Chapter 8
Model Updating Techniques for Structures Under Seismic Excitation

Serdar Soyoz

Abstract Vibration-based system identification of structures has become a well-established way of condition assessment with the main steps of modal analyses and tracking any change in the identified modal parameters. In addition, Finite Element Model (FEM) updating is crucial especially for damage detection and reliability estimation under seismic excitation. In literature, it was shown that seismic reliability of structures with and without FEM updating turned out to be different. The main idea behind FEM updating is minimizing the difference between modal parameters obtained from FEM and system identification by changing values of parameters such as Young's modulus of materials and soils springs constants. Real-world examples of FEM updating cover bridges, tall buildings and historical structures.

Keywords System identification · FEM updating · Seismic excitation

8.1 Introduction

In Structural Health Monitoring (SHM) field, mainly four objectives; namely, determination of damage existence, location, severity and consequences exist. The first steps have been investigated extensively and related research outcome can be found in literature; however, little research exists on the estimation of damage consequences. The main reason for this gap is due to need of FEM and verification of results obtained from FEM and system identification.

FEM updating allows both validation of FEM representing intact structure without any damage and obtaining damage levels and locations during a seismic event. Validation of FEM of intact structure is important because using validated FEM, engineers can perform more reliable assessments under future earthquake scenarios. On the other hand, FEM updating under a seismic event allows determination of

---

S. Soyoz (✉)
Department of Civil Engineering, Bogazici University, Bebek,
34342 Istanbul, Turkey
e-mail: serdar.soyoz@boun.edu.tr

M. P. Limongelli and M. Çelebi (eds.), *Seismic Structural Health Monitoring*, Springer Tracts in Civil Engineering, https://doi.org/10.1007/978-3-030-13976-6_8

damage on the structure. After obtaining FEM of the damaged structures, seismic reliability estimation can also be performed to estimate remaining life of structures.

Although there are more detailed methods as explained in following sections, FEM updating is performed mainly by minimizing the difference between the identified modal frequencies and shapes and the corresponding ones obtained from FEM. The minimization is achieved by changing structural parameters in the model. Selection of structural parameters to be changed plays a crucial role in FEM updating. The first step in the updating procedure should be the construction of a detailed model which especially includes elements for soil domain. This can be the whole soil medium or soil springs representing the medium. There are two reasons to include soil springs in the model. The first reason is that without the soil springs; FEM updating procedure would artificially soften the structure to minimize difference between experimentally and analytically obtained modal properties. The other reason is that without soil springs, higher seismic demands would occur on structural members especially at foundation level artificially.

After obtaining a representative FEM, the main structural parameter to be changed can be considered as Young's modulus of structural material. Under ambient vibration and seismic excitation, structural stiffness would be different. This difference is important if linear models are used for seismic performance assessment because effective stiffness values obtained from system identification during seismic excitation should be used in FEM. However; current practice of seismic performance assessment is based on nonlinear analyses; therefore, updating stiffness values based on ambient vibration survey and let nonlinear modeling take care of the damage progress leads to accurate results.

The other parameter which can change modal frequencies is structural mass. It is considered to be known (or determined) exactly; therefore, it is not treated as a structural parameter to be changed in FEM updating process. However, in the seismic analysis of special structures such as offshore platforms, one should be careful with marine growth effects which changes structural mass significantly.

Therefore, Young's modulus and soil stiffness values are mostly used as parameters to be changed so that error between identified and analytical modal values is minimized. Theoretically, different combinations of structural and soil stiffness values would give the same modal frequencies; however, utilization of mode shapes in addition to modal frequencies in FEM updating process would solve this uniqueness problem. Also, one should pay attention to the ranges of soil and structure stiffness values i.e. they should be within reasonable ranges in terms of engineering judgment and existing literature.

In FEM updating, mostly modal frequencies and shapes are chosen as parameters for which error is minimized. On the other hand, identification of actual damping and assigning it in the model is important to obtain a representative FEM. Identified damping ratios based on seismic and ambient vibration measurements would be different; however, similar to discussion related with stiffness values, ambient vibration-based identified damping values would be representative in a nonlinear seismic performance assessment because hysteretic damping would already be taken care of by nonlinear modeling itself.

In the following sections; first, summary of previous studies on FEM updating is presented. Here, the focus is on FEM updating of real-world structures or large scale models in conjugation with seismic excitations. Afterwards, different FEM updating methods are discussed. Finally, case studies on FEM updating of a tall building and a stone arch bridge are presented.

8.2 Previous Studies

Most of the studies in literature demonstrate that dynamic characteristics obtained from FEM and vibration data exhibit remarkable differences. The assumptions made in development of FEM due the uncertainties in structures are one of the main reasons of these differences. By the virtue of vibration-based system identification, these differences can be minimized and more reliable seismic assessments at design stage become possible through FEM updating procedures.

There is significant amount of FEM updating studies in literature especially related with mechanical and aerospace engineering which mainly considers small scale models. Comprehensive background on FEM updating can be found in Friswell and Mottershead [1] from mechanical engineering perspective. Doebling et al. [2] and Carden and Fanning [3] summarizes vibration-based condition monitoring methodologies including FEM updating techniques.

There are studies on FEM updating such as Ghanem and Shinozuka [4] and Beck and Katafygiotis [5] which mainly establishes theoretical framework. There are other significant studies which deal only with calibration or validation of FEM using ambient vibration such as Brownjohn et al. [6], Caetano et al. [7]. Also, studies such as Boroschek and Yanez [8] validate modeling assumptions by comparing dynamic properties obtained analytically and experimentally. In addition, these procedures can also be developed for damage detection by correlating FEM's with the results of vibration measurements acquired from damaged or deteriorated structures such as Teughels and De Roeck [9] and Soyoz and Feng [10].

Following literature focuses on civil engineering related examples which especially considers realistic models and seismic inputs. Literature summary and the following sections mainly present studies on

- FEM updating with linear models for seismic performance assessment.
- FEM updating with linear models for damage detection.
- FEM updating using nonlinear models.

8.2.1 FEM Updating with Linear Models for Seismic Performance Assessment

Venture and Ding [11] presents FEM updating of a 52 story steel frame tall building using seismic measurements from Sierra Madre and Northridge earthquakes. They both compare the modal frequencies and shapes obtained from FEM and identification and also time history response of the structure and sensor readings. In the second phase of the study, they perform nonlinear time history and pushover analyses for seismic performance assessment of the building.

Skolnik et al. [12] investigated 15-story steel building which suffered damage to exterior brick veneer during 1994 Northridge event and afterwards was instrumented with permanent monitoring system by USGS. Authors identified modal properties based on ambient vibration and low level seismic response and then, they updated FEM by considering a fictitious stick element which adds flexural rigidity to the structure. Afterwards, they carried out performance assessment of the updated model under Northridge earthquake.

Casarin and Modena [13] carried out both non-destructive testing and ambient vibration survey to determine to physical and global dynamic values of Reggio Emilia Cathedral. They also calibrated FEM and estimated seismic vulnerability of the structure.

Ntotsis et al. [14] developed a methodology for FEM updating based on Bayesian framework and applied it to two existing bridges in Greece for the purpose of condition monitoring. They used ambient vibration and low-level seismic input data to verify their methodology. Structural parameters to be updated were chosen as Young's modulus and moment of inertia of the deck and pier.

Pela et al. [15] investigated the seismic performance of two masonry arch bridges, a stone masonry bridge with brick-made vaults and a stone masonry bridge with concrete made vaults. The structural capacity, which was obtained through pushover analysis, was compared with the demand of the earthquake ground motion described by an inelastic response spectrum. In the study, core tests allowed the determination of stone and mortar characteristics. Additionally, based on ambient vibration test results, Young's modulus, unit weight and Poisson's ratio of masonry materials were further tuned.

Ramos et al. [16] carried out modal and structural identification of two historical structures. They presented the relation between the identified frequency and environmental conditions such as temperature and humidity. They modeled the structure in DIANA with solid elements which have the same Young's modulus values for different portions of the tower in the initial model but different values after model updating. A minor earthquake occurred and response of the structure was collected by permanent monitoring system but no change on the identified modal frequencies was observed.

De Matteis and Mazzolani [17] presented ambient vibration test results and FEM of a masonry structure. Based on identified modal values, a refined FEM was developed. Afterwards, they carried out limit analysis to identify the most vulnerable parts of the structure providing an estimation of its actual seismic vulnerability. Finally, a shaking-table test on a 1/5.5-scale model was carried out both to investigate the dynamic response of the structure and to validate FEM of the test model.

Soyoz et al. [18] extended their previous study on the identification of stiffness values of a bridge model and obtained failure probabilities under severe earthquake inputs. They obtained failure probabilities at different level of damage states and examined the effects of identification on reliability estimation.

Butt and Omenzetter [19] presented system identification and modeling of a three story RC building monitored for two years. Modal identification was conducted for 50 earthquake response records considering soil-structure interaction. Afterwards, FEM of the building was developed to investigate the influence of various structural and non-structural components such as cladding and partitions, as well as soil underneath the foundation and around the building, on the building dynamics. FEM was then calibrated using a sensitivity based technique by tuning the stiffness of structural concrete, soil and cladding.

Ozer and Soyoz [20] performed a study which presents FEM updating using linear systems based on error minimization. In the same study, reliability estimation at each damage level was carried out for non-updated and updated model using fragility curves. To obtain fragility curves, nonlinear analyses under input motions with increasing intensities for each damage state were performed.

Karmakar et al. [21] studied seismic vulnerability of Vincent Thomas suspension bridge. FEM of the bridge was developed and verified by identified modal values obtained from ambient vibration and a moderate earthquake response data. In addition, FEM was further validated by simulating the dynamic response of the Northridge earthquake and comparing with the recorded response. Finally, nonlinear time history analyses were performed and the ductility demands of critical sections were presented in terms of fragility curves.

Costa et al. [22] carried out modal updating of three masonry arch bridges based on the modal parameters obtained from operational modal analysis. The material properties of the initial FEM were obtained from material tests and results of previous similar studies. Even though significant amount of material tests was conducted, there were still differences between the analytical and identified modal properties. Therefore, at the final step, each FEM was tuned by adjusting the material properties and soil conditions based on the modal values obtained from dynamic tests.

Sevim et al. [23] investigated near and far fault ground motion effects on a masonry arch bridge in terms of displacement and stress values. Dynamic properties of the bridge were inferred from ambient vibration test by using Frequency Domain Decomposition method. Researchers preferred linear FEM of the structure due to high uncertainties associated with the nonlinear modeling of masonry. FEM was calibrated according to identified modal parameters by changing only boundary conditions.

8.2.2 FEM Updating with Linear Models for Damage Detection

Yu et al. [24] determine an updated FEM of a reinforced concrete building which was damaged during 1994 Northridge earthquake. They used frequency response functions and modal frequencies for FEM updating. The building was excited using a linear inertial shaker located at the roof. Flexural stiffness values of structural members, modal damping ratios, and translational and rotational mass values were chosen as the updating parameters. They validated the updated FEM by comparing the predicted and measured dynamic responses under sine-sweep vibration test. These results indicate that the updated model replicates the dynamic behaviour of the building reasonably well. Furthermore, the updated stiffness factors correlate well with the observed building damage patterns.

Gentile and Saisi [25] identified modal values of a masonry bell tower with the presence of major cracks. They carried out ambient vibration test on a 74 m high masonry tower and assigned different material properties for damaged and undamaged zones. Calibration of FEM was achieved by changing the material properties of the tower and they show that material properties of damaged zones after FEM updating process are significantly lower than other parts of the tower as expected.

Soyoz and Feng [26] developed an extended Kalman filtering (EKF) method and applied it to instantaneously identify elemental stiffness values of a structure during damaging seismic events based on vibration measurement. Identification of the structural elemental stiffness enables location as well as quantification of structural damage. The elemental stiffness values of the structure were instantaneously identified in real time during the damaging earthquake excitations using the EKF method. The identified stiffness degradations and their locations agreed well with the structural damage observed by visual inspection and strain measurements. More importantly, the seismic response accelerations analytically simulated using the instantaneous stiffness values thus identified agreed well with the measured accelerations, demonstrating the accuracy of the identified stiffness.

Weng et al. [27] presented a methodology for FEM updating of structural parameters including connection rigidities using non-linear least-square technique. The proposed method was verified through a shaking table test of a 1/4-scale six-story steel frame structure by loosening the connection bolts for damage simulations and a two-story RC frame subject to different levels of ground excitations back to back.

Moaveni et al. [28] tested a full-scale seven-story reinforced concrete building section on the UCSD-NEES shake table such that the building experienced progressive damage. Ambient vibration tests and low-amplitude white noise base excitations were applied to the building at each level of damage to identify modal parameters of the building. Afterwards, sensitivity-based FEM updating strategy was used to detect, localize and quantify damage. Damage in the building was identified based on the change in Young's modulus. Identified damage correlated well with the observed damage at the bottom two stories of the building. It was noted that the assumption of linear systems used for identification purposes was progressively violated with increasing level of excitation.

Ji et al. [29] presented full-scale shaking table test study which considers realistic seismic damage on a model of a high-rise steel building. Damage to concrete slabs, beam-column connections, and nonstructural walls were generated by three levels of ground motion. Dynamic properties of the model were obtained using white noise response and change in these properties before and after damage were estimated. A numerical study was also conducted to validate the vibration-based identification studies.

Binda et al. [30] identified the modal values of Spanish Fortress after L'Aquila Earthquake using ambient vibration data and indicated that the structure had the unitary vibration mode in spite of high level of damage probably due to provisional emergency steel cables.

Cimellaro et al. [31] identified modal values of a tower and a damaged palace after L'Aquila Earthquake using different output identification methods such as frequency domain decomposition, random decrement, eigensystem realization algorithm. They also updated FEM by changing material properties.

Moaveni et al. [32] identified progressive damage, using an equivalent linear finite-element model updating strategy, on a two-thirds-scale, 3-story, 2-bay, infilled RC frame was tested on the UCSD-NEES shake table. The building experienced progressive damage and ambient vibration tests and low-amplitude white noise base excitations were applied to the building at each level of damage to identify modal parameters of the building. A sensitivity-based FEM updating strategy was employed to detect, locate, and quantify damage (as a loss of effective local stiffness) based on the changes in the identified effective modal parameters. The results indicated that proposed method could reliably identify the location and severity of damage observed in the tests.

Belleri et al. [33] investigated the damage assessment of a three-story half-scale precast concrete building tested on the UCSD–NEES shake table. Modal parameters of the structure at different damage states have been identified from white-noise and earthquake response with the assumption that the structure was in linear range. The changes in the identified modal parameters were correlated with the observed damage.

Bassoli et al. [34] presented FEM updating procedure for a masonry tower that suffered seismic damage. Mechanical properties of the tower in its current damaged state were investigated. Different material properties have been assigned corresponding to the regions where damaged masonry existed.

Ubertini et al. [35] presented the change in identified modal frequencies of a historical bell tower located in Italy due to 2016 Central Italy earthquakes. They predicted and compared the nonlinear response of the structure using a calibrated FEM and observed that decrease in identified modal frequencies agreed well with the ones obtained from non-linear FEM.

8.2.3 FEM Updating with Non-linear Models

Asgarieh et al. [36] proposed a methodology to update hysteretic behavior of structural elements by minimizing an error function which was defined as the difference between experimentally identified time-varying modal parameters and those obtained from FEM at selected time instances. The proposed methodology was applied on a three-story RC frame with masonry infill tested on a shaking table with increasing intensities of input motions. Asgarieh et al. [37] applied the same methodology to a different test model, a seven story shear wall building. In addition to proposed method, they applied unscented Kalman filter approach and validated that both approach predicted the nonlinear behavior satisfactorily.

Chatzis et al. [38] developed a methodology to transform time domain identification results into physical parameters and compared them with the ones obtained from Unscented Kalman Filter. They also verified their method on the small-scale shaking table model where input was different earthquake motions and damage was simulated by removing structural elements.

8.3 Methods

FEM updating can be performed based on pre and post event measurements and a linear system or seismic measurement and a non-linear system. In this chapter, only FEM updating methods using linear methods are covered.

The first method is based on error minimization and second method is sensitivity-based updating. These two methods are principally the same; mainly, the first one searches the minimum error for a given set of parameters whereas the second approach updates the search domain itself. The first method is more robust and more applicable to real-world structures if the boundaries of the parameters to be changed for FEM updating purposes are estimated confidently.

Although FEM updating has the potential of improving knowledge in structural parameters, problems which may be encountered during updating process should be tackled with care. For instance, local minima, difficulties in mode matching, low sensitivity of global modes to local structural features and high uncertainty on identified parameters are some of the possible problems in FEM updating.

8.3.1 Error Minimization-Based FEM Updating

In this method, an error function as given in Eq. (8.1), compares similarity between modal frequencies and mode shapes obtained from identification and FEM.

$$E(\alpha) = \sum \left(k_i . \left[\frac{\left(f_i^* - f_i\right)}{f_i^*} \right]^2 + h_i . [1 - MAC_i]^2 \right) \tag{8.1}$$

α is stiffness correction coefficient,
i is mode number,
k_i is the weighting coefficient for *ith* is modal frequency,
h_i is the weighing coefficient for *ith* modal assurance criteria,
f_i^* is the measured modal frequency of *ith* mode,
f_i is the simulated modal frequency of *ith* mode,
MAC_i is the modal assurance criteria for *ith* mode shape.

Weighing coefficients can be determined by considering contribution (e.g. mass participation ratio) of different modes to dynamic behavior of the structure. For the purpose of FEM updating, a Matlab code, which automatically creates FEM by changing the values of the chosen structural parameters within pre-determined limits, can be utilized. This code will obtain the modal parameters of different non-updated models and obtain the error based on Eq. (8.1), and the FEM resulting in minimum error will be chosen as the updated model.

8.3.2 Sensitivity-Based FEM Updating

Sensitivity-based methods update structural parameters by minimizing an error function expressing the difference between FEM predicted and experimentally identified dynamic properties such as natural frequencies and mode shapes. Optimum solutions of the problem are reached through sensitivity-based constrained optimization algorithms. Main steps of this method are given in Eqs. (8.2–8.6).

$$z_{ID} = \left(\omega_{ID}^1, \phi_{ID}^1, \omega_{ID}^2, \phi_{ID}^2, \ldots \omega_{ID}^r, \phi_{ID}^r\right) \tag{8.2}$$

$$z_{FEM} = \left(\omega_{FEM}^1, \phi_{FEM}^1, \omega_{FEM}^2, \phi_{FEM}^2, \ldots \omega_{FEM}^r, \phi_{FEM}^r\right) \tag{8.3}$$

$$\delta z = S\delta\theta \tag{8.4}$$

$$\delta z = z_{ID} - z_{FEM} \tag{8.5}$$

$$\delta\theta = \theta_a - \theta \tag{8.6}$$

where

S is the sensitivity matrix
$\delta\theta$ is the perturbation in structural parameters

δz is the error in the measured output
θ_a is the actual structural parameters that reproduce $z_{ID.}$

Sensitivity matrix is the first derivative of the eigenvalues and mode shapes with respect to the parameters evaluated at the current parameter estimate. Calculation of sensitivity matrix can be formulated as follows:

$$\left[K - w_j^2 M\right]\phi_j = 0 \overset{\partial/\partial\theta}{\Rightarrow} \frac{\partial K}{\partial\theta}\phi_j + \frac{\partial\phi_j}{\partial\theta}K = \frac{\partial w_j^2}{\partial\theta}M\phi_j + \frac{\partial M}{\partial\theta}w_j^2\phi_j + \frac{\partial\phi_j}{\partial\theta}w_j^2 M \tag{8.7}$$

$$\Rightarrow \left[K - w_j^2 M\right]\frac{\partial\phi_j}{\partial\theta} = -\left[\frac{\partial K}{\partial\theta} - w_j^2\frac{\partial M}{\partial\theta} - M\frac{\partial w_j^2}{\partial\theta}\right]\phi_j \tag{8.8}$$

Premultiplying Eq. (8.7) with θ_j^T, we obtain

$$\frac{\partial w_j^2}{\partial\theta} = \phi_j^T\left[\frac{\partial K}{\partial\theta} - w_j^2\frac{\partial M}{\partial\theta}\right]\phi_j \tag{8.9}$$

Equations (8.8) and (8.9) give derivatives of frequency and mode shape with respect to structural parameters.

The ultimate objective in sensitivity based FEM updating is to minimize $J = \varepsilon^T\varepsilon$.

$$\varepsilon = \delta z - S\delta\theta \tag{8.10}$$

$$\Rightarrow J = (\delta z - S\delta\theta)^T(\delta z - S\delta\theta) \tag{8.11}$$

$$= \delta z^T\delta z - 2\delta\theta^T S^T\delta z + \delta\theta^T S^T S\delta\theta \tag{8.12}$$

$$\frac{\partial J}{\partial\delta\theta} = 0 \; gives \; \delta\theta = \left[S^T S\right]^{-1} S^T\delta z \tag{8.13}$$

$$\theta_{j+1} = \theta_j + \delta\theta \tag{8.14}$$

8.4 Case Studies

In this section, two case studies are presented. The first one is related with a tall building for which modal identification, FEM updating and seismic analysis under predicted earthquake motions are discussed. In the second case study, similar framework is presented for a stone arch bridge.

For these two examples, FEM updating is performed based on ambient vibration measurements. The motivation of such a study is to estimate seismic performance of structures based on updated FEM.

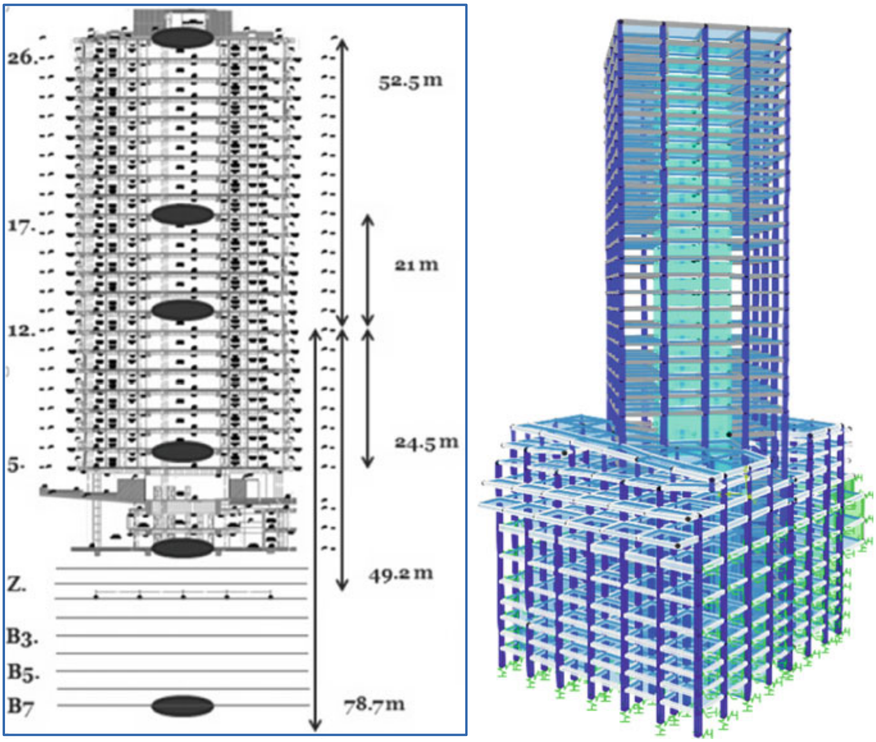


Fig. 8.1 Sensor layout and FEM of the building

Table 8.1 Identified and analytical frequencies

Mode	Identification (Hz)	Updated FEM (Hz)	Non-updated FEM (Hz)
1	0.59	0.59	0.50
2	2.15	2.03	1.77
3	3.18	3.18	2.62

8.4.1 Case1-Tall Building

Kaynardag and Soyoz [39] demonstrated the importance of FEM updating based on system identification on the seismic performance of a tall building. For this purpose, a twenty-six story, core-wall tall building in Istanbul was instrumented with thirteen accelerometers (Fig. 8.1). Modal values were identified using EFDD algorithm. FEM of the building was updated based on the identified modal shapes and frequencies by changing structural parameters such as Young’s modulus of the building, soil spring values and interaction with the adjacent buildings. Table 8.1 and Fig. 8.2 compare the results obtained from identification and updated and non-updated FEMs.

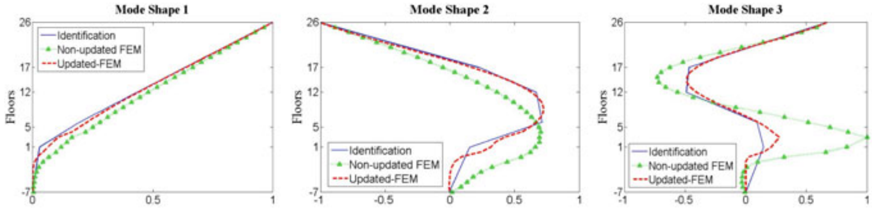


Fig. 8.2 Identified and analytical mode shapes

Table 8.2 Change in structural parameters

Model definition	Fundamental frequency (Hz)
Initial model	0.50
Initial model + Interaction with adjacent building	0.56
Updated FEM	0.59

FEM of the building was created in SAP2000 software platform based on the design drawings and site investigations. The shear walls, columns and beams were modeled as beam elements and the slabs were explicitly modeled.

Decoupling of modes in linear analyses demonstrate that the first three modes produce significant portion of seismic demand on the structure. Therefore, only the first three modes are considered in the updating process and weighing coefficients are determined as 0.60, 0.25 and 0.15 respectively.

Table 8.2 presents the change in fundamental frequency of the building due to calibration of the model. Here, the important point is that before starting updating process a very detailed FEM was established. For example, interaction with adjacent structures were taken into account which was not a common practice both in engineering and research; however, it shows that it has a significant effect on fundamental frequency and exclusion of such an effect would lead to wrong updating results. After completion of FEM updating, Young's modulus, horizontal spring and vertical spring values were changed to 1.15, 3 and 5 times of their initial values respectively.

Afterwards, NLTH analyses were performed with the updated and the non-updated FEM to observe the influence of the identified modal frequencies and shapes. In order to observe the performance of the building in a possible earthquake caused by the North Anatolian Fault, probability density functions in terms of inter-story drift ratios were established (Fig. 8.3). And by setting a threshold value failure probabilities for the updated and non-updated models were obtained. This kind of probabilistic assessment of seismic performance of tall building with the integration of vibration-based identified modal values comprises a unique approach. In addition, the investigation of the results of this study reveals the importance of the detailed modeling and selecting an appropriate viscous damping ratio for tall buildings.

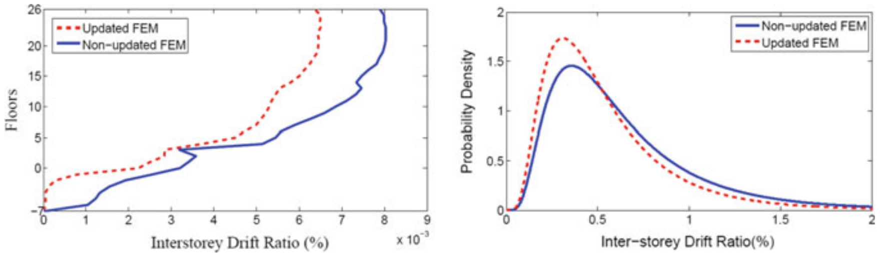


Fig. 8.3 Drift ratios for updated and non-updated models

8.4.2 *Case 2-Stone Arch Bridge*

Aytulun et al. [40] presented system identification and seismic performance assessment of a masonry arch bridge located on the railway route which is on the northeastern part of Turkey (Fig. 8.4). 41 masonry arch bridges were registered as historical and needed to be preserved on the route. On the other hand, the railway line passes through North Anatolian Fault, resulting in high seismic demand on bridges. Therefore, seismic assessment of the bridges was carried out by finite element analysis; however, masonry structures such as stone arch bridges have significant uncertainties in terms of material properties, boundary conditions and modeling assumptions. As a result, it becomes almost unavoidable to perform dynamic identification tests to validate FEM.

Modal properties of twelve bridges such as modal frequencies, mode shapes and modal damping ratios were identified through vibration measurements collected under ambient conditions, impact loading and train passage. Figure 8.5 shows one representative bridge and its sensor layout. Based on identified modal parameters, FEM of the bridges were updated to obtain actual values of Young's modulus of masonry and soil. FEM updating procedure was performed by minimizing the difference between experimental and analytical modal properties.

In the process of FEM updating procedure, initial FEM of the bridge was established using ANSYS software. Studies in literature verified that changes in frictional coefficient did not affect modal parameters of the stone arch bridge. Therefore, modal calibration was conducted by changing only Young's modulus of masonry and soil. Table 8.3 presents identified, non-updated, and updated modal frequencies of the bridge. Elasticity modulus of masonry was changed from 7.80 to 14.05 GPa and Elasticity modulus of soil was changed from 20 to 30 GPa (soil formation was identified as rock formation in soil investigation reports)

Afterwards, seismic performance assessment of a representative bridge was carried out using ANSYS software. In the analyses, macro modeling approach was followed to develop homogenized behavior of stone and mortar. Seismic performance of the bridge was obtained by nonlinear time history analyses. It was also observed that tensile strength capacity was reached on spandrel walls which may result in a probable local failure (Fig. 8.6).

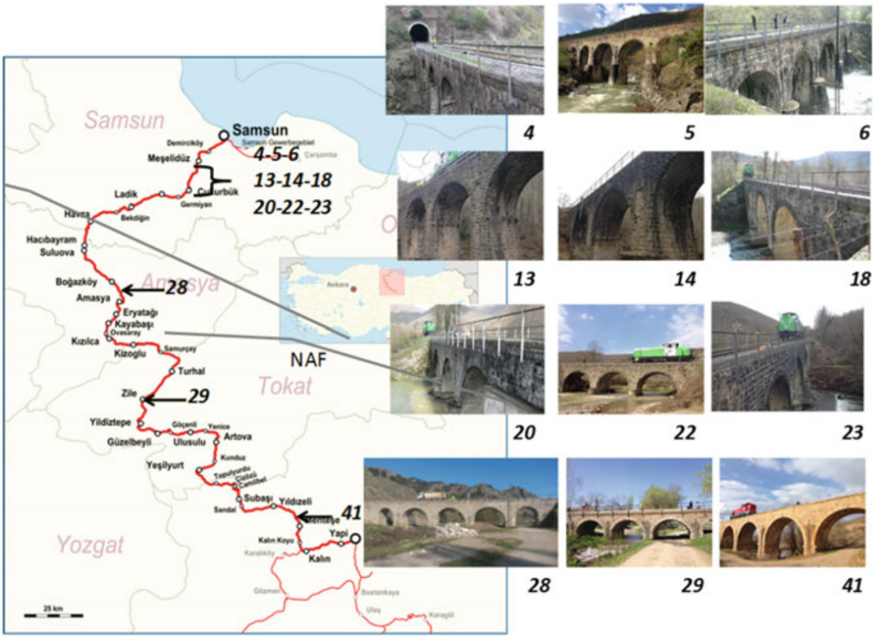


Fig. 8.4 Bridges on the railway

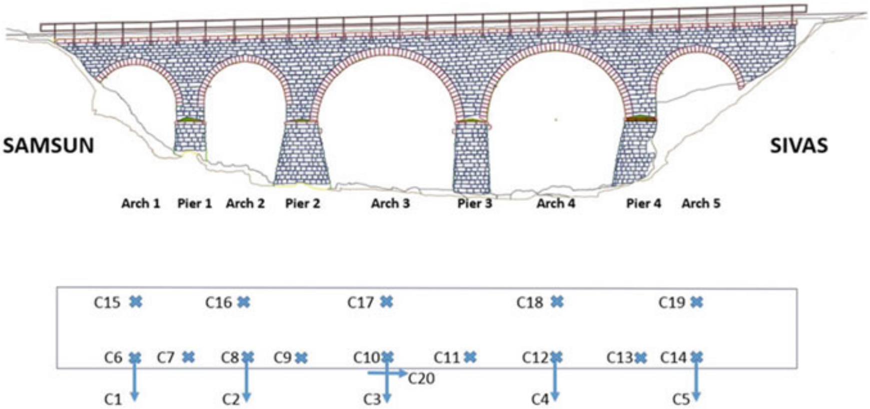
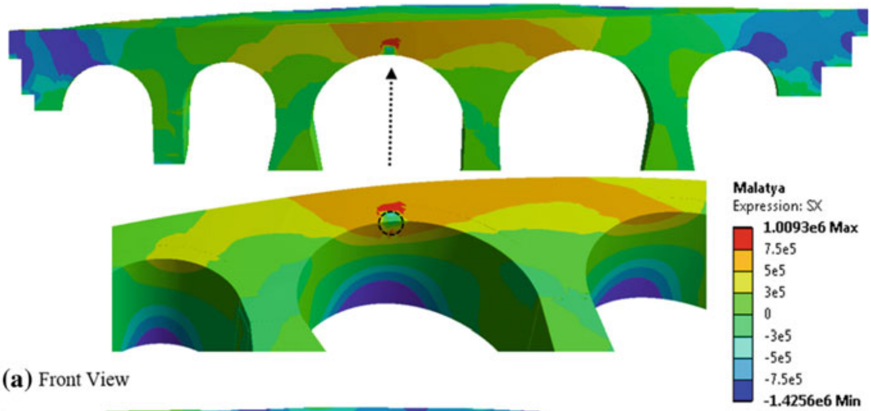


Fig. 8.5 Sensor layout on the bridge

Table 8.3 Identified and analytical frequencies

Mode	Identification (Hz)	Updated FEM (Hz)	Non-updated FEM (Hz)
1. Trans	8.31	7.17	5.37
2. Trans	10.84	10.83	8.11
3. Trans	13.18	15.65	11.72
1. Vert	20.02	22.90	17.15
2. Vert	24.32	25.05	18.77



(a) Front View

(b) Back View

Fig. 8.6 Stress distribution (Pa) in longitudinal direction

8.5 Conclusions

In this chapter, summary of FEM updating of civil structures under seismic excitation is given. FEM updating can be used both for damage detection or validation of intact model to perform more reliable seismic performance assessment. It was shown that estimated reliability of structures for updated and non-updated cases would be different.

FEM updating is performed mainly by minimizing the difference between the identified modal frequencies and shapes and the corresponding ones obtained from FEM. The minimization is achieved by changing structural parameters in the model. The main difference between civil engineering and other engineering field in terms of FEM updating is that civil structures have significantly more degrees-of-freedom and relation with soil medium which imposes an important boundary condition; therefore, FEM updating methodologies should be chosen properly.

Along this line, detailed localization and detection of damage can be achieved only for some types of structures such as reinforced concrete highway bridges which have less number of degrees-of-freedom. On the other hand, FEM updating of structures such as tall buildings may only deal with the validation of FEM in terms of modal values. Even this level of validation will lead to obtaining a more representative FEM and therefore more reliable seismic performance assessment would be possible.

Acknowledgements Case studies presented in the chapters were possible with contributions of Mr. Korkut Kaynardag and Mr. Emre Aytulun.

References

1. Friswell MI, Mottershead JE (1995) Finite element model updating in structural dynamics. Kluwer Academic Publishers, Boston
2. Doebling SW, Farrar CR, Prime MB, Shevitz DW (1996) Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: a literature review. Los Alamos National Laboratory, LA-13070-MS
3. Carden EP, Fanning P (2004) Vibration-based condition monitoring: a review. Struct Health Monit 355–377
4. Ghanem R, Shinozuka M (1995) Structural system identification. J Eng Mech 121(2):255–273
5. Beck JL, Katafygiotis LS (1998) Updating models and their uncertainties. J Eng Mech 124(4):455–467
6. Brownjohn JMW, Pan TC, Deng XY (2000) Correlating dynamic characteristics from field measurements and numerical analysis of a high-rise building. Earthq Eng Struct Dyn 29:523–543
7. Caetano E, Cunha A, Gattulli V, Lepidi M (2008) Cable-deck dynamic interactions at the International Guadiana Bridge: on-site measurements and finite element modeling. Struct Control Health Monit 15:237–264
8. Boroschek LR, Yanez FV (2000) Experimental verification of basic analytical assumptions used in the analysis of structural wall buildings. Eng Struct 22:657–669
9. Teughels A, De Roeck G (2004) Structural damage identification of the highway bridge Z24 by FE model updating. J Sound Vib 278:589–610
10. Soyoz S, Feng MQ (2009) Long-term monitoring and identification of bridge structural parameters. Comput-Aid Civ Infrastruct Eng 24:82–92
11. Ventura CE, Ding Y (2000) Linear and nonlinear seismic response of a 52-storey steel frame building. Struct Des Tall Build 9:25–45
12. Skolnik D, Lei Y, Yu E, Wallace JW (2006) Identification, model updating, and response prediction of an instrumented 15-story steel-frame building. Earthq Spectra 22(3):781–802
13. Casarin F, Modena C (2008) Seismic assessment of complex historical buildings: application to Reggio Emilia Cathedral, Italy. Int J Archit Heritage 2:304–327
14. Ntotsis E, Karakostas C, Lekidis V, Panetsos P, Nikolaou I, Papadimitriou C, Salonikos T (2009) Structural identification of Egnatia Odos bridges based on ambient and earthquake induced vibrations. Bull Earthq Eng 7:485–501
15. Pela L, Aprile A, Benedett A (2009) Seismic assessment of masonry arch bridges. Eng Struct 31:1777–1788
16. Ramos LF, Marques L, Lourenco PB, De Roeck G, Campos-Costa A, Roque J (2010) Monitoring historical masonry structures with operational modal analysis: two case studies. Mech Syst Signal Process 24:1291–1305

17. De Matteis G, Mazzolani FM (2010) The Fossanova Church: seismic vulnerability assessment by numeric and physical testing. Int J Archit Heritage 4:222–245
18. Soyoz S, Feng MQ, Shinozuka M (2010) Remaining capacity estimation based on structural identification results. J Eng Mech 136(1):100–106
19. Butt F, Omenzetter P (2014) Seismic response trends evaluation and finite element model calibration of an instrumented RC building considering soil–structure interaction and non-structural components. Eng Struct 65:111–123
20. Ozer E, Soyoz S (2015) Vibration-based damage detection and seismic performance assessment of bridges. Earthq Spectra 31(1):137–157
21. Karmakar D, Ray Chaudhuri S, Shinozuka M (2015) Finite element model development, validation and probabilistic seismic performance evaluation of Vincent Thomas suspension bridge. Struct Infrastruct Eng 11(2):223–237
22. Costa C, Arede A, Costa A, Caetano E, Cunha A, Magalhaes F (2015) Updating numerical models of masonry arch bridges by operational modal analysis. Int J Archit Heritage 9:760–774
23. Sevim B, Atamturktur S, Altunişik AC, Bayraktar A (2016) Ambient testing and seismic behavior of historical arch bridges under near and far fault ground motions. Bull Earthq Eng 14:241–259
24. Yu E, Taciroglu E, Wallace JW (2007) Parameter identification of framed structures using an improved finite element model-updating method. Earthquake Eng Struct Dyn 36:619–660
25. Gentile C, Saisi A (2007) Ambient vibration testing of historic masonry towers for structural identification and damage assessment. Constr Build Mater 21:1311–1321
26. Soyoz S, Feng MQ (2008) Instantaneous damage detection of bridge structures and experimental verification. Struct Control Health Monit 15(7):958–973
27. Weng JH, Loh CH, Yang JN (2009) Experimental study of damage detection by data-driven subspace identification and finite-element model updating. J Struct Eng 135(12):1533–1544
28. Moaveni B, He X, Conte JP, Restrepo JI (2010) Damage identification study of a seven-story full-scale building slice tested on the UCSD-NEES shake table. J Struct Eng 32:347–356
29. Ji X, Fenves GL, Kajiwara K, Nakashima M (2011) Seismic damage detection of a full-scale shaking table test structure. J Struct Eng 137:14–21
30. Binda L, Modena C, Casarin F, Lorenzoni F, Cantini L, Munda S (2011) Emergency actions and investigations on cultural heritage after the L'Aquila earthquake: the case of the Spanish Fortress. Bull Earthq Eng 9:105–138
31. Cimellaro GP, Pianta S, De Stefano A (2012) Output modal identification of ancient L'Aquila city hall and civic tower. J Struct Eng ASCE 138:481–491
32. Moaveni B, Stavridis A, Lombaert G, Conte JP, Shing PB (2013) Finite element model updating for assessment of progressive damage in a 3-story infilled RC frame. J Struct Eng 139(10):1665–1674
33. Belleri A, Moaveni B, Restrepo JI (2014) Damage assessment through structural identification of a three-story large-scale precast concrete structure. Earthq Eng Struct Dyn 43:61–76
34. Bassoli E, Vincenzi L, D'Altri AM, Miranda S, Forghieri M, Castellazzi G (2017) Ambient vibration-based finite element model updating of an earthquake-damaged masonry tower. Struct Control Health Monit [online]
35. Ubertini F, Cavalagli N, Kita A, Comanducci G (2018) Assessment of a monumental masonry bell-tower after 2016 Central Italy seismic sequence by long-term SHM. Bull Earthq Eng 16:775–801
36. Asgarieh E, Moaveni B, Stavridis A (2014) Nonlinear finite element model updating of an infilled frame based on identified time-varying modal parameters. J Sound Vib 333:6057–6073
37. Asgarieh E, Moaveni B, Barbosa AR, Chatzi E (2017) Nonlinear model calibration of a shear wall building using time and frequency data features. Mech Syst Signal Process 85:236–251

38. Chatzis MN, Chatzi EN, Smyth AW (2015) An experimental validation of time domain system identification methods with fusion of heterogeneous data. Earthq Eng Struct Dyn 44:523–547
39. Kaynardag K, Soyoz S (2017) Effect of identification on seismic performance assessment of a tall building. Bull Earthq Eng 15:3227–3243
40. Aytulun E, Soyoz S, Karcioglu E (2018) Comparison of nonlinear time history and pushover analyses for the assessment of stone arch bridges. In: 16th European conference on earthquake engineering, Thessaloniki, Greece, 17–21 June