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Studies on Nonlinear Vibrational Characteristics of Reinforced Concrete Beams

Preethy Dharanya. Y¹, Dr. Srinivas. V², Dr. Anand. N³

P.G. Student, School of Civil Engineering, Karunya University, Karunya Nagar, Coimbatore, India¹

Principal Scientist, Bridge Engineering Group, CSIR-SERC, Taramani, Chennai, India²

Assistant Professor, School of Civil Engineering, Karunya University, Karunya Nagar, Coimbatore, India³

ABSTRACT: Assessing the condition of a structure and evaluating the performance periodically under in-service conditions will help to maintain/monitor the structure. The main aim of the present work is to assess the feasibility of using linear and non-linear features in the vibration characteristics under simulated damage conditions of reinforced concrete beams with simply supported and free-free support condition. Numerical simulations are carried out under static and dynamic loading conditions of the of the reinforced concrete beam with different damage levels. Damage in the beam is induced in the form of cracks of varying magnitudes. Simultaneously, experimental investigations are carried out on the RC beams under static and dynamic loads. Linear and non-linear features from the vibration characteristics are evaluated from the measured data based on the signal processing methods. The data obtained from experimental and numerical simulation is compared and found to be well correlated.

KEYWORDS: RC beams, Finite element analysis, Vibration testing, Signal analysis, damage detection.

I. INTRODUCTION

Detecting damage in a structure at an early stage of its development had of great interest for researchers in recent years. Current damage detection methods are either visual or localised experimental methods, e.g. acoustic or ultrasonic methods. These methods require that the damage location to be known. The need for a more global damage detection method has led to the development of methods that investigate changes in the vibration properties of the structure.

Vibration techniques are used to detect damage in a structure for many years based on assuming that modal properties do not vary with amplitude of oscillation (Linear Vibration). Most amount of work on developing methods of detecting damage assuming linear vibration, there has been very little research on the feasibility of using the vibration nonlinearities to assess the condition of structures. Most of the research on nonlinear vibration damage detection has centred on fatigue cracks in metals. One of the major problems with this work is that a baseline undamaged set of modal parameters is required to assess any changes in the parameters due to damage. The best thing that can be done for an existing structure is to compare future results with a present day baseline but for this to be meaningful the present day damage must be accurately known.

Damage modifies the vibration characteristics such as natural frequencies, mode shape and modal damping ratios of undamaged structure [4]. The characteristics of undamaged structure are often used as base line data in damage detection. In comparison with the base line data, any deviation of structural parameters measured during the service life reflects possible damage and used to locate the damage and identify the severity of damage. Natural frequencies are widely used as indicator of damage in a structure, since it can be simply identified from modal tests with sufficient accuracy[9]. Stiffness degradation and reduction in natural frequencies takes palace when damage occurs in structure.

Damaged structure often vibrates in a nonlinear fashion under dynamic loads [5]. In general, a cracked reinforced concrete member reveals the nonlinear behaviour due to opening and closing of the cracks. Therefore, using nonlinear features of vibration to detect damage has received increasing attention in research. Nonlinear features are more sensitive to many common damages than linear features like natural frequencies. For linear vibration, the



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frequency response function is proportional to the magnitude of dynamic loads and its relation with the excitation frequency is unique. For nonlinear vibration, the function typically depends upon the loading history and its time relation with the excitation frequency could be non –unique.

The concept of vibration induced damage in structures was introduced by Rizos et al., [1]. The method was inspired by the crack locations in the simply supported beam under vibration controls [2]. The concept was enlarged by the detection of location and size of a crack in stepped cantilever beams based on measurements of natural frequencies [3]. The nonlinear features in the concrete beam used to find the damages in the concrete beam and carried out feasibility study on damage detection of RC structures using dynamic signature tests, as well as destructive and non-destructive testing of Bridge [6]. A full research paper on finite element analysis of the beam strengthened with prefabricated reinforced concrete plate[11]. The non-linear behaviour of reinforced concrete beams under low-amplitude cyclic and vibration loads[8]. Crack identification and forced response of RC beam was carried out in Ansys and experimental using forced response in the beam [12,13]. Low-frequency vibration modulation of guided waves to image nonlinear scatterers for structural health monitoring [10].The research was undergone on the experimental investigations on effect of damage of vibration characteristics of the reinforced concrete beam [14].

The present work described in this paper is divided into 3 stages. 1) Finite element modelling, 2) Numerical investigations, 3) Experimental investigations. Finite element modelling contains the element types which are used to model the reinforced concrete beam in ANSYS and the corresponding material properties of those particular elements. Linear and nonlinear vibration characteristics of the reinforced concrete beams obtained using the Ansys software is explained in section 2. The experimental investigation was conducted on the corresponding reinforced concrete beam and the results obtained are described in section 3.

1.FINITE ELEMENT MODELLING

Finite element method (FEM) is a numerical technique for finding approximate solutions to boundary value problems for partial differential equations. It uses subdivision of a whole problem domain into simpler parts, called finite elements, and variational methods from the calculus of variations to solve the problem by minimizing an associated error function. One of the advanced method used to finding the solution in FEM is ANSYS software. Here, the reinforced concrete beam was modelled in ANSYS software. Rhe elements which s used in the ANSYS described below.

1.1 Reinforced concrete beam:

An eight node solid element (SOLID 65) was used to model the concrete. The solid is capable of cracking in tension and crushing in compression. The solid element has eight nodes with three degrees of freedom at each node translations in the nodal x, y, and z directions. The element is capable of plastic deformation, cracking in three orthogonal directions, and crushing. The geometry and node locations for this element type are shown in Fig 1.1 solid 45 element was used to model the steel plates and supports.

1.2 Steel Reinforcement:

A Link 8 element was used to model the steel reinforcement. Two nodes are required for this element. The element is defined by eight nodes and each node has three degrees of freedom, translations in the nodal x, y, and z directions. The element is also capable of plastic deformation. The geometry and node locations for this element type are shown in Fig 1.2

1.3 Spring Element:

COMBIN14 has longitudinal or torsional capability in 1-D, 2-D, or 3-D applications. The longitudinal springdamper option is a uniaxial tension-compression element with up to three degrees of freedom at each node, translations in the nodal x, y, and z directions. No bending or torsion is considered. The torsional spring-damper option is a purely rotational element with three degrees of freedom at each node: rotations about the nodal x, y, and z axis. No bending or axial loads are considered. The spring-damper element has no mass. Masses can be added by using the appropriate mass element. The spring or the damping capability may be removed from the element.



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1.3 FE model input data:

For concrete, ANSYS requires input data for material properties as follows; elastic modulus E_b , ultimate uniaxial tensile strength f_c , poisson ratio v, shear transfer coefficient β , and compressive uniaxial stress strain relationship for concrete. The shear transfer coefficient β_t ranges from 0 to 1.0, with 0 representing smooth crack (complete loss of shear transfer and 1.0 representing rough crack and no loss of shear transfer. The values of β used in many studies of reinforced concrete structures, however varied between 0.2 to 0.5. A number of preliminary analyses were attempted in this study with various values for the shear transfer coefficient within this range, but convergence problems were encountered at low loads with β less than 0.2. therefore, the shear transfer coefficient used in this study was equal to 0.3

Sl no	Element in ANSYS	Usage
1.	Solid 65	For Concrete
2.	Solid 45	For Steel plates and Supports
3.	Link 8	For Reinforcement
4.	Combin14	Spring element for free free condition



Table 1.1 - Elements used in ANSYS

Fig 1- Cross section of beam and reinforcement details

The beams were modelled as volumes. The beam is 1800 mm long, with a cross-section of 150mm x 200mm. The reinforcement at the bottom beams is 2-12 mm diameter, top reinforcements are 2-8mm diameter and 8 mm diameter stirrups @ 275 mm c/c. To obtain good results from the Solid65 element, the use of a rectangular mesh is recommended. Therefore, the mesh was set up such that square or rectangular elements are formed. This properly sets the width and length of elements in the plates to be consistent with the elements and nodes in the concrete portions of the model. The necessary element divisions are noted. The meshing of the reinforcement is a special case compared to the volumes. No mesh of the reinforcement is needed because individual elements were created in the modelling through the nodes created by the mesh of the concrete volume. However, the necessary mesh attributes as described above need to be set before each section of the reinforcement is created. The command merge items merge separate entities that have the same location. These items will then be merged into single entities. Caution must be taken when



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merging entities in a model that has already been meshed because the order in which merging occurs is significant. Displacement boundary conditions are needed to constrain the model to get a unique solution. The symmetry boundary conditions were set first. To model the symmetry, nodes on this plane must be constrained in the perpendicular direction. These nodes, therefore, have a degree of freedom constraint UX = 0. Second, all nodes selected at Z = 0 define another plane of symmetry. These nodes were given the constraint UZ = 0. The support was modelled in such a way that a roller was created. A single line of nodes on the plate were given constraint in the UY, and UZ directions, applied as constant values of 0. By doing this, the beam will be allowed to rotate at the support.

The force, P, at the steel plate is applied across the entire centreline of the plate. The force applied at each node on the plate is one tenth of the actual force applied.



II. NUMERICAL INVESTIGATIONS

NONLINEAR STATIC ANALYSIS FOR ULTIMATE LOAD BEHAVIOUR

Linear procedures are applicable when the structure is expected to remain nearly elastic for the level of ground motion or when the design results in nearly uniform distribution of nonlinear response throughout the structure. As the performance objective of the structure implies greater inelastic demands, the uncertainty with linear procedures increases to a point that requires a high level of conservatism in demand assumptions and acceptability criteria to avoid unintended performance. Therefore, procedures incorporating inelastic analysis can reduce the uncertainty and conservatism.

2.1 LOADING AND BOUNDARY CONDITIONS:

The reinforced concrete beam modelled in ANSYS and subjected to point loading. Displacement boundary conditions are needed to constrain the model to get a unique solution. Boundary conditions of simply supported beam



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were given in one side roller and another one is hinged. Nodes' defining a vertical plane through the beam cross-section centroid defines a plane of symmetry. To model the symmetry, nodes on this plane must be constrained in the perpendicular direction. These nodes, therefore, have a degree of freedom constraint UX = 0. Second, all nodes selected at Z = 0 define another plane of symmetry. These nodes were given the constraint UZ = 0. The support was modelled in such a way that a roller was created. A single line of nodes on the plate were given constraint in the UY, and UZ directions, applied.

2.2 ANALYSIS TYPE AND RESULTS:

In numerical, the analysis is done by 2 conditions. One is simply supported and other is free free condition. Initially the force, P, applied at the steel plate is applied across the centreline of the plate. The force applied at each node on the plate is one tenth of the actual force applied. Load was applied in the reinforced concrete beam under simply supported condition and the corresponding displacement and crack behaviour was found. Fig 2(a), 2 (b), 2(c) shows the corresponding numerical results from the ANSYS software. And corresponding load vs deflection curve also plotted. (graph 2.1).



Graph 2.1 - Load vs Deflection

Graph 2.2- Crack Initiation

MODESHAPES FREQUENCIES FROM NUMERICAL:

Mode shapes	Simply Supported condition	Free Free condition	
1	43.698	69.424	
2	183.827	168.929	
3	310.112	305.467	

Table 2.1 - Elements used in ANSYS



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2.3 TRANSIENT DYNAMIC ANALYSIS FOR DIFFERENT DAMAGE CONDITIONS:

In non-linear dynamic analysis, the non-linear properties of the structure are considered as part of a time domain analysis. This approach is the most rigorous, and is required by some building codes for buildings of unusual configuration or of special importance.

Transient dynamic analysis is a technique used to determine the dynamic response of the structure under the action of any general time -dependent loads. This type of analysis can be used to determine the time-varying displacements, strain, stresses and forces in a structure as it responds to any combination of static, transient and harmonic loads. This paper discussed about this technique for the support conditions discussed below.

- 1. Simply Supported Condition
- Free- Free Condition 2.

SIMPLY SUPPORTED CONDITION:

The beam was supported on the ends which are free to rotate and have no moment resistance. Simply supported beam was modelled in ANSYS (fig 2.3.1) and the dynamic response of that beam used to find out with the time depending loads. Here, the impact load (graph-1.3) was applied in the reinforced concrete beam and the corresponding acceleration response (graph -1.4) was taken from the ANSYS. And corresponding mode shapes also obtained from the ANSYS are shown in the figure 2(a),2(b),2(c).



Fig 2.3.1 - S.S beam modelled in ANSYS



Graph 2.4-Time vs Acceleration

FREE FREE CONDITION:

10000

9000 8000

7000 6000

5000 4000

3000

2000

1000 0

ø -1000

0.002

0.004

Graph 2.3- Impact loading

0.006

0.008

0.01

A simple beam with both ends extends beyond its supports on both the ends. In Free free condition was simulated by using combin 14 element in ANSYS (Fig -1.4). in experimental, threaded rope was used to locate the



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beam in free free condition. For that rope the corresponding initial length or the stiffness value was given in ANSYS. Combin 14 was acted like a threaded rope in Ansys. With Corresponds the rope stiffness value, mode shpes of the free free beam are obtained.

2.4 NONLINEAR VIBRATION CHARACTERISTICS:

In the non linear analysis the total load is applied to a finite element model is divided series of load increments called load steps. At the completion of each incremental solution, the stiffness matrix of the model is adjusted to select nonlinear changes in structural stiffness matrix before proceeding to the next load increment using newton raphson equilibrium iterations for updating model stiffness. A nonlinear newton raphson approach was utilised to trace the equilibrium during the load deformation response.

SIMPLY SUPPORTED CONDITION:





Fig - 2.4.1(a.b.c) - Shows the 1st ,2nd & 3rd modes shapes respectively.



FREE FREE CONDITION:

Fig = 2.4.2(a,b,c) - Shows the 1st, 2nd & 3rd modes shapes respectively.

III. EXPERIMENTAL INVESTIGATIONS

The reinforced concrete beam 1.8m x 0.2m x 0.15m was experimentally investigated under two certain conditions. 1) simply supported condition, 2) free-free condition. Acceleration, strain, and deflection were obtained from the reinforced concrete beam. Acceleration measured using accelerometers placed at 7 equal intervals on the beam. Accelerometers were connected through spider 8 to the laptop and acquisition was done by Engineering Data Management System software. From that modal parameters such as Frequency Response function, Auto power spectra, and Frequency Fourier transform data's were obtained. Three LVDT's were placed at the bottom of the beam at 3 equal intervals to measure the deflection of the beam and 60mm strain gauge were used to measure the compressive strain



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which is also placed at 3 equal intervals on the bottom of reinforced concrete beam. All strain gauge and LVDT channels were connected in the MGC plus and data acquisition was done by using a laptop with Catman professional software. For every loading condition deflection, strain values and modal parameters obtained from the experimental investigation.

SIMPLY SUPPORTED CONDITION:

For simply supported condition, support conditions were arranged one side hinged and other side is roller support. Fig 4(b) shows the experimental setup of the simply supported condition. The load applied through the hydraulic jack through the centre line of the steel plate placed in the beam. Strain gauges, accelerometers, LVDT's were fixed in the beam to measure corresponding, strain, deflection and Frequencies in the beam.

FREE FREE CONDITION:

The beam was supported by the threaded ropes in free free condition. Every stage of loading the beam shifted to the threaded ropes and corresponding vibration data's were taken using the hammer. Accelerometers used to find the corresponding modal frequencies in the beam.



Fig 3.1(b)- Simply supported beam with loading



Fig 3.1a)- Free-Free Beam

MODE SHAPES FREQUENCIES UNDER DIFFERENT DAMAGE SCENARIOS: SIMPLY SUPPORTED CONDITION:

Modes	Different loading conditions				
	UNDAMAGED	60 KN	65 KN	70 KN	ULTIMATE LOAD
1	40.6	40.6	39.4	36.2	33.7
2	159	152	122	104	78.7
3	389	382	339	312	279

Table 3.1 – mode shapes of different levels of damage (s.s)

FREE-FREE CONDITION:

Modes	Different loading conditions				
	UNDAMAGED	60 KN	65 KN	70 KN	ULTIMATE LOAD
1	256	233	229	215	131
2	664	613	593	546	416
3	1200	1110	1100	1070	829

Table 3.2 – mode shapes of different levels of damage (free free)



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Fig3.1- Shift in modal frquencies(Simply supported condition) Fig 3.2- Shift in modal frequencies (Free Free condition)

From the above graphs it is observed that there is a decrease in frequency for the first three modes from undamaged to cracking and failure conditions of the beam. It was also observed that there is clear shift in natural frequencies with the increase in damage level and also the experimental values are in close agreement with those obtained numerically.



Graph 3.3 –Load	Vs Experimental
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	NUMERICAL		EXPERIMENTAL	
	Load(KN) Deflection(mm)		Load(KN)	Deflection(mm)
1 st crack	15.5	0.527	20	1.05
Ultimate load	63.4	3.95	75	5.65

Table 3.3 - Comparison of numerical and experimental results

IV. CONCLUSION

Most of the structures need assessment, maintenance and monitoring to insure their integrity. Recent development in signal processing made it possible to perform on damage assessment which has several advantages over current expensive and time-consuming inspections. A literature review has revealed much work has been conducted on the use of vibration tests to detect damage and non-linear vibration properties of concrete beams. An investigation into the possibility of using non-linear vibration characteristics to detect damage in reinforced concrete beams under simply supported and free free conditions were focused. Initially, modelling of reinforced concrete beam was carried out using Ansys12.1 software and simulations results were obtained for linear, nonlinear, modal analysis and transient dynamic analysis.



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Forced vibration testing of reinforced concrete beam has been carried out using small hammer and random loadings to identify the changes in the vibration characteristics under different damage conditions. Along with the dynamic characteristics, the static response of the beam during application of the loading is also obtained to evaluate the damage state. Dynamic characteristics (frequencies and mode shapes) have been evaluated from the FRF matrices based on the responses measured through accelerometers. It was observed that the damage causes the changes in flexural rigidity of the beam which is clearly observed by the shift in natural frequency at different levels of damage (Graph -). From the vibration testing, it is observed that there is a decrease in frequency of 10–15% for the first three modes from undamaged to cracking and failure conditions of the beam. It was observed that there is clear shift in natural frequencies with the increase in damage level and also the experimental values are in close agreement with those obtained numerically.

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