In this regard a useful and more thorough, Non destructive evaluation tool is vibration monitoring. I in the past two decades, a significant amount of research has been conducted in the area of nondestructive damage detection through changes in modal properties of structures [2]. The damage or fault detection in structure as determined by changes in dynamic properties of structures or response of the structures is a subject that has received considerable attention in recent years. The basic idea is that the occurrence of damage or loss of structural integrity leads to change in dynamic characteristics of structures such as natural frequency, damping and modeshape. Periodic structural condition monitoring of reinforced concrete structures is necessary to ensure that they provide a continued safe service condition.

Conventional assessment procedures usually rely on visual inspection and location dependent methods. Structural damage is considered as a weakening of the structure that negatively affects its performance. Damage may also be defined as any deviation in the structure's original geometric or material properties that may cause undesirable stresses, displacements, or vibrations on the structure. These weakening and deviations may be due to cracks, loose bolts, broken welds, corrosion, fatigue, and so on.

Due to the special role of the beams in most of the civil engineering structures, dynamic system identification of beams, especially during service time, is of high importance. This paper describes the variation in modal properties of reinforced concrete beams due to damage induced by cyclic loading through modal testing. Modal tests on the beams were conducted to determine the modal parameters, namely natural frequencies, modal damping and mode shapes. Modal parameters are functions of the physical properties of the structure, which are mass, damping, and stiffness; and changes in the physical properties will cause detectable changes in these modal properties. The main objective of the research is to identify the changes occurred in the modal parameters due to damage induced to the beams by cyclic loading.

2. EXPERIMENTAL INVESTIGATION

An experimental program is carried out to establish the relation between damage due to cyclic loads and change of structural dynamic characteristics due to induced damage. In this investigation, four reinforced concrete beams of size 2000mmx120mmx200mm were cast with mix proportion of 1:1.25: 2.8: 0.44(cement: Fine Aggregate: Coarse Aggregate: water cement ratio) which represents M30 grade of concrete according to IS: 10262, of which two were under reinforced beams (URB) and two over reinforced beams (ORB). Under reinforced beams consists of 2-12mm diameter bars as tension reinforcement, where as over reinforced beams consists 2-12mm+2-20mm as tension reinforcement, both category beams consists of 8mm vertical stirrups at the spacing of 70mm c/c as shear reinforcement. The grade of steel reinforcement used was Indian standard Fe: 415.There was no significant top reinforcing, only two 4mm diameter mild steel bars to aid positioning of shear stirrups. The testing of beams consists of static flexure tests, fatigue flexure tests and dynamic tests.

2.1 Static flexure tests

The four point static flexure tests were performed on the two beams (one URB and one ORB) for obtaining its ultimate static flexural strength. The loading was applied on the beams with a distance of 300mm between point loads and support span was 1800mm as shown in Figure 1. During the test both loading and mid span deflection were recorded. The results obtained such as ultimate strength (Pult in Kn) and its corresponding deflection (δ in mm) in static tests are shown in Table 1.

Table 1: Details of fatigue flexural tests

Beam designation	**Frequency of loading**	**Pult Kn**	**δ mm**	**Pmax =70% of Pult**	**δmax mm**	**Pmin= 20% of Pmax**	**Δmin mm**
ORB	1.5	96	11.65	67.2	7.68	13.44	1.49
URB	1.0	65	13.0	45.5	7.99	9.10	1.55

2.2 Fatigue flexure tests

Cyclic loading was applied with100T Servo Controlled Dynamic Testing Machine under four point bending similar to that of static flexure tests. The load ranges applied were expressed as percentages of the static load carrying capacity of the beam. The cyclic loading with sinusoidal waveform was applied with a loading range P_{max}-P_{min}. The maximum load applied on the beams was 70% of the ultimate flexural strength of corresponding beams. The minimum load $P_{min} = 0.2P_{max}$ in fatigue test was applied in order to maintain the contact of the actuator with the beam [3]. The details of fatigue test are shown in table.1. At every ten thousand load cycles, loading is stopped and dynamic testing is followed up. Experimental set up for static and fatigue testing is as shown in Figure 1.

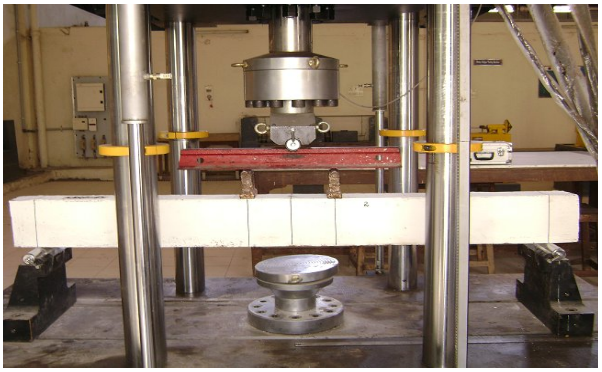


Figure 1. Experimental set up for static and fatigue flexure test

2.3 Dynamic tests

A dynamic measurement is first performed for undamaged state of the test beams. The excitation points were marked on the top surface of the beams both along the length and width [4, 5]. The distance between each point was 200mm and 6mm in the longitudinal and transverse directions of the beam respectively. This test results serves as a reference for later comparison of dynamic characteristics at the different damage stages. After each loading phase, the beam is unloaded, and the dynamic test is performed with impact hammer. In this case, an accelerometer which is used to measure vibration response had a fixed position, whilst an instrumented impact hammer was roved along the excitation points. The schematic experimental setup and screen shot of the dynamic testing is as shown in Figure 2.

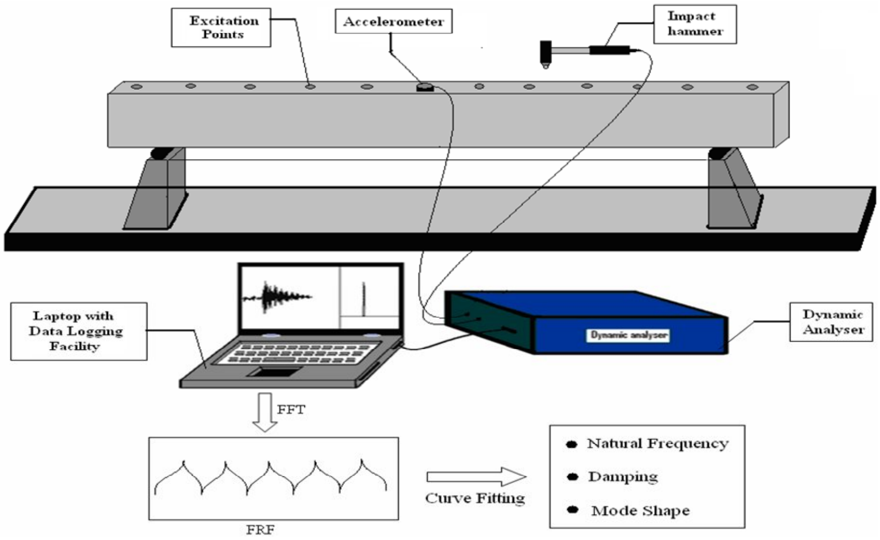


Figure 2. Schematic representation of dynamic test setup

The instruments used in this study were the PCB Impact hammer of weight 320g (model Impulse hammer PCB 086D05) for exciting the beam, an Accelerometer of weight10g (DYTRON model 3055B2) and 8-channel OROS dynamic analyzer for obtaining Frequency response Functions (FRFs) [6], in the process of obtaining FRFs, the analyzer performs the operations like Filtering of signals, Digitization of signals, Windowing, and conversion of signals from time domain to frequency domain. The obtained frequency response functions were then processed to get the Modal Parameters (frequency, damping and animated mode shapes) using NV Solutions Smart Office software package [7].

2.4 Results and discussion

The results obtained from the two beams were compared. The control beams (Un- damaged state) provides the reference readings which form the basis of the comparison of the modal parameters obtained in successive damage states as described below.

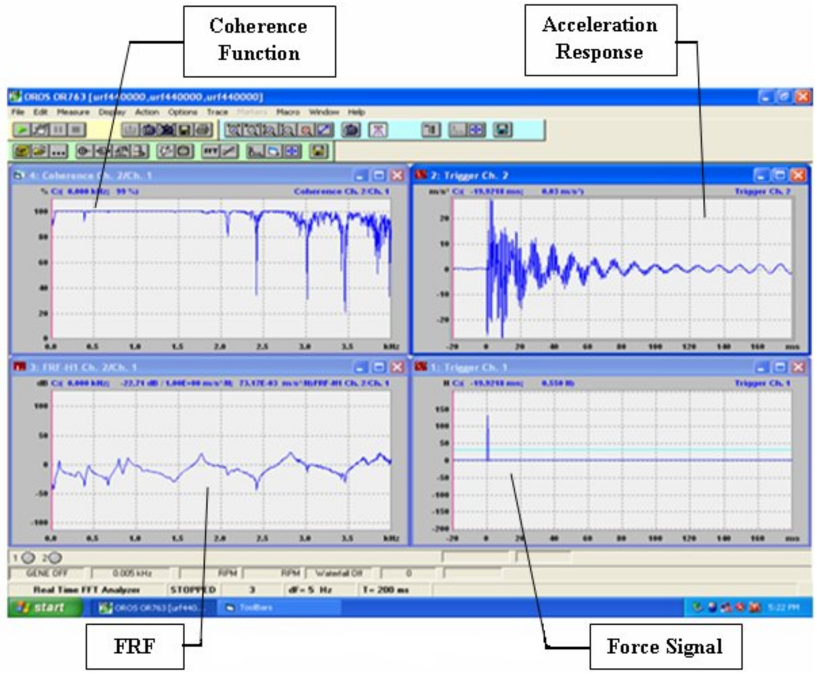


Figure 3. Screen shot of dynamic test

2.5 Frequency response function

A frequency response function is a fundamental measurement that isolates the inherent dynamic characteristics of a test system. Experimental modal parameters (frequency, damping and mode shape) are obtained from a set of FRF measurements. Frequency corresponds to the Peaks in the FRF represents resonant frequency. Some of the frequency response functions of test beams were shown in figures below.

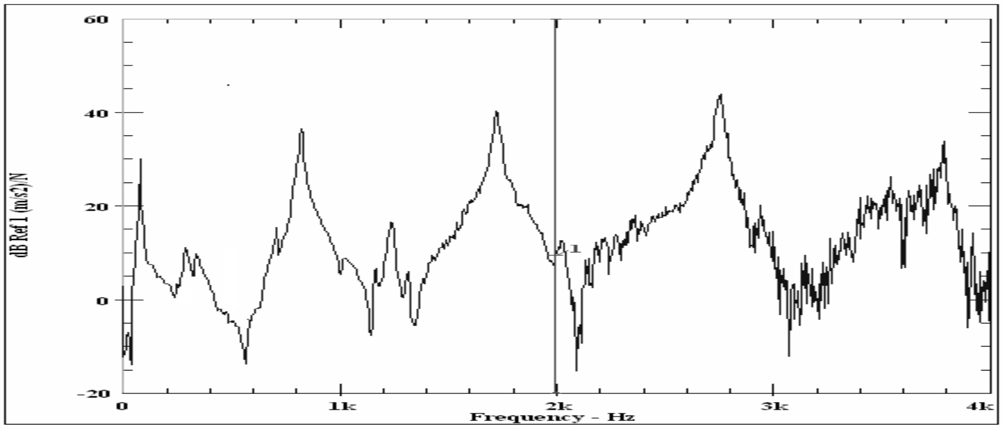


Figure 4. Frequency response function of ORB at undamaged state

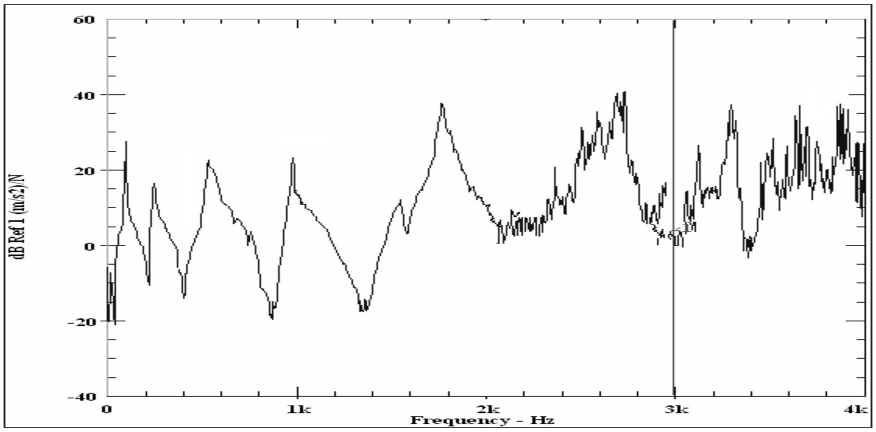


Figure 5. Frequency response function of ORB after 50000 cycles

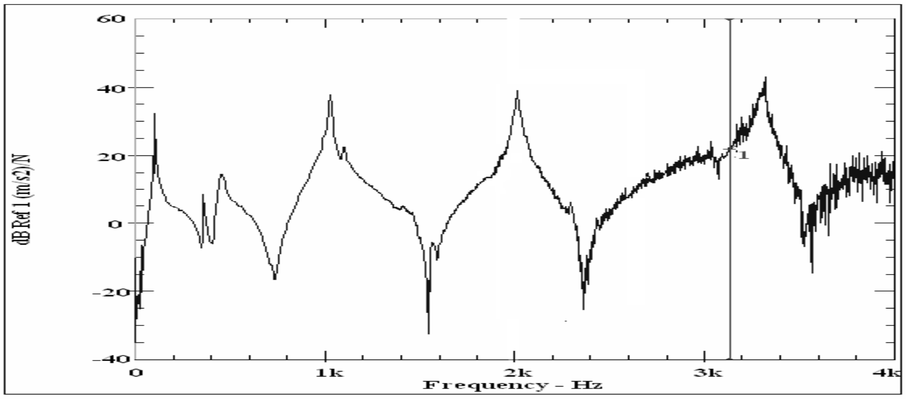


Figure 6. Frequency response function of URB at undamaged state

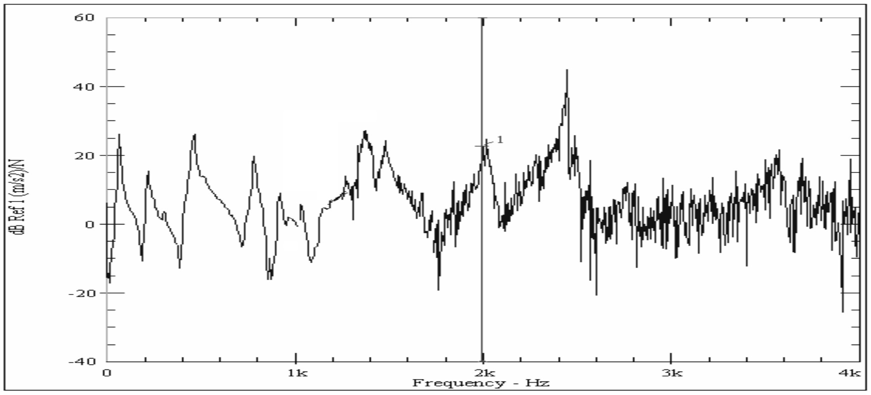


Figure 7. Frequency response function of URB after 80000 cycles

2.6 Natural frequency

When a system is subjected to certain degree of damage or deterioration, it experiences a change in stiffness [8, 9, 10]. Subsequently it causes the natural frequency to change. The magnitude of the changes is also an indicator of the severity or state of the damage experienced. This is apparent in the changes in the natural frequencies of the damaged beams as compared to the control beam. The values of natural frequencies for the test beams are tabulated in Table 2 and in Table 3.

Table 2: Change in natural frequencies of over reinforced beam

Damage level	**Mode number**							
	1		**2**		**3**		**4**	
	Frequency (Hz)	**Decrease (%)**	**Frequency (Hz)**	**Decrease (%)**	**Frequency (Hz)**	**Decrease (%)**	**Frequency (Hz)**	**Decrease (%)**
0	106.70	0.00	451.10	0.00	1029.00	0.00	2039.00	0.00
10000	92.04	13.74	356.60	20.95	920.80	10.52	1971.00	3.33
20000	84.45	20.85	338.32	25.00	900.30	12.51	1902.00	6.72
30000	80.17	24.86	324.79	28.00	889.50	13.56	1893.00	7.16
40000	76.54	28.27	320.77	28.89	820.30	20.28	1806.00	11.43
50000	74.29	30.37	316.74	29.78	800.70	22.19	1512.00	25.85

Table 3: Change in natural frequencies of under reinforced beam

Damage level	**Mode number**							
	1		**2**		**3**		**4**	
	Frequency (Hz)	**Decrease (%)**	**Frequency (Hz)**	**Decrease (%)**	**Frequency (Hz)**	**Decrease (%)**	**Frequency (Hz)**	**Decrease (%)**
0	96.30	0.00	460.00	0.00	987.40	0.00	1953.00	0.00
10000	85.22	11.51	445.00	3.26	975.60	1.20	1854.00	5.07
20000	82.65	14.17	437.73	4.84	966.40	2.13	1790.00	8.35
30000	78.30	18.69	422.92	8.06	930.60	5.75	1752.00	10.29
40000	75.50	21.60	420.11	8.67	902.40	8.61	1670.00	14.49
50000	73.74	23.43	413.63	10.08	891.30	9.73	1605.00	17.82
60000	72.00	25.23	396.93	13.71	825.50	16.40	1532.00	21.56
70000	68.39	28.98	382.07	16.94	782.30	20.77	1502.00	23.09
80000	67.60	29.80	358.40	22.09	776.20	21.39	1460.00	25.24

There is a higher decrement in natural frequency for the over reinforced beam compared to under reinforced beam. Maximum decrease in natural frequency 59.96% and 36.41% was observed respectively in ORB and URB in the first mode from undamaged state to final damaged state, similar trend was observed by the authors [10, 11]. As the effect of damage was more severe in beam ORB as compared to beam URB, it might be concluded that ORB experienced a greater loss in bending stiffness and hence bigger drop in natural frequencies.

2.7 Modal damping

Modal damping of concrete members is of interest in several, it is associated with the dynamic response of concrete structures because it limits the response of the structures at resonance and affects the rate at which vibrations decay and its use has been propped as a means to assess material integrity or damage occurred. The values of modal damping ratio for the test beams are tabulated in Table 4 and in Table 5. These ratios which represent the damping characteristic of the beams are associated with the energy dissipation or energy loss within the system. It has been observed that the damping ratios obtained increased as the level of damage increases, similar trend was observed by the author [5, 10]. In general the trend for the damping ratios obtained should increase as the level of damage increases. It was observed that damping was increased from 1.41% to 5.19% in the first mode of over reinforced beam where as damping was increased from 1.5% to 4.61% in the same mode of under reinforced beam. It can also be observed that the values of damping ratio decrease with higher modes indicating that lower modes have the tendency to decay much earlier.

Table 4: Variation in damping of over reinforced beam

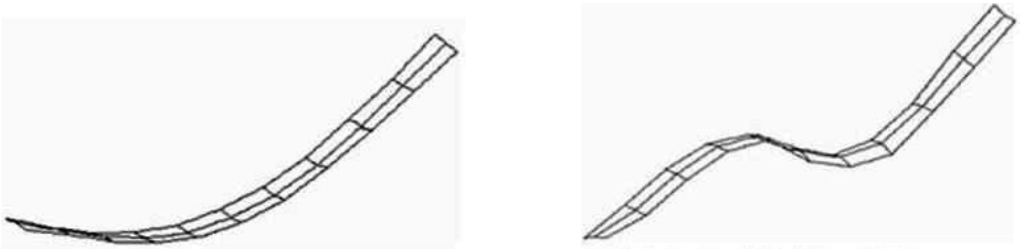
Damage level	**Mode number**							
	1		**2**		**3**		**4**	
	Damping	**Increase (%)**	**Damping**	**Increase (%)**	**Damping**	**Increase (%)**	**Damping**	**Increase (%)**
0	1.41	0.00	1.20	0.00	0.62	0.00	0.39	0.00
10000	2.65	87.94	1.66	38.00	0.93	50.00	0.49	25.64
20000	2.90	105.67	1.94	62.00	1.05	69.35	0.81	107.69
30200	3.46	145.39	2.02	68.33	1.40	125.81	0.92	135.90
40000	4.12	192.20	2.34	95.00	1.67	169.35	1.01	160.00
50000	4.63	228.37	2.86	138.67	1.90	206.45	1.13	189.74

2.8 Mode shapes

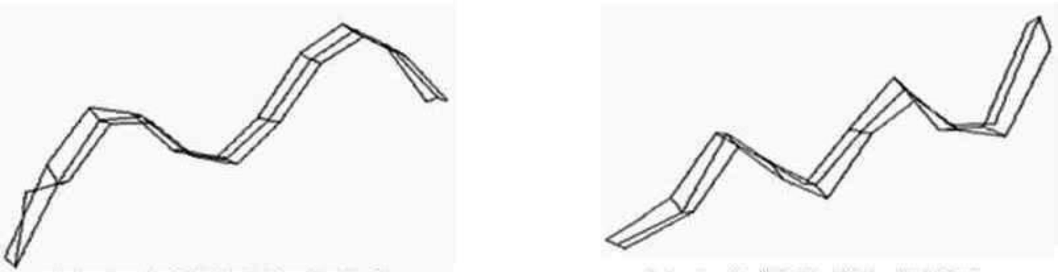
A mode shape is a specific pattern of vibration executed by a mechanical system at a specific frequency. Different modes will be associated with different frequencies. The mode shapes of test beams are shown below.

Table 5: Variation in damping of under reinforced beam

Damage level	Mode number							
	1		2		3		4	
	Damping	Increase (%)	Damping	Increase (%)	Damping	Increase (%)	Damping	Increase (%)
0	1.50	0.00	1.35	0.00	0.70	0.00	0.52	0.00
10000	1.89	26.00	1.62	20.00	0.95	35.71	0.57	9.62
20000	2.69	79.33	1.78	31.85	1.38	97.14	0.66	26.92
30000	2.99	99.33	1.89	40.00	1.52	117.14	0.69	33.46
40000	3.24	116.00	1.93	42.96	1.72	145.71	0.79	51.92
50000	3.59	139.33	2.16	60.00	1.97	181.43	0.85	63.46
60000	3.81	154.00	2.34	73.33	2.04	191.43	1.10	111.54
70000	4.25	183.33	2.62	94.07	2.12	202.86	1.16	123.08
80000	4.61	207.33	2.99	121.48	2.14	205.71	1.46	180.77



Mode.1 106.7 Hz 1.41%   Mode.2 451.1Hz 1.2%



Mode.3 1029.0Hz 0.62%   Mode.4 2039.0Hz 0.39%

Figure 8. Mode shapes of over reinforced beam at un-damaged state

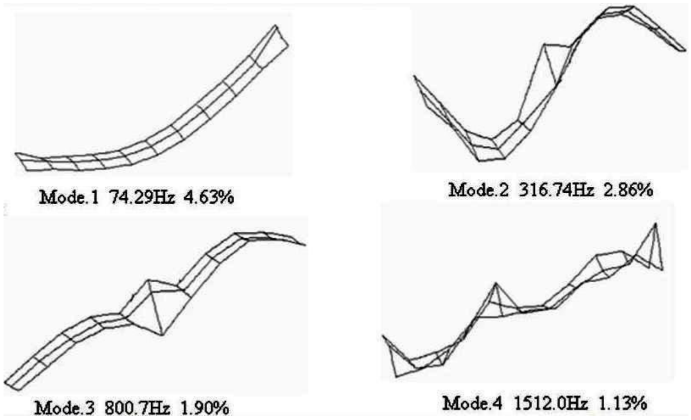


Figure 9. Mode shapes of over reinforced beam after 50000 cycles

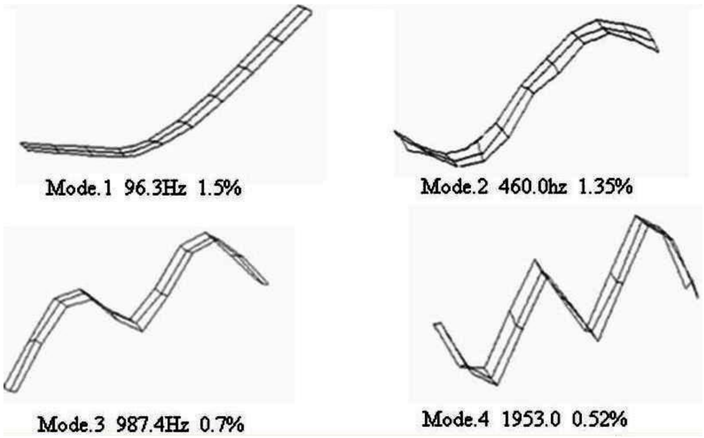


Figure 10. Mode shapes of under reinforced beam at un-damaged state

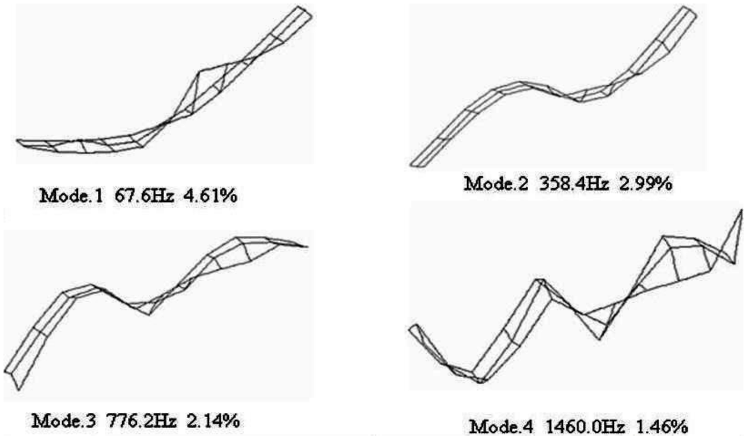


Figure 11. Mode shapes of under reinforced beam after 80000 cycles

3. CONCLUSIONS

Based on the experimental investigations, the following conclusions have been drawn.

- As damage level on the beams increased, Natural frequency decreased.
- As damage level on the beams increased, Damping values increased
- In the successive damage states percentage drop in Natural frequency is more in over reinforced beam than under reinforced beam.
- The maximum decrease in natural frequency 30.37% was observed in the first mode of over reinforced beam from un-damaged state to final damaged state. Where as in case of under reinforced beam maximum decrease in natural frequency was 29.80% in the fist mode.
- Maximum increase in damping 228.37% was observed in the first mode of over einforced beam from un-damaged state to final damaged state and 207.33% incase of under reinforced beam in the same mode.

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