Experimental and Numerical Studies on Free Vibration Characteristics of a Three-Storied Building Frame

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***Abstract*— Experimental studies were carried out on a three storied building frame model consisting of columns and slabs. The base of the building frame was subjected to harmonic motion using horizontal shake table. The natural frequencies and mode shapes were obtained. The same building frame was analyzed using ANSYS Version 11 and ETABS 2013 Ultimate 13.2.2 for both natural frequencies and mode shapes. The natural frequencies and mode shapes were also computed from eigenvalue analysis by modeling the building frame as a 3 degree of freedom undamped lumped mass system. The analytical, experimental and FEM values of natural frequencies obtained were compared. It is observed that ANSYS Version 11 predicts the experimental values of natural frequencies more closely than ETABS 2013 Ultimate 13.2.2. The analytical values of natural frequencies are observed to be lower when compared to the experimental values. The analytical, experimental and FEM values of natural frequencies are found to be in reasonable agreement with another.**

Keywords — Natural frequency, mode shape, finite element, horizontal shake table

1. INTRODUCTION

Recently it has become mandatory to design all the civil engineering structures including building frames for the earthquake effects in addition to dead load, live load and wind load effects [1, 2, 3]. The determination of natural frequencies and mode shapes is of vital importance in the dynamic analysis of structures. A few of the dynamic studies made by earlier research workers are briefly mentioned here. C.S Sanghvi et al [4] conducted an experiment on regular steel frame and irregular frame model with soft storey using horizontal shake table and compared the results with the numerical method using SAP software. The natural frequency and time period obtained from both the methods were found to be very close. A damping of 0.9% was obtained and relative acceleration of first mode in regular model was 3.5 times the acceleration in the irregular model. Cinitha A et al [5] studied the fundamental natural period and natural frequency for the steel frames of various bay lengths and heights by numerical methods. An equation for the time period was derived by regression method. These results were compared with the results of IS code 1893-2002. The fundamental natural frequency was found to decrease as the height of the frame increases. The fundamental frequency was found to increase with an increase in the plan area.

Not many experimental studies have been made on the free vibration characteristics of structures such as natural frequencies and mode shapes. In the present work a shake table test is performed on a three-storied building frame and the natural frequencies and mode shapes are determined. These experimental results are compared with the FEM solutions provided by ANSYS Version 11 and ETABS 2013 Ultimate 13.2.2.

2. EXPERIMENTAL METHOD

The horizontal shake table test is performed on the three-storied building frame. This experiment enables one to understand the occurrence of resonance phenomenon in simple multi-degree of freedom (MDOF) systems. The selected building frame is rectangular in plan with stiffness and mass properties distributed uniformly in plan as well as in elevation. The frame is designed to facilitate the visualization of the first three mode shapes with bare eyes. Also, the frame is so configured that the three degrees of freedom model would serve as a reasonable model, at least to a first approximation.

2.1 Experimental Model

The instruments used for conducting the experiment include MILDAQ Data Acquisition System, Accelerometers and Horizontal Shake Table. The test building model is a regular three-storied rectangular model made up of aluminium. The section of the column is rectangular. Its width is 3mm and depth is 25.11mm. There are four columns. The length of the slab is 300mm and the width of the slab is 150mm. The thickness of the slab is 12.7mm.

The slabs are attached to the columns at an interval of 400mm. The height of the each storey is 400mm. The modulus of elasticity and Poisson ratio of aluminium are 69 x 10^9 MPa and 0.34 respectively. The material of the model is a linear elastic isotropic material with a density of 2700 kg/m^3.

2.2 Experimental Setup and Procedure

Fig. 1 Experimental Setup

The experimental setup is shown in Fig.1. The entire building assembly is placed on the shake table driven by an electric motor and the base of the model is constrained in all the directions except in one horizontal direction. The base motion in horizontal direction is applied by a cam-follower arrangement on the shake table. The RPM of the motor can be varied to achieve harmonic base motions at different frequencies and of constant amplitude. The accelerometers are connected to each storey to get the horizontal displacement value at each natural frequency.

The procedure is as follows:

- Measure the data pertaining to geometric and material properties of the vibrating system.
- Fit the three-storied building model over the shake table.
- Adjust the amplitude of base to 1 mm of the shake table and frequency to 0 Hz and connect four accelerometers at base as well as at all the floor levels in such a way that displacement along x-direction can be picked up. Then connect the USB cable from MILDAQ System to Computer/Laptop.
- For a given motor RPM (Frequency), allow the frame to oscillate for a few seconds so that the frame reaches its steady state. At this stage note down from the software accompanying the equipment the corresponding displacement values for each floor. Identify the frequencies at which the structure undergoes resonance by observing the variation of response amplitudes. At resonance of the model, note down the natural frequency and corresponding displacement values.
- Repeat the experiment at least three times and take the average values.

2.3 Experimental Results

The three natural frequencies obtained experimentally are: $f_1 = 3.0$ Hz, $f_2 = 8.30$ Hz, $f_3 = 12.15$ Hz. The details of the three modes are given in Table 1.

Table 1: Mode Shapes (Experimental)

	First Mode	Second Mode	Third Mode
First Floor	1	1	1
Second Floor	1.742	0.425	-1.251
Third Floor	2.163	-0.852	0.641

3. ANALYTICAL METHOD

The aforesaid problem is treated as an eigenvalue problem and the analytical values of natural frequencies and mode shapes are computed using the model described below.

3.1 Analytical Model

The building system is idealized as undamped spring mass system shown in Fig.2.

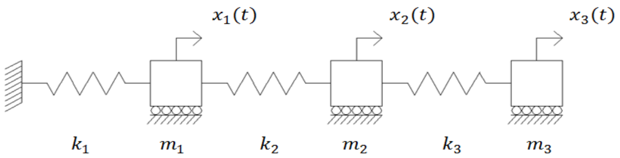

Fig.2: Undamped spring mass system

The equations of motion of the system shown in Fig.2 are given by

$$\begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix} \begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \\ \ddot{x}_3 \end{bmatrix} + \begin{bmatrix} k_1 + k_2 & -k_2 & 0 \\ -k_2 & k_2 + k_3 & -k_3 \\ 0 & -k_3 & k_3 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = 0$$

$$\text{that is, } [m][\ddot{x}] + [k][x] = 0$$

where m_1 = mass of the storey 1, m_2 = mass of the storey 2, m_3 = mass of the storey 3, k_1 = stiffness of the storey 1, k_2 = stiffness of the storey 2, k_3 = stiffness of the storey 3, x_1= displacement of the storey 1, x_2= displacement of the storey 2, x_3= displacement of the storey 3.

The natural frequencies are found out from the characteristic equation

$$|[k] - [m]\omega_n^2| = 0$$

where ω_n= natural frequency in rad/s.

The eigenvalues are found out from the equation

$$[[k] - [m]\omega_n^2][x] = 0$$

The square roots of the eigenvalues are ω_i, the structure's natural circular frequencies (rad/s). The natural frequencies f_i are then calculated as

$$f_i = \frac{\omega_i}{2\pi} \quad \text{(Hz)}.$$

where f_i = i^{th} natural frequency in Hz.

3.2 Analytical Results

The three natural frequencies obtained analytically are: f_1 = 2.87 Hz, f_2 = 7.98 Hz, f_3 = 11.39 Hz. The details of the three modes are given in Table 2.

Table 2: Mode Shapes (Analytical)

	First Mode	Second Mode	Third Mode
First Floor	1	1	1
Second Floor	1.792	0.392	-1.284
Third Floor	2.21	-0.848	0.647

4. NUMERICAL METHOD USING ANSYS VERSION 11

4.1 Methodology

ANSYS is a widely used software designed to analyze many engineering problems with the help of advanced computer facilities. Modal analysis is a technique used to determine a structure's vibration characteristics like natural frequencies, mode shapes and mode participation factors. It is the most fundamental of all the dynamic analysis types. Mode extraction is the term used to describe the calculation of eigenvalues and eigenvectors. Several mode extraction methods are available in ANSYS: Block Lanczos, Subspace, Power Dynamics, Reduced, Unsymmetric, Damped (full) and QR Damped. The method chosen for the analysis depends upon the model size and the particular application. In this study the Block Lanczos method has been used. Linear solver used in this method is sparse matrix. This method is used because of its efficient extraction of large number of modes in a frequency range even in complex models with mixture of solids/shells/beams etc and it also handles the rigid-body modes well. The modeling of the building is done in ANSYS Version 2011 by using SOLID187element. SOLID187 element is a higher order 3-D, 10-node element. SOLID187 has quadratic displacement behaviour and is well suited to modeling irregular meshes. The geometry, node locations and the coordinate system for this element are shown in the Fig. 3.

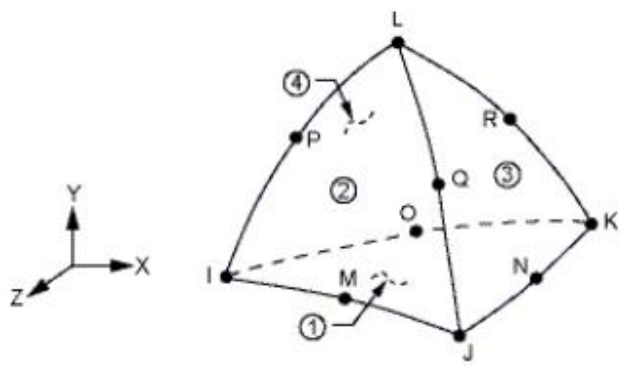

Fig.3: Finite Element used

The finite element mesh used in the analysis is shown in the Fig.4. This mesh has been selected after making necessary convergence studies.

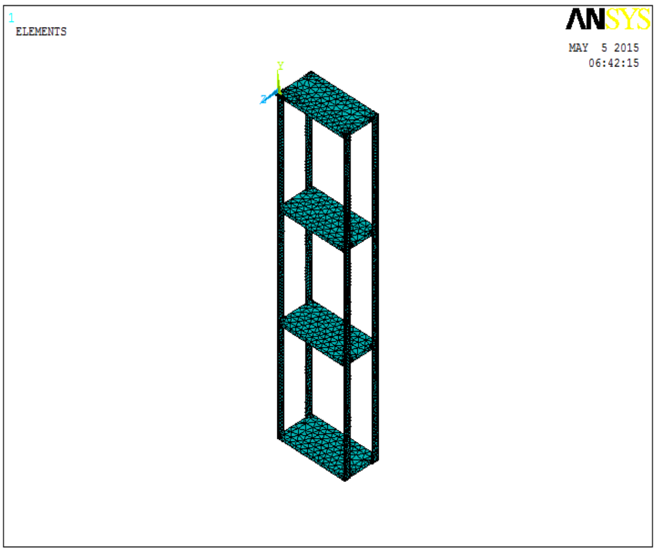

Fig. 4: Finite Element Mesh

The modal analysis is performed and the natural frequencies obtained are noted down. The displacement values obtained from the analysis are also noted down and the corresponding eigenvectors are computed.

4.2 ANSYS Results

The three natural frequencies obtained from ANSYS are: f_1 = 3.0473 Hz, f_2 = 8.6142 Hz, f_3 = 12.566 Hz. The details of the three modes are given in Table 3.

Table 3: Mode Shapes (ANSYS)

	First Mode	Second Mode	Third Mode
First Floor	1	1	1
Second Floor	1.804	0.399	-1.275
Third Floor	2.231	-0.843	0.637

The mode shapes are shown in Fig. 5(a), 5(b) and 5(c).

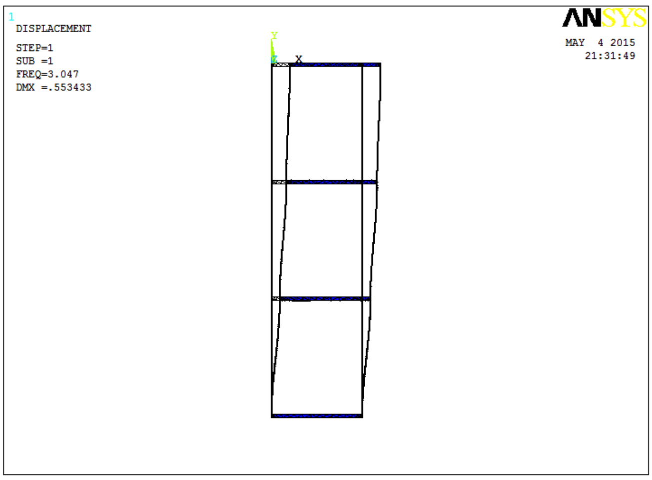

Fig. 5(a): First Mode (ANSYS)

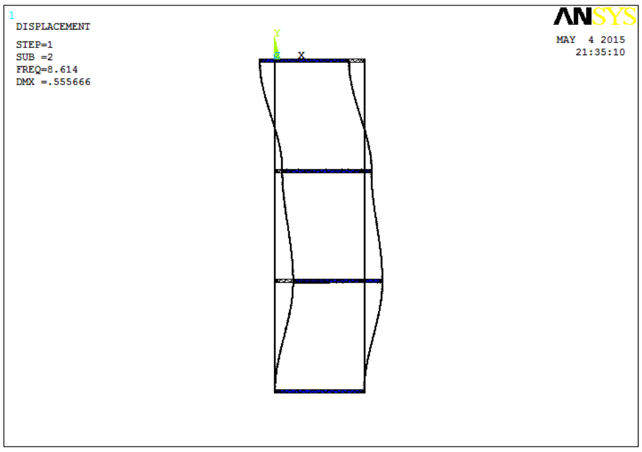

Fig.5(b): Second Mode (ANSYS)

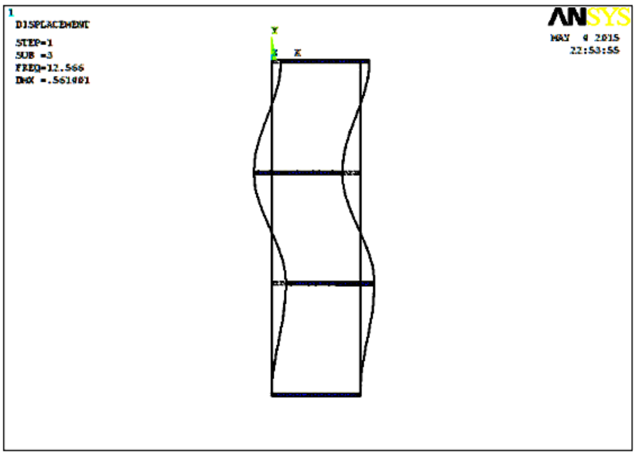

Fig.5(c): Third Mode (ANSYS)

5. NUMERICAL METHOD USING ETABS 2013 ULTIMATE 13.2.2

5.1 Methodology

ETABS 2013 Ultimate 13.2.2 is used to perform finite element analysis. Shell element is used for the slab. Beam element is used for the column. The columns and slabs of the building frame model are modeled as described above. The base is constrained in all directions and the modal analysis is done using eigenvalue matrix method. The analysis model is shown in Fig.6.

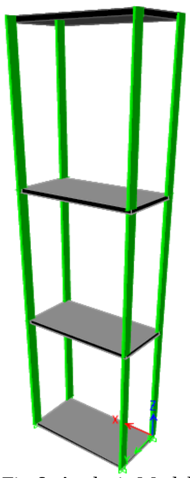

Fig.6: Analysis Model

5.2 ETABS Results

The three natural frequencies obtained from ETABS are f_1 = 2.863 Hz, f_2 = 7.965 Hz, f_3 = 11.398 Hz and the details of the corresponding mode shapes are given in Table 4.

Table 4: Mode Shapes (ETABS)

	First Mode	Second Mode	Third Mode
First Floor	1	1	1
Second Floor	1.808	0.395	-1.286
Third Floor	2.231	-0.843	0.639

The mode shapes are shown in Figs. 7(a), 7(b) and 7(c).

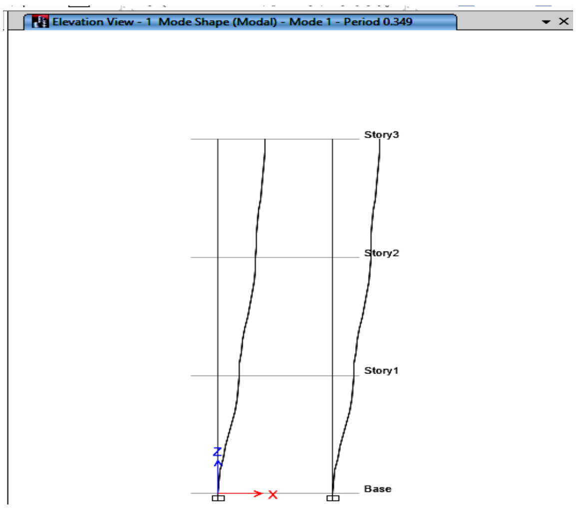

Fig. 7(a): First Mode (ETABS)

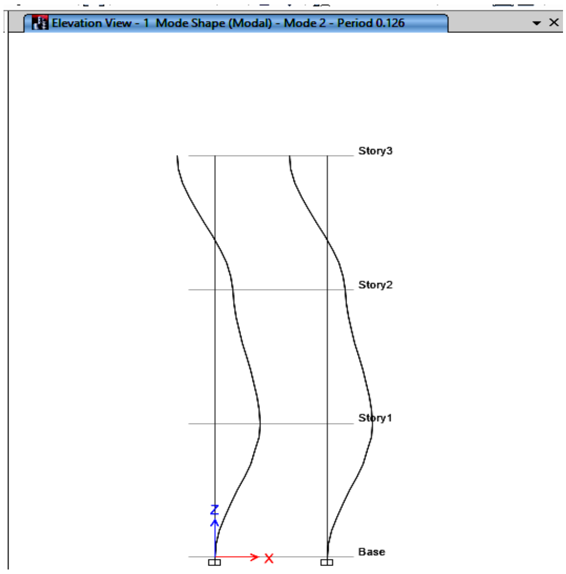

Fig. 7(b): Second Mode (ETABS)

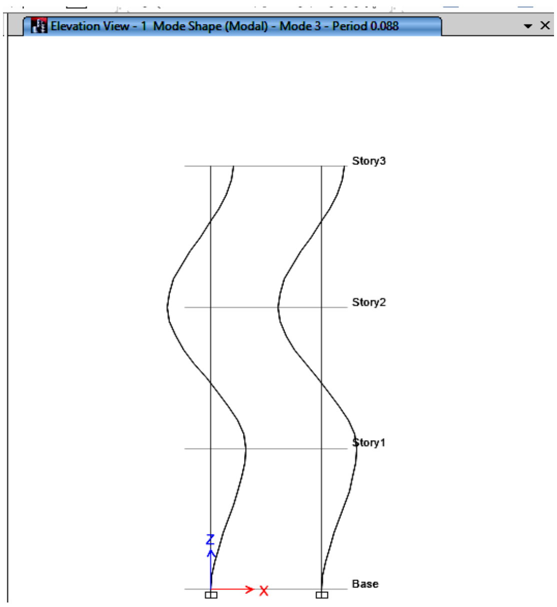

Fig. 7(c): Third Mode (ETABS)

6. DISCUSSION OF RESULTS

The natural frequencies obtained from analytical, experimental, ANSYS, ETABS software are compared.

Table 5: Comparison of Natural Frequencies.

Modes	Natural frequencies (Hz)			
	Experimental	ANSYS	ETABS	Analytical
I Mode	3.0	3.0473 (1.577 %)	2.863 (4.567%)	2.87 (4.333 %)
II Mode	8.30	8.6142 (3.786 %)	7.965 (4.036%)	7.98 (3.855 %)
III Mode	12.15	12.566 (3.424%)	11.398 (6.189%)	11.39 (6.255 %)

Note: The percentage of error relative to experimental value is mentioned within parentheses.

Fig. 8 shows the above results in graphical form.

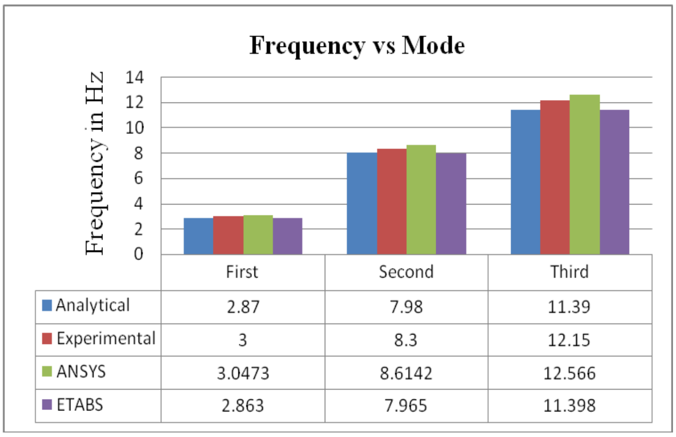

Fig. 8: Natural frequency versus Mode

7. CONCLUSIONS

- ANSYS Version 11 predicts the experimental values of natural frequencies more closely than ETABS 2013 Ultimate 13.2.2.
- The analytical values of natural frequencies are observed to be lower when compared to the experimental values.
- The analytical, experimental and FEM values of natural frequencies and mode shapes are found to be in reasonable agreement with another.

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