Validation of Modal Analysis of Two-Storey Reinforced Concrete Frame

I F Azmi*1, N H Hamid2, W I I Wan Iskandar Mirza3, M N Abdul Rani3 and M A Yunus3
1Faculty of Civil Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia.
2Institute of Infrastructure Engineering, Sustainable and Management, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia.
3Structural Dynamics Analysis & Validation (SDAV), Faculty of Mechanical Engineering, Univesiti Teknologi MARA (UiTM), 40450 Shah Alam, Selangor, Malaysia

*Corresponding e-mail: ilina_azmi@yahoo.com

Abstract. The aim of this paper is to perform experimental modal analysis of two-storey reinforced concrete frame which designed using BS 8110 without seismic load and validate the experimental result with model using finite element analysis software. Experimental Modal Analysis (EMA) is the process of determining the modal parameters such as natural frequencies, damping factors, modal vectors and mode shape of a structure from a set of frequency response functions. The experimental work was conducted on half-scale of two-storey reinforced concrete frame at Heavy Structural Laboratory. Moreover, the Impact Modal Testing and response accelerometer are employed to determine the modes of vibration of a structure during experiments without imposed any in-plane lateral force. The experimental natural frequencies, which are extracted from measurements, exhibit good agreement with analytical model predictions. It shows that experimental modal analysis method can be usefully employed to investigate the dynamic behaviour of reinforced concrete frame due to the minimum percentage error between experimental modal analysis and computer software analysis.

Keywords. Modal Analysis, Natural Frequencies, Mode Shape, Reinforced Concrete Frame

1. Introduction

West Malaysia is considered as low seismic region and East Malaysia is categorized as moderate seismic region. However, Malaysia is located not far away from the active seismic fault zones known as Ring of Fire as shown in Figure 1 [1-2]. Most of the reinforced concrete (RC) buildings in Malaysia were designed in accordance with the BS8110 where not specification for seismic load. Past earthquake records showed that most of RC building which designed using non seismic code of practice proved that they cannot survive under moderate or strong earthquakes [3]. After experiencing several tremors originating from neighbouring countries especially from Sumatra, Indonesia and the 2015 Sabah Earthquake, Malaysians start to ask the question on the integrity of existing structures in Malaysia to withstand the earthquake load. In non-seismic code of practice such as BS8110, there are no specification on beam-column joint detailing, no ductility designed based on target displacement and only 10% nominal load specification for wind load in this standard [3-4]. The 2015 Sabah Earthquake had caused moderate and severe structural damage to a school, mosque and residential house. The total
cost of damage after this disaster were around RM100 million which affected 61 buildings, 22 roads, 22 slopes and 200 families in Ranau and Kota Belud, Sabah [5]. However, these structural damages can be prevented or minimized if more attentions were focused on the structural health monitoring, repaired and retrofitting technique. As the consequences, structural health monitoring is an attractive filed to be explored especially in civil engineering especially for bridges, high rise buildings and other infrastructures due to ground motions [6].

Figure 1. Active volcanoes, plate tectonics and the ‘Ring of Fire’ around the world [1-2]

Experimental Modal Analysis (EMA) can be employed as a basis for health monitoring for structures and infrastructures under earthquake excitations. Experimental modal analysis is generally defined as the process of an effective mean for identifying, understanding, and simulating the dynamic characteristics and response of a structure through determining the modal parameters such as natural frequencies, mode shape and damping factors of a linear, time-invariant system [6-9]. Experimental work and analyses usually are very costly and long time consuming to be performed as compared to numerical simulations using the finite element method. However, it is found that the finite element results are frequently not in good agreement with experimental counterparts due to the invalid assumptions made in the finite element modelling. Therefore, the correct assumption and justification needed to minimize the percentage difference between experimental result and finite element analysis result. This is due to the fact that modal parameters of a structure have an important role on its behaviour under dynamic loading. A comparative study of the natural frequencies and mode shape of concrete frame structure designed using BS8110 is performed based on the measured by experimental and predicted results by using finite element analysis using Hyperworks program. Usually the structural damage of the structures depends on the natural frequencies of the buildings [10]. Thus, it is important to determine the natural frequencies of this two-storey building using Hyperworks program before conducting destructive test in Heavy Structural Laboratory, Faculty of Civil Engineering, Universiti Teknologi MARA, Shah Alam, Selangor.

2. Equipment and Instrumentation
In order to achieve the subsequent steps of experimental modal analysis, there are four types of equipment and instrumentation that going to use in the laboratory for conducting experimental work. Prior to testing, a half-scale two-storey reinforced concrete frame was designed using BS 8110 and constructed in the laboratory. The two-storey frame was placed on top of the foundation beam and bolted together to the strong floor. A special based isolation system with superior elastic performance rubber will be used as based isolation system.
2.1. Impact Hammer
Impact hammer equipped with a force transducer from PCB Electronics, which allowed the measurement of the applied impulse. The reference sensitivity is 2.73mV/N. A force sensor mounted in the head of the hammer transforms the input force pulse into a waveform that contains the necessary amplitude and phase information to completely describe the forcing function. Impact tip material stiffness helps determine the frequency content of the input forcing function by controlling the impact pulse duration. By defining the frequency and amplitude of the forcing function, impulse hammers present a fast, simple way to excite structures in a well-defined fashion. Figure 2 shows the impact hammer with the red head which can capture the amount of force exerted to the surface of concrete.

![Figure 2. Impact Hammer](image)

2.2. Accelerometer
Four accelerometers MMF (KS48C) model were used in the analysis, accelerometers with a sensitivity of about 104.23mV/ms$^2$ (1022.1mV/g) and frequency range between 1 Hz-100 Hz. One important characteristic of accelerometer is that it includes integrated amplifier that converts the movement of the seismic mass into acceleration signal in the form of voltage. In order to measure the acceleration response of the RC frame, steel anchor was bolted first at side of the concrete frame. Then, the accelerometers were screw to the steel anchor which attached to the two-storey reinforced concrete frame. Figure 3 shows the accelerometer MMF(KS48C) model attached to RC frame and connected to personal computer using special electric cable.

![Figure 3. The accelerometer MMF(KS48C) model attached to RC frame](image)

2.3 Amplifier
In experiment modal analysis, the amplifier is a necessary device to boost the very small electrical charges which are generated by the accelerometer into a signal. The signals were fed to the data acquisition card after filtering.
2.4 Personal Computer
Personal computer was used to measure the experimental data. Moreover, personal computer with signal processing software was also used to analyses the signals. A special program is used to transform from signal data to amplitude versus frequencies graph.

3. The Measurement Procedure
In this study, experimental modal analysis was performed on a half-scale two-storey reinforced concrete frame structure at the Heavy Structure Laboratory, Faculty of Civil Engineering, UiTM, Shah Alam, Selangor. The height of each floor is 1100mm with the size of the column is 200×200mm and beam size 300x200mm. The upper level of RC frame was constructed using reinforced concrete flat slab. The thickness of the slab is 200mm while the first-floor level is one bay frame without any infill of brick wall or masonry. Figure 4 shows a half-scale one-bay two-storey reinforced concrete frame with steel plate placed on top of foundation beam. The non-destructive test is conducted in order to determine the natural frequencies and mode shape of this frame.

Figure 4. One-half scale of two-storey reinforced concrete frame

Before conducting experimental modal analysis using impact hammer, four numbers of accelerometers were bolted to left hand side of RC frame as shown in Figure 5. The impact hammer with force sensor was applied to the concrete frame as shown in Figure 6. The vibration from the impact hammer was captured by four sensitive accelerometers which attached adjacent to the frame.
Figure 5. Four accelerometers placed at one side of the RC frame.

Figure 6. Impact hammer was exerted on the surface of the concrete.

Figure 7 shows the numbers of nodes for 3D two-storey RC frame based on the guidance from the results of modal parameters of the frame obtained from the finite element analysis program. There are a total number of twelve nodes for two-storey RC frame with fixed support at four columns. Prior to perform the experimental work, there are several factors that contribute to the significant results such as the number of accelerometers used, measuring points and amount of force exerted to the surface of concrete.

Figure 7. 12 number of nodes for two-storey RC frame

A total number of three significant mode shapes were detect based on the experimental result, which label as Mode Shape 1, Mode Shape 2 and Mode Shape 3 from the computer. The other mode shapes have very small peak and did not include in this analysis. Since only four accelerometers were placed at node 3, 4, 5 and 6, therefore only 4 nodes were involved in the measurement and validation process. The frequency bandwidth of interest was between 0 to 32Hz. In this experimental work, an impact hammer and accelerometers were used to measure the dynamic behavior of the frame structure.

Before the modal analysis experiment conducted in laboratory, the finite element analysis using HYPERWORK program must be perform. The natural frequencies and mode shapes of the finite
element model of the structure were predicted using normal modes analysis in which the model properties of the finite element models were defined as follows: Young’s modulus = 30000MPa, Poisson’s ratio = 0.2 and density = 2400 kg/m³. This data input of the finite element defined based on the standard properties of the reinforced concrete. The support of the specimens was assigned as fixed support for total four numbers of columns.

4. Validation of Result and Discussion

Basically, there are three important mode shapes to be analysed, validate and discuss for 3D two-storey reinforced concrete frame. The dynamic properties for this type of buildings will be discussed in term of frequencies, lateral displacement, damping ratio and times with respective of each mode shape. Figure 8, 9 and 10 shows the dynamic behaviour of the first, second and third mode shape which obtained from HYPERWORK program.

![Figure 8. First Mode Shape of two-storey of RC frame](image)

![Figure 9. Second Mode Shape of two-storey of RC frame](image)

![Figure 10. Third Mode Shape of two-storey of RC frame](image)

Three experimental natural frequencies were match with analytical results in order to find the accuracy of the experimental modal analysis as shown in Table 1. The relative error between three
analytical and experiment nature frequencies reported. The percentage error for each mode shape is expressed using equation 1 as follows:

\[
\text{Percentage Error} = \frac{\text{Higher Frequency} - \text{Lowest Frequency}}{\text{Total Frequency}} \times 100
\]  

(1)

**Table 1.** Natural Frequency of the RC frame obtained from modal analysis experiment and HYPERWORK software

| Mode Shape | Natural Frequency | % Error |
|------------|-------------------|---------|
|            | EMA (Hz)          | FEA (Hz) |
| 1          | 7.94              | 11.8    | 19.6    |
| 2          | 14.49             | 12.8    | 6.2     |
| 3          | 19.26             | 19.6    | 0.9     |

As mentioned earlier, only three mode shapes are consider in this study. The first mode is what often defines the highest loads in a structure or how that structure will interact with the rest of the system around it when vibrating. For the first mode, the experimental natural frequency of the two-storey reinforced concrete building is 7.94Hz and 11.8Hz obtained from model natural frequency. The percentage difference error for first mode shape is 19.6%. The experimental natural frequency for second mode shape is 14.49Hz and 12.8Hz for model natural frequency with percentage error of 6.2%. Finally, the smallest difference percentage error for third mode shape is 0.9% where experimental and model natural frequencies are 19.26Hz and 19.6Hz, respectively. The comparison of the results clearly reveals that there is a good correlation between the experimental and computer analysis software natural frequencies with percentage of error maximum only 19.6%. Such a difference is quite acceptable due to the complex behavior of RC frame and characteristics of support idealization. More specifically, the finite element computer analysis software model assumes the reinforced concrete frame to be linear, elastic, homogenous and isotropic. Whereas in reality, concrete is heterogeneous and anisotropic material and the specimens inevitably contain imperfections in forms of crack, defects and steel bars misalignment.

Table 2 shows the maximum lateral displacement with respect each of mode shape at the top of the two-storey reinforced concrete frame which obtained from finite element analysis program. The first mode shape in the modal frequencies is the most important parameters to be considered during earthquake excitations and it is the common failure mode which normally occurred during the disaster. The second and third mode shape not commonly occurred unless the structures did not design in accordance current seismic code of practice. The most common failure for these types of structures is known as soft-storey mechanism. The highest displacement of reinforced concrete two-storey frame is 0.02261mm which obtained from finite element analysis software addressing the first mode shape.

**Table 2.** Displacement of RC Frame obtained from the HYPERWORK software

| Mode Shape | Displacement (mm) |
|------------|-------------------|
| 1          | 0.02261           |
| 2          | 0.0003            |
| 3          | 0.0009            |

Table 3 shows the modal damping ratio of two-storey reinforced concrete frame with respect to mode shapes which obtained from experimental data. The first mode shape has 1.01% intrinsic damping ratio, second mode shape has 1.11% intrinsic damping ratio and the third mode has 1.64% intrinsic damping ratio. It can be clearly seen that as the percentage intrinsic damping ratio increases as the number of
mode shape increases. The equivalent viscous damping comprises of radiation damping, intrinsic damping and hysteresis damping. The equivalent viscous damping for normal reinforced concrete building usually has the value of 5% and this value normally used to model the structures using nonlinear time history analysis. Table 4 shows the time taken to complete one cycle for first, second and third mode shape. From the frequency data, the time taken to complete one cycle or period can be determine for RC frame for mode shape 1, mode shape 2 and mode shape 3 using Equation 2 as follows.

\[
\text{Period, } T = \frac{1}{\text{frequency, } f}
\]  

**Table 3.** Damping Ratio of RC Frame obtained from the experimental work

| Mode Shape | Damping Ratio ξ % |
|------------|-------------------|
| 1          | 1.01              |
| 2          | 1.11              |
| 3          | 1.64              |

**Table 4.** Time of RC Frame by calculation

| Mode Shape | Time (s) |
|------------|----------|
| 1          | 0.085    |
| 2          | 0.078    |
| 3          | 0.051    |

5. Conclusion
The main goal of this paper is to validate the natural frequencies between experiment modal analysis and modelling finite element program. From the modelling, the natural frequencies, mode shapes and modal damping of the reinforced concrete frame can be obtained and analysis based on different level of earthquake excitation. To judge the reliability of experimental results of RC frame, a comparison between experimental and finite element analysis natural frequencies had been made. The finite element analysis of natural frequencies was obtained using HYPERWORK program while experimental natural frequencies were determined from laboratory work. The differences in results are relatively small, hence within acceptable limits for the reasons mentioned in the discussion section above. Overall, the experimental work shows successful extraction of experimental modal parameters when the frame is excited by impact hammer. Such promising investigation can be deemed as the right step towards the description of dynamic behaviour of the structures.

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