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Health monitoring and reliability estimation of a tall building

E. Kirkpinar[1], E. Özer[1], S. Soyöz[1]

[1]Department of Civil Engineering, Bogazici University, Istanbul, Turkey

ABSTRACT: In mega cities such as Istanbul, tall buildings are inevitable outcomes of limited construction areas; however in earthquake prone mega cities again such as Istanbul, adequate precautionary measures for tall buildings must be taken before and after an expected earthquake. Structural health monitoring techniques have been used to understand existing conditions of structures, as well as their post-earthquake conditions. In order to investigate possible solutions to such necessities, a twenty-six story, core-wall tall building in Istanbul is instrumented with sixteen accelerometers. Natural frequencies and modal shapes of the building are obtained by frequency domain decomposition method. These results are compared with the modal values obtained from the finite element model of the building created according to design drawings. Time history analyses under probable earthquake input motions are performed. Analyses results are compared based on probability density functions as a measurement of structural reliability. In this study it was shown that model updating based on identified modal values are significant in the determination of seismic demands on tall buildings.

1 INTRODUCTION

Structural health monitoring (SHM) or damage detection of a structure can be realized by the examination of modal parameters. SHM is based on analyzing the data acquired by vibration data on a structure, using identification techniques. SHM System identification has been carried out in civil engineering from the early 1980s. In several studies (Beck & Jennings (1980); Yun & Shinozuka (1980); Safak (1991); Ghanem & Shinozuka (1995); Lus et al. (1999)), structure is analyzed as a linear system and the modal parameters of this system are obtained in time or frequency domain. These studies were on ordinary buildings, bridges or tall buildings. Earthquake responses of tall buildings are also investigated using system identification techniques (Celebi & Safak (1991); Celebi & Safak (1992)). In tall buildings, like all other structures, modal paramaters obtained show differences between finite element model (FEM) and the experimental data. The main reason for that difference is the assumptions made in the finite element modeling (Brownjohn et al. (2000)). Therefore there is a need for updating the FEM according to the experimental data. This technique is applied successfully to structures, bridges (Jaishi & Ren (2005)) and wind turbines (Hartmann et al. (2011)).

In this research a twenty-six story, core-wall tall building in Istanbul is instrumented with sixteen accelerometers. Natural frequencies, modal shapes of the building are obtained by Frequency Domain Decomposition (FDD) method. These results are compared with the modal values obtained from FEM of the building created according to design drawings. Time-history analyses under probable earthquake input motions are performed. Analyses results are compared based on probability density functions as a measurement of structural reliability. In this study it was shown that modal values are significant in seismic demand of tall buildings.

2 DATA ACQUISITION

A recently constructed tall building in Istanbul (Figure 1) has been temporarily instrumented as shown in Figure 2. Permanent instrumentation is being carried out which will allow us to monitor the building continuously. Accelerometers are placed at sixteen locations to measure vibration response with a sampling frequency of 500 Hz. In order to catch mode shapes, sensors are located in floors according to the estimated the mode shapes of the building. As a result, for the first four mode shapes, sensors are placed so that modal displacement values for each mode are obtained. Figure 3 shows locations of the accelerometers.

Figure 1. The building monitored in the project.

Figure 2. Sensors and receiver.

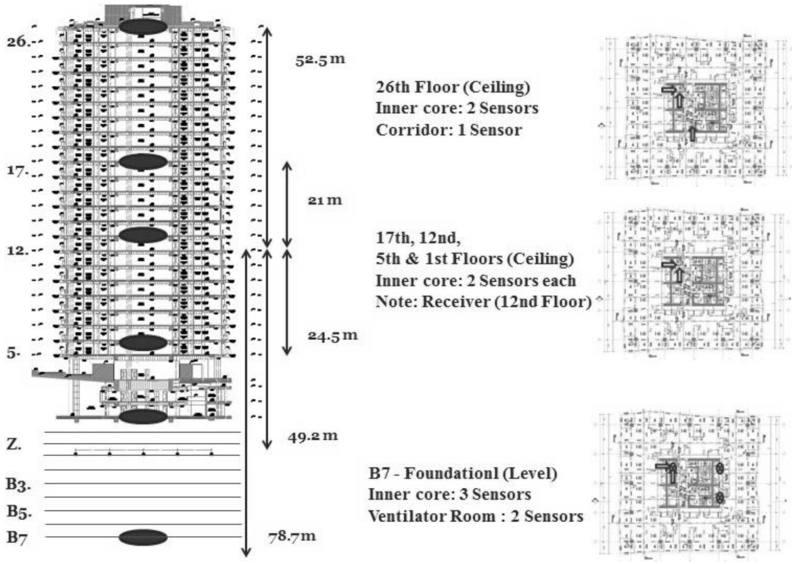

Figure 3. Sensor positions.

3 SYSTEM IDENTIFICATION

Figure 4 shows representative ambient vibration data taken from the 5th and 26th floors at the same time. Vibration response is analyzed by FDD method to obtain modal frequencies and mode shapes of the structure. Figure 5 shows the first singular value in the frequency domain in Y directions. The peaks in this figure represent the structural modal values. The first four mode shapes are also presented in Figure 6.

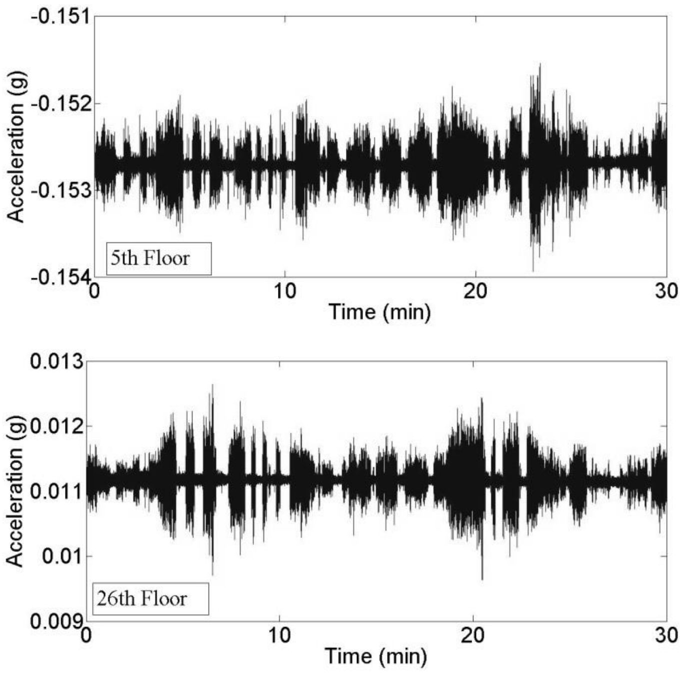

Figure 4. Structural response in time domain

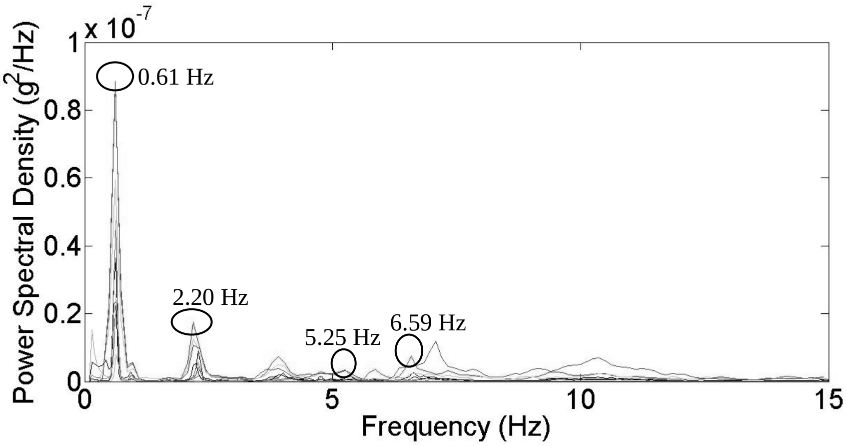

Figure 5. Structural response in frequency domain for all collected data.

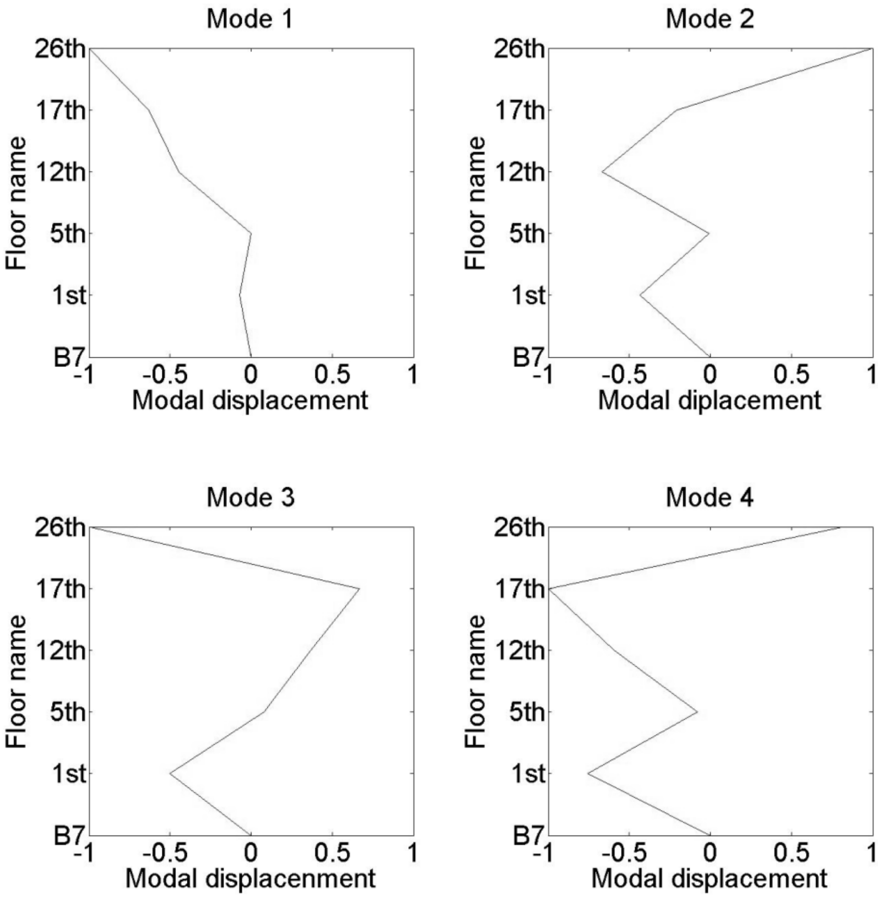

Figure 6. Mode shapes.

4 FINITE ELEMENT MODEL

In addition to experimental determination, modal values were also obtained analytically. Architectural drawings are used in finite element modeling of the building in SAP2000 as shown in Figure 7. The building has twenty-six floors above the ground and seven floors underground. A core-wall is connected to sixteen columns at each floor. In the real building there is also a shopping mall which is a wider structure in the first five floors around the tower. For the sake of simplicity this part is not modeled explicitly but represented with a stick element which will contribute to the lateral stiffness representing the shopping mall.

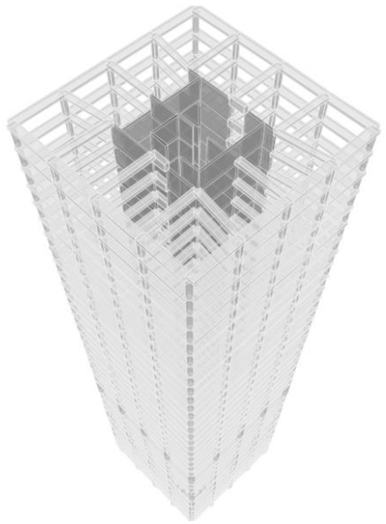

Figure 7. Finite Element Model.

5 MODEL UPDATING

FEM updating is carried out via Matlab platform. An iterative program is written to automatically update desired structural parameter. In model updating three parameters are used: Modulus of elasticity of the concrete, starting from 33 GPa to 51Gpa and found as 45Gpa, dimensions of the stick element in the x and y directions, starting from 0.1 m to 9.1 m and found as 0.1 m. Then an error function is used in Matlab platform to find the optimum set of variables to represent the real structure. This is done by comparing the identified modal values with the ones obtained from the finite element model. Identified modal frequencies and the ones obtained from FEM before and after updating are presented below:

- System Identification Results
    - 1st Frequency: 0.61 Hz
    - 2nd Frequency: 2.20 Hz
    - 3rd Frequency: 5.25 Hz
    - 4th Frequency: 6.59 Hz
- Non-updated Finite Element Model
    - 1st Frequency: 0.43 Hz
    - 2nd Frequency: 1.90 Hz
    - 3rd Frequency: 4.19 Hz
    - 4th Frequency: 6.85 Hz

- *Updated Finite Element Model*
    - 1^{st} Frequency: 0.60 Hz
    - 2^{nd} Frequency: 2.65 Hz
    - 3^{rd} Frequency: 5.85 Hz
    - 4^{th} Frequency: 9.56 Hz

6 DETERMINATION OF SEISMIC DEMAND

Twenty seven time history analyses are carried out for each updated and non-updated finite element models. Ground motion data are selected according to the expected earthquake in Istanbul which is approximated as magnitude 7.5, and the fault segment is 30 km away to the building site (Erdik et al. (2004)). Interstory drift ratios, which are the difference of displacements between two consecutive floors divided by interstory height, are compared as a measure for the seismic response of the models. A representative interstory drift from one of the time history analyses, which is Imperial Valley, can be seen in Figure 8. Time history analyses results show that there is a significant change in maximum drift ratios as a result of finite element model updating. Furthermore, probability density functions of drift ratios for updated and non-updated cases for both 2% and 5% damping ratio values are obtained as shown in Figure 9. Similarly, the probability distributions of updated and non-updated models show that consideration of vibration measurements, in other words, use of finite element model updating, have a significant effect on structural reliability.

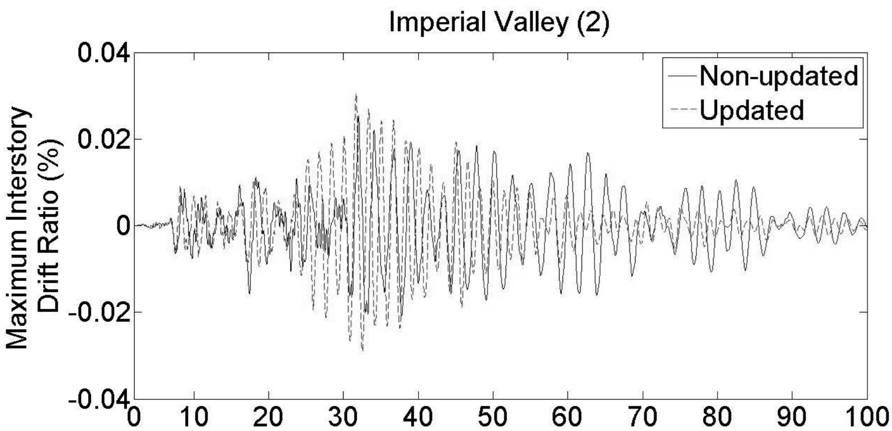

Figure 8. Maximum interstory drift ratio time-history between 4^{th} and 5^{th} floor for Imperial Valley record

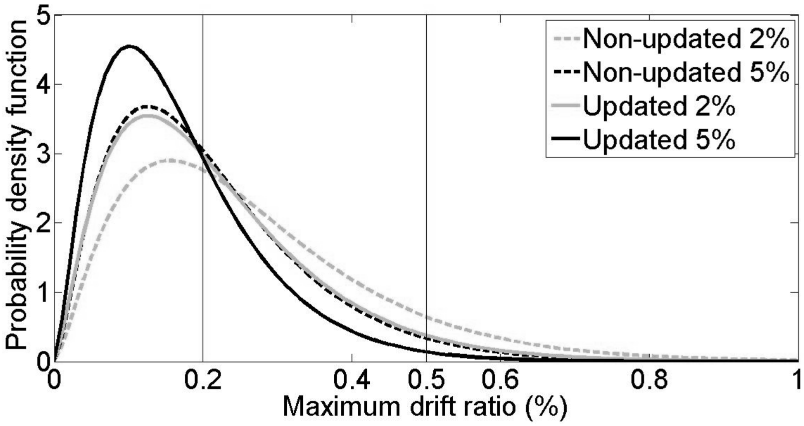

Figure 9. Probability density function of updated and non-updated maximum cases for drift ratio values

7 CONCLUSION

This study covers instrumentation, system identification and FEM updating of a tall building structure. First four mode shapes in both directions are obtained via instrumentation. For higher modes, more detailed instrumentation may be applied. Moreover, the effect of the proposed procedure on seismic demand is investigated by comparing interstory drift ratios with the non-updated model. Interstory drift ratios are used as damage indicators which represent different values for different inputs. In this study, FDD method is used for system identification. Moreover, FEM updating is carried out considering modulus of elasticity, and the dimensions of a stick element which represent the uncertainties of material, and the boundary conditions due to the shopping mall structure.

The drift ratio results show that time history analyses based on updated and non-updated models lead to significantly different results. For instance, drift ratio obtained from Imperial Valley is 0.34% for non-updated case, whereas it becomes 0.41% with finite element model updating for 5% damping ratio. A further conclusion is that reliability estimations based on finite element model updating turn out to be different than non-updated estimations. For example, in case limit drift ratio is set equal to 0.2%, the failure probabilities of updated and non-updated models are 0.32 and 0.45, respectively for 5% damping ratio. Another example, in order to inspect the behavior around the tail region of the density functions, is that when the limit drift ratio is 0.5%, the failure probabilities of updated and non-updated models are 0.012 and 0.036, respectively for 5% damping ratio. Therefore, the difference between updated and non-updated failure probabilities increase dramatically around the tails of probability density functions.

Efforts spent on system identification, and finite element model updating processes show that there are many uncertainties to be clarified and assumptions to be made for more accurate results. Especially the effect of modeling decisions is significant on the analyses results. Assumptions which are made in finite element modeling phase such that restraining effect due to the shopping center around the tower or the effect of underground part of the structure have a significant change in analyses results. Moreover, modeling techniques which are used such that using stick elements or shell element in order to model the shear walls or the rate of meshing which is used in shell elements directly has an effect on the dynamic character of the structure. Also, in the system identification process it is seen that determining the exact modal values of the system is showing importance as it affects the finite element updating phase as well. Current identification procedure is able to update FEM effectively in terms of natural frequency, but the error due to higher modes tends to increase as a result of updating. Therefore; even though the first mode of vibration is dominant on dynamic characteristics of the structure; higher modes, especially in tall buildings like the one studied in this paper, should be considered as well. Nevertheless, current results point out significant difference between seismic demands obtained from updated and nonupdated models, which might be critical since seismic demand is underestimated in the non-updated case. Further studies are going to involve modifications in the structural parameter identification procedure to obtain more reliable outcomes. In conclusion, even the current state of methodology shows that drift ratios, therefore, seismic demand is sensitive to changes due to identified parameters; and such changes should essentially be investigated in order to assess structural performance accurately.

8 REFERENCES

Beck, JL and Jennings, PC. 1980. Structural Identification Using Linear Models and Earthquake Records, *Earthquake Engineering and Structural Dynamics,* 8:2, 145-160

Brownjohn, JMW. 2000. Ambient vibration studies for system identification of tall buildings, *Earthquake Engineering and Structural Dynamics,* 32:71–95

Celebi, M and Safak E. 1991 Seismic Response of Transamerica, *Journal* of *Structural Engineering ASCE,* 117:8, 2389-2425.

Celebi, M and Safak E. 1992 Seismic Response of Pacific Park Plaza, *Journal of Structural Engineering ASCE,* 118:6, 1547-1589.

Erdik, M, Demircioglu, M, Sesetyan, K, Durukal, E, and Siyahi, B. 2004 Earthquake hazard in Marmara Region, Turkey, *Soil Dynamics and Earthquake Engineering,* 24 (2004) 605–631

Ghanem, R and Shinozuka, M. 1995 Structural System Identification, *Journal of Engineering Mechanics ASCE,* 121:2, 255-273.

Hartmann, D, Smarsly, K and Law KH. 2011 Integration Of Structural Health And Condition Monitoring Into The Life-Cycle Management Of Wind Turbines, Proceedings of the 4th Workshop on Civil Structural Health Monitoring (CSHM-4). Berlin, Germany, November 6, 2012

Jaishi, B, Ren, W. 2005 Structural Finite Element Model Updating Using Ambient Vibration Test Results, Journal of Structural Engineering, Vol. 131, No. 4, April 1, 2005

Lus, H, Betti, R and Longman, RW. 1999 Identification of Linear Structural Systems Using Earthquake Induced Vibration Data, *Earthquake Engineering and Structural Dynamics*, 28, 1449-1467.

Safak, E. 1991 Identification of Linear Structures Using Discrete-Time Filters, *Journal of Structural Engineering ASCE,* 117:10, 3064-3085.

Yun CB and Shinozuka, M. 1980 Identification of non-linear structural dynamical systems, *Journal of Structural Mechanics,* 8(2): 187-203.