IDENTIFICATION OF DYNAMIC PROPERTIES OF LOW-RISE RC BUILDING BY AMBIENT VIBRATION MEASUREMENTS DURING CONSTRUCTION

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ABSTRACT :

Dynamic properties of a building play an important role in the determination of the equivalent lateral forces as well as responses from natural disturbances such as seismic and wind forces. To quantify these properties, a measurement approach is considered to provide the most accurate results, and an alternative approach of the numerical analysis yields more comprehensive results. Thus the combined study of the measurement and numerical analysis are complementary and would provide more rational outputs. In particular, more comprehensive information on building's characteristics could be obtained from measurements taken during several different stages of construction than from only a single measurement at the complete stage of the building. This paper presents results of a study on dynamic testing and numerical analysis of a 6-story RC building with an attempt to develop more understanding and add more informative results for the problem in this area. The influence of masonry walls and foundation flexibility on the natural frequencies, damping ratios and mode shapes were extensively examined through ambient vibration measurements in conjunction with numerical modeling. An examination began just after completion of the structural frame and continued at 12 different stages of construction until the masonry infill wall was completely in place and the building was occupied. The calculations from finite element models at each stage had been conducted and their results were compared to the results from measurement. The increases in natural frequencies of the building with the amount of partition masonry wall are discussed. The effect of soil-structure-interaction is examined from the modal parameters obtained at different stages.

KEYWORDS: Dynamic properties, Vibration test, RC building, Infill wall, Foundation flexibility

1. INTRODUCTION

Dynamic properties of building play an important role in the determination of the equivalent lateral forces as well as responses from natural disturbances such as wind and seismic forces. These properties include natural frequencies (or natural periods), damping ratios and vibration mode shapes of a building.

Empirical formulas in simple form or recommendations for an estimation of these properties are generally specified in building design standards. For the natural frequency of building, the empirical formula is currently available for the fundamental mode where it is a simple relation between the frequencies of buildings and their geometry. The lateral mode shapes of the fundamental mode of buildings are incorporated into the framework of the analysis, and it is always assumed as a linear shape in the existing design standards. The rational ranges of damping ratios are specified as recommendation for the design purpose in most standards. Even though these recommendations are considered as a rough estimation, the predictions made using only a few of data of building configuration were shown to be as accurate as a more complex computer based methods.

In general, buildings are always designed on an individual basis (for example; slab, beam, column or foundation) and the investigation of completely integrated structures is rarely undertaken. In addition, neglecting non-structural components such as partition walls, claddings, stairs, and flexibility of foundations in the numerical model are common practice. Although the effect of an individual exclusion of non-structural components on the analysis results may be negligible, the cumulative effects of several exclusions could be significant.

To identify where the numerical model needs to be improve and to provide a better understanding of the building behavior, the calculations from numerical analysis should be compared to the existent results from measurement of the actual building.

The results from measurement are normally considered to be accurate but incomplete since only few modes are obtained while the numerical study yields complete results but likely to be inaccurate. Therefore, the measurement and numerical studies are complementary. In particular, the measurement taken during construction provides more information on structure than that obtained from only the complete stage. Several works done of such investigation include Meyyappa et. al. (1981), Torkamani and Ahmadi (1988), Ellis and Ji (1996), Memari et. al. (1999), Canisius and Ellis (1999), and De Sortis et. al. (2005). This study is an effort to improve understanding in some more aspects which had not been covered in the past researches. The influence of masonry walls and foundation flexibility on the natural frequencies, damping ratios and mode shapes was examined in this paper. Ambient vibration measurements were conducted on a 6-story reinforced concrete building just after completion of its structural frame and continued at 12 different stages of construction until the masonry infill wall was completely in place. The calculations from finite element models at each stage had been conducted and their results were compared to the results from measurement.

2. DESCRIPTION OF THE STRUCTURE AND MEASUREMENT TECHNIQUES

2.1 Building Description

The building selected for this study is a reinforced concrete frame residential building. It has six stories with a height of 16.1 m, 3 bays in its 17.0 m length and 5 bays in its 16.4 m width. Figure 1 depicts the building configuration and Figure 2 shows its plan.

Figure 1. Configuration of the study building

2.2 Instrument

The vibration measuring system used in this work consists of two units of tri-axial velocity sensors and a portable seismic recorder. The resolution of the analog to digital converter is 24 bits with maximum converting speed of 50 kHz, and maximum input voltage of 2.5 V. The sensitivity is 1 V/(cm/s) and the frequency range is from 0.5 to 20 Hz. The system can measure velocity in the scale of micro-m/s and the maximum scale is ± 2.5 cm/s.

2.3 Identification Technique

To identify the natural frequencies of building, measurements were taken place on the top floor with different sensor arrangement schemes so that translation modes in two orthogonal axes, i.e. north-south and east-west directions, and torsional modes could be detected. The natural vibrations from ambient disturbances of the building were recorded and analyzed further with an assumption that excitations are stationary random process with a board band spectrum. The natural periods were, then, estimated from peaks in the Fourier spectra (Triunac 1970). The measured signal is then divided into a number of segments and the statistical characteristics of each segment were compared so that the abnormal part of record, which may arise from some unforeseen circumstances, could be indicated and excluded from the analysis.

Mode shapes of building, as the vertical profile of translation modes, were obtained by comparing the magnitudes and phases of the Fourier spectral of each story. However, due to a limit number of sensors, simultaneous measurement of all stories is not possible, thus one sensor was set at the top of building and the other was moved step by step to lower levels. Figure 2 shows arrangement of sensors on roof for identification of the natural frequencies, and Figure 3 shows arrangement of sensors for identification of mode shapes.

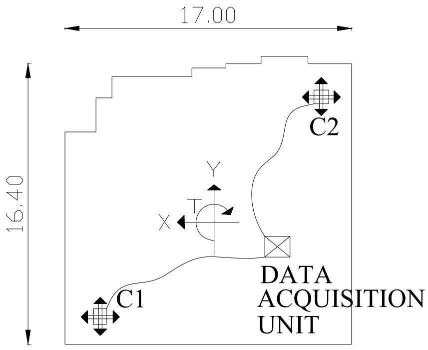

Figure 2. Arrangement of sensors on roof for identification of the natural frequencies

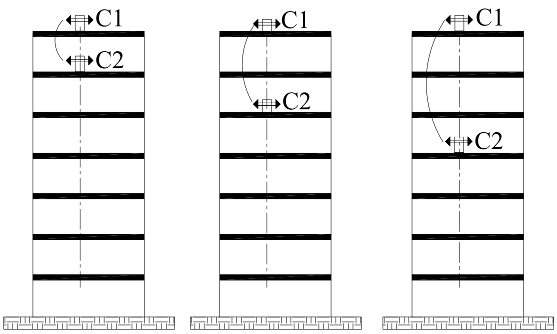

Figure 3. Arrangement of sensors for identification of mode shapes

In addition to the simple identification technique in frequency domain employed in this work, more advanced identification technique in time domain was also utilized when the frequency domain technique could not yield satisfactory results, i.e. for higher vibration mode or damping quantities. The recent and effective technique known as the Natural Excitation Technique (NExT) combined with the Eigensystem Realization Algorithm (ERA) (Juang 1994) were applied.

3. FINITE ELEMENT MODEL

From construction drawing details of the building, the FE models were formulated in SAP 2000 software. One-dimension structural member such as beam, column and foundation were modeled by a single element of frame section, while two-dimensional structural member such as slab and wall were modeled by a single element of shell section. Temporary load from construction materials were observed and included in the model as self weight of slab.

For concrete, modulus of elasticity was approximately 27,000 MPa and the value for masonry wall was 2,940 MPa. For the wall panel before plastering, thickness was 0.055 m, and unit weight was 15.70 kN/m^3, and after plastering they were assumed as 0.10 m and 17.65 kN/m^3, respectively.

The foundation model considered was fixed and flexible types. For flexible model of foundation, the lateral soil spring element for each layer of soil was estimated based on subgrade-reaction model (Bowles, 2001) where key geotechnical properties of Bangkok soil were taken from Shibuya and Tamayaka (1997).

4. RESULTS

4.1 Stage of Measurement

The measurement began when the construction of structural frame was complete and masonry work was started and then continued for total 12 different stages of construction. In stage 11, the entire construction including structural, electrical, sanitary and finishing works was completed. In stage 12, the building was operated for residential purpose. Since the major change in each construction stage was the contribution of partition masonry wall, the key indices for investigating dynamic characteristics of the building are amount of completion of wall for each stage, which influence the lateral stiffness of the building, and the overall additional weight per floor. Figure 4 and 5 show amount of wall completion per story and ratio of change in mass with respect to total change in mass per story for each stage of measurement, respectively.

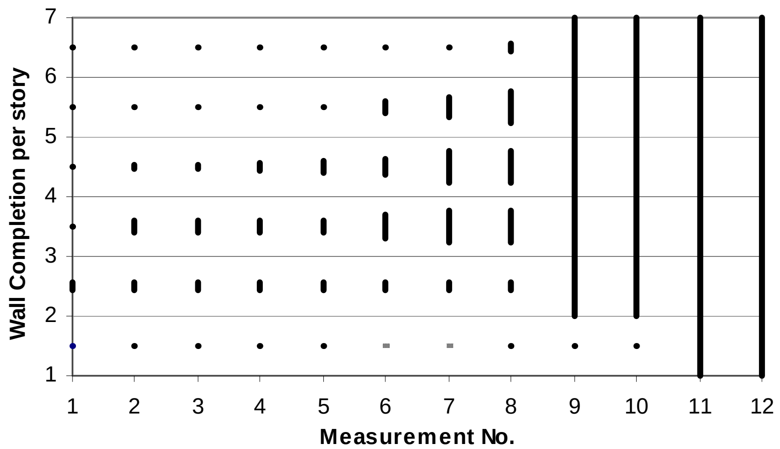

Figure 4 Amount of wall completion per story

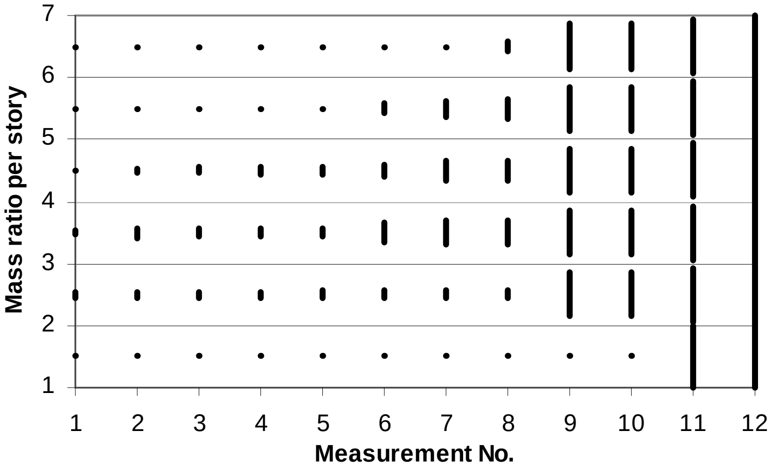

Figure 5. Ratio of change in mass with respect to total change in mass per story

4.2 Natural Frequency

The identified natural frequencies in the fundamental mode of vibration in two translation directions (i.e. X-direction parallels to 17.0 m length and Y-direction parallels to 16.4 m width) and rotation were compared to the corresponding results from numerical analysis. The identification techniques were the Discrete Fourier Transform (DFT) in the frequency domain and Eigensystem Realization Algorithm (ERA) in the time domain. Two models of foundations were investigated in the analysis, fixed and flexible models. Figure 6-8 present the natural frequencies in Y-direction, X-direction and rotation, respectively.

From these figures, natural frequencies of the building develop significantly with installation of partition walls. The installed walls contribute mainly on lateral stiffness of the structure than on mass, resulting in increasing in the natural frequencies. From these observations, the fundamental natural frequency in Y-direction increase from 1.83 Hz at the first measurement to 3.24 Hz at the twelfth measurement (77 % increase), and the similar results in X-direction and rotational direction are, 2.45 to 3.91 Hz (60 % increase) and 2.92 to 5.36 Hz (84 % increase), respectively. The increments are most pronounced at construction stage 8 to 9, which were due to plastering work on masonry walls in the second to the sixth story. The results from measurement and analysis are in good agreement where the frequencies from measurement lie within envelop of the upper-bound value from model with fixed type foundation and the lower-bound value from its flexible counterpart. It is important to note on the influence of foundation flexibility to natural frequencies of the building that, the discrepancy between the natural frequencies from fixed model to those from flexible model enlarge with the increase in the value of natural frequency. In this study, differences in the results from 2 model are 18% at the lowest frequency (stage 1) and 32% at the highest frequency (stage 12) for Y-direction. Similar findings are; for X-direction and rotation, the differences are from 17 to 39% and 26 to 38%, respectively. These numbers directly indicate level of the effect of foundation flexibility on behavior of structure. Since the stiffness of building develop consequently to constructions while the stiffness of foundation is rather invariant, this observation explains that the effect of soil-structure-interaction increase when the relative stiffness of the building with respect to the soil is higher.

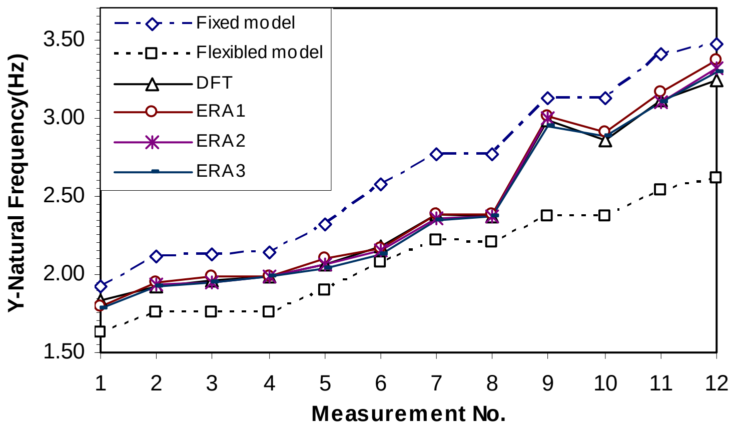

Figure 6. Fundamental frequencies in Y-direction

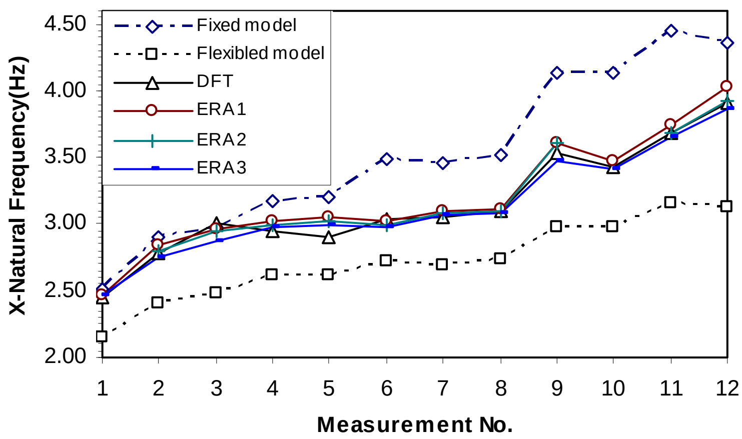

Figure 7. Fundamental frequencies in X-direction

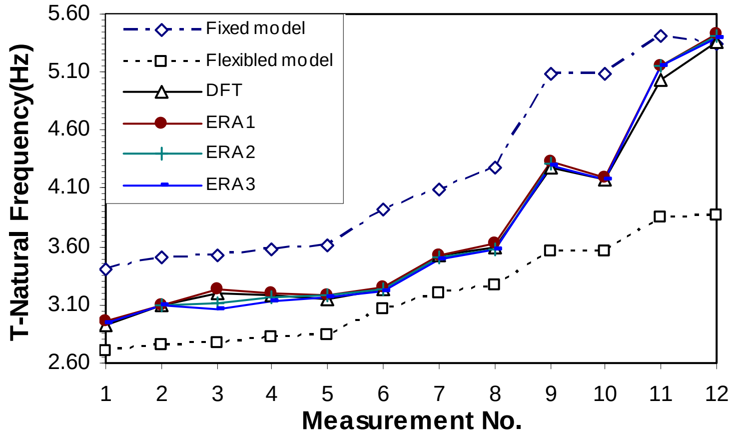

Figure 8. Fundamental frequencies in rotation

4.3 Movement at Base from Mode Shape

The vertical plots of the measured vibration mode shape reveal movement at base to a certain degree. The normalized movements at base relative to the maximum motion at the top floor are presented in Figure 9 for X and Y-direction. The calculations from flexible foundation model are in accordance with the measurement.

These effects result from soil-structure interaction which shifts the mode shapes at ground level from those of a similar structure on a rigid foundation. It is clearly shown that the movements at base increase with the natural frequencies. This finding in buildings founded on soft soils obviously confirms the hypothesis once again that soil-structure interaction effects are more pronounced when the relative stiffness of the building with respect to the soil is higher, and emphasize the critical roles of the soil-structure interaction effects.

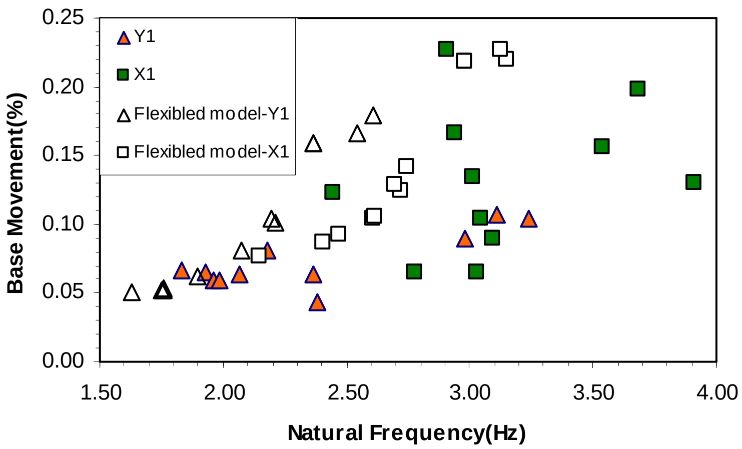

Figure 9. Movement at base and natural frequency

4.4 Damping Ratio

Damping ratios of translation mode in two directions were identified from NExT/ERA technique and the results are shown in Figure 10. There is tendency of damping ratios increase with the increment of mass and stiffness components of the building.

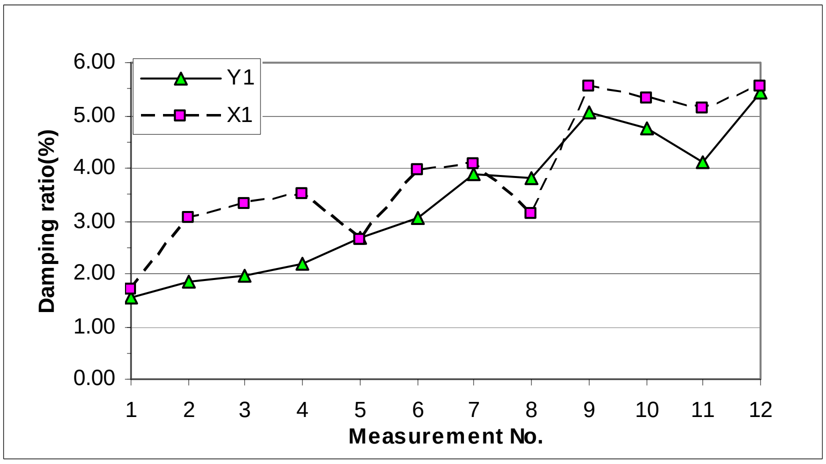

Figure 10. Damping ratio

5. CONCLUDING REMARKS

This study presents an investigation on dynamic properties of a 6-story RC building during construction by ambient vibration measurements. The changes in components of the building at 12 stages of measurement were taken into account in the numerical model for analysis. By this way, the study can identify where the numerical model needs to be improve and provide a better understanding of the building behavior. The results from model established in this study are in good agreement with the measurement.

The natural frequencies of the building increase with the amount of partition masonry walls. This concludes that masonry wall gives higher contribution in lateral stiffness than in mass of the system. The fundamental natural frequency in Y-direction increase from 1.83 Hz at the first measurement to 3.24 Hz at the twelfth measurement (77 % increase), and the similar results in X-direction and rotational direction are, 2.45 to 3.91 Hz (60 % increase) and 2.92 to 5.36 Hz (84 % increase), respectively. The increments of natural frequency are most pronounced at construction stage of plastering work on infill masonry walls.

The effect of soil-structure-interaction was observed through the discrepancy in the natural frequencies obtained from fixed and flexible foundation models. The difference extends when the natural frequency increase. In addition, movements at base observed from vibration mode shape increase with the natural frequencies. This is the cause of soil-structure interaction effect which is obvious in this case of buildings founded on soft soils and the effect are more pronounced in building where the relative stiffness of the building with respect to the soil is higher

REFERENCES

Meyyappa, M., Palsson, H. and Craig, J.I. (1981). Modal parameter estimation for a highrise building using ambient response data taken during construction. *Proceedings of the Second Specialty Conference on Dynamic Response of Structures: Experimental, Observation, Prediction and Control*, ASCE. 141-151.

Torkamani, M.A.M. and Ahmadi, A.M., (1988). Stiffness identification of a tall building during construction period using ambient test. *Earthquake Engineering and Structural Dynamics*; **16**, 1177-1188.

Ellis, BR. and Ji, T. (1996) Dynamic testing and numerical modeling of the Cardington Steel Framed Building from construction to completion. *The Structural Engineer*; **74**, 186-192.

Memari, A.M., Aghakouchak, A.A., Ghafory Ashtiany, M. and Tiv, M. (1999) Full-scale dynamic testing of a steel frame building during construction. *Engineering Structures*; **21**, 1115-1127.

Canisius, T.D.G. and Ellis, BR. (1999). Dynamic analysis of the Cardington concrete building during construction. *Structural Dynamics-EURODYN 99*, 877-882.

De Sortis, A., Antonacci, E. and Vestroni, F. (2005). Dynamic identification of a masonry building using forced vibration tests. *Engineering Structures*; **27**, 155-165.

Trifunac, M.D. (1970). Ambient vibration test of a thirty-nine story steel frame building. *Report no. EERL 70-02. Earthquake Engineering Research Lab. California Institute of Technology*, Passadena.

Juang, J.N. (1994). Applied System Identification, Eagle Wood Cliffs, New Jersey, Prentice Hall.

Bowles, J.E. (2001). Foundation Analysis and Design, McGraw-Hill Book Company.

Shibuya, S. and Tamayaka, S.B. (1997). In-situ and laboratory investigatons into engineering properties of Bangkok clay. *Proc. of Intl. Symp. Characterization of Soft Marine Clay-Bothkenner,Drammen,Quebec and Ariake Clay*. Balkema.