Computational and Experimental Modal Analysis of a Three Storied Building Model

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Abstract. Vibration-based health monitoring assists in determining the modal parameters and damage identification of a structure. This paper presents the computational and experimental modal analysis of a single bay three-storied building with steel slabs and aluminium columns. Three-dimensional finite element (FE) model of the structure is analysed using ABAQUS, and natural frequencies in the first three translational modes are determined. These results are compared with those obtained from field impact testing. A small variation in analytical and experimental results may be due to the simplified assumptions in FEA, physical and numerical uncertainties.

1. Introduction

The pace and complexity in construction of civil infrastructure have shown a rising trend towards the beginning of the 21st century. It demands the need for appropriate monitoring and proactive maintenance system to ensure safety and longer lifespan of the structure.

Structural health monitoring (SHM) is the continuous evaluation of the state of a structure with the help of data collected from different types of transducers attached to the system on a real-time basis. On comparing with other non-destructive monitoring methods, SHM has the advantage that it can be deployed even in non-accessible locations, and it needs no downtime [1][2]. Vibration-based techniques in SHM use modal analysis as the basic tool for the identification of damage and health evaluation of the structure [4]. Modal analysis is the method of determining the dynamic characteristics of a structure under vibration excitations. The basic idea of vibration-based health monitoring is that changes in structural properties such as mass, stiffness, and damping affect the dynamic properties of the structure. Thus by examining the changes in dynamic characteristics, identification of damage, and appropriate maintenance can be implemented [3][5].

In this study, Numerical as well as experimental modal analyses are carried out to extract the modal parameters, mainly natural frequencies from dynamic responses. A three-storied building model with steel slabs and aluminium columns is selected as the test specimen. Numerical analysis is done by developing and analysing the 3D FE model of the structure using FEM software, ABAQUS[6]. Further, the structure is excited experimentally, and dynamic responses are extracted by means of a system of transducers attached to the model. Data collected from the transducers are processed to get the required modal parameters. The accuracy of the results from the experimental modal analysis is ensured by comparing it with the numerical results.
2. Description of the test structure

An acceptable member/structure compatible with the available laboratory conditions has to be identified before starting with the modal analysis. This study concentrates on the analysis of a single bay-three storied building model with mild steel slabs and aluminium columns. This material combination is selected as it accounts for the real-time condition of flexible columns compared to the stiffer slab system. Material properties of steel and aluminium such as Young’s modulus, density, and Poisson’s ratio used in modelling of the structure are shown in table 1.

| Property                  | Steel     | Aluminium |
|---------------------------|-----------|-----------|
| Young’s Modulus (N/mm²)   | 210000    | 70000     |
| Density (tonne/mm³)       | 7.85 × 10⁹| 2.7 × 10⁹ |
| Poisson’s Ratio           | 0.3       | 0.3       |

Rectangular sections of cross sectional dimensions 25mm × 6mm are used as columns while 12 mm thick slabs of plan area 300mm × 255mm are used as floors. Floor to floor height is kept as 300mm and fixed boundary condition is given at the bottom.

3. Computational modal analysis

With the development of computational structural dynamics, modal analysis using FEM is widely used to predict the vibration parameters of a structure under study. The FE model of the structure is developed using ABAQUS, a software suite for FE Analysis and computer-aided engineering. The columns and slabs are meshed with ten noded quadratic tetrahedron elements of sizes 5mm and 20mm, respectively, as shown in figure 1. Mesh sizes are finalised by conducting the mesh convergence study from a coarser mesh to a finer one in such a way that the analysis produces acceptable results with least simulation time. Tie connection corresponding to the required bolt area is provided between each slab-column connection, and base slab is fixed to the ground.

Figure 1. Finite element model showing meshing.

Natural frequencies and mode shapes of first three translational modes in x coordinate direction obtained from numerical modal analysis are shown in table 2 and figure 2, respectively.
### Table 2. Natural frequencies from computational modal analysis.

| Mode | Natural frequency (Hz) |
|------|------------------------|
| M1   | 5.67                   |
| M2   | 16.15                  |
| M3   | 23.84                  |

Figure 2. Mode shapes from computational analysis a) First mode b) Second mode 3) Third mode.

4. **Experimental modal analysis**

Experimental modal analysis (EMA) deals with measurement and analysis of the structural dynamic response when excited by known stimulus. It is useful in verifying numerical results as well as in determining the vibration parameters of the structure [5].

The specimen is placed at a level surface and tightly fixed at the bottom with the ground to get a fixed boundary condition. A uni-axial accelerometer is fixed at the top floor and is connected to the Data Acquisition System with controlling software through coaxial cables. Known excitations are imparted at different floor levels using impact hammer with sensitivity 2.25mV/N and is also connected to the DAQ system. The time-domain dynamic signals extracted from the data analyser are exported to the processing software, ModalVIEW for modal parameter identification. Figure 3 and figure 4 shows the experimental set-up and Frequency Response Function (FRF) obtained from the processed data, respectively.

Figure 3. Experimental setup.
Figure 4. Frequency Response Function from the software.

Figure 5. Natural frequency extraction by peak picking.

Figure 6 shows the first three mode shapes obtained from the experimental analysis.

Peak picking modal parameter extraction algorithm is used to identify the natural frequencies from the FRF. The procedure is shown in figure 5. The first three Natural frequencies of translational modes in the x-coordinate direction obtained from EMA is shown in table 3 along with percentage damping.

Table 3. Natural frequencies and percentage damping from EMA.

| Mode | Natural frequency (Hz) | Damping (%) |
|------|------------------------|-------------|
| M1   | 5.39                   | 1.92        |
| M2   | 15.84                  | 0.83        |
| M3   | 23.67                  | 0.37        |
5. Results and discussions
Natural frequencies obtained from the computational and experimental modal analysis are compared. Percentage error between the results of both methods is summarised in table 4.

| Mode | Natural frequencies (Hz) | % change |
|------|--------------------------|----------|
|      | Computational modal analysis | Experimental modal analysis |        |
| M1   | 5.67                      | 5.39     | 4.94    |
| M2   | 16.15                     | 15.84    | 1.92    |
| M3   | 23.84                     | 23.67    | 0.71    |

6. Conclusion
Modal frequencies from the experimental modal analysis are having smaller values when compared with those obtained from numerical analysis. This variation in modal parameters may be due to the physical and numerical uncertainties like boundary conditions, joint stiffness, and material properties. The numerical models give the responses based on ideal assumptions of material homogeneity like mass distribution, isotropy, and Poisson's ratio. However, in real cases, the materials may not behave like the ideal one. Comparing numerical and experimental analysis, a minimum of 0.71% and a maximum of 4.94% percentage error in modal frequencies are observed.

To improve the consistency between the results, it is recommended to calibrate the FE model realistically with respect to experimentally obtained results so that the errors resulting from simplified assumptions and material uncertainties are minimised. Also, advanced comparative study of mode shapes will further enhance the study.
7. References

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