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FINITE ELEMENT MODEL UPDATING AND DAMAGE IDENTIFICATION OF A SCHOOL BUILDING IN SANKHU, NEPAL

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Abstract

In this paper, a finite element model of a school building is calibrated in its linear range using the identified modal parameters from recordings of its ambient vibration. The structure, located in Sankhu, Nepal, is a four-story masonry-infilled reinforced concrete frame which experienced severe damage during the Gorkha earthquake on April 25th, 2015. The authors visited the country, in June 2015, to conduct a post-earthquake assessment for certain structures including the case study building. To achieve this purpose, post-earthquake ambient vibration data were collected to be used for performance assessment of the building. The ambient acceleration response of the structure was recorded using 12 uniaxial accelerometers at two setups. The modal properties of the building (i.e., natural frequencies, mode shapes, and damping ratios) are identified using an operational modal analysis method, namely the Natural Excitation Technique combined with the Eigen-system Realization Algorithm. An initial finite element model of the structure is created based on the gathered design information as well as site inspections. To account for the effects of earthquake induced damage on the effective stiffness of the model, severely damaged structural elements are removed from the model. The initial model is then updated through a finite element model updating approach by minimizing an objective function. The objective function is defined as the difference between identified and model estimated modal parameters and a regularization term. To achieve this goal, different structural elements are grouped together and their equivalent stiffness parameters (i.e., effective elasticity moduli) are updated through a global optimization approach. Performance of the updating approach is studied when considering different regularization terms in the objective function. Finally, the obtained changes in the updating parameters are compared to the observed damage in the building.

Keywords: FE model updating, Damage identification, Infilled RC frame structure, 2015 Nepal earthquake

1. Introduction

Finite element (FE) models are commonly used for performance assessment of civil structures. Use of available information about the geometry and material properties of structural components contributes to the reduction of modeling errors and results in more reliable models. Model updating based on measured vibration data can further improve the accuracy of FE models [1, 2]. The updated FE models can then be used for reliable performance assessment of structures at their current state. In the application of FE model updating approach, certain dynamic features of the model such as modal parameters are matched with those from the experimental data. Successful applications of FE model updating for structural performance assessment and damage identification can be found in the literature [3-6].

The magnitude 7.8 Gorkha earthquake occurred 80 km northwest of Kathmandu (district of Gorkha), Nepal on April 25, 2015 (Fig. 1). A magnitude 7.3 major aftershock also occurred on May 12 with its epicenter 80 km northeast of Kathmandu along with several medium level aftershocks hitting the region for a few months after the main earthquake. As a catastrophic event, the Gorkha earthquake caused numerous structural failures resulting in thousands of fatalities and injuries in the affected areas. More information on the seismic performance of structures during the Gorkha earthquake can be found in [7]. To perform a post-earthquake assessment for certain structures affected by the earthquake, the authors visited the country two months after the main event. Ambient vibration recordings along with data from advanced sensing technologies (LiDAR) were collected to be used for the identification of structural damage due to the earthquake [8].

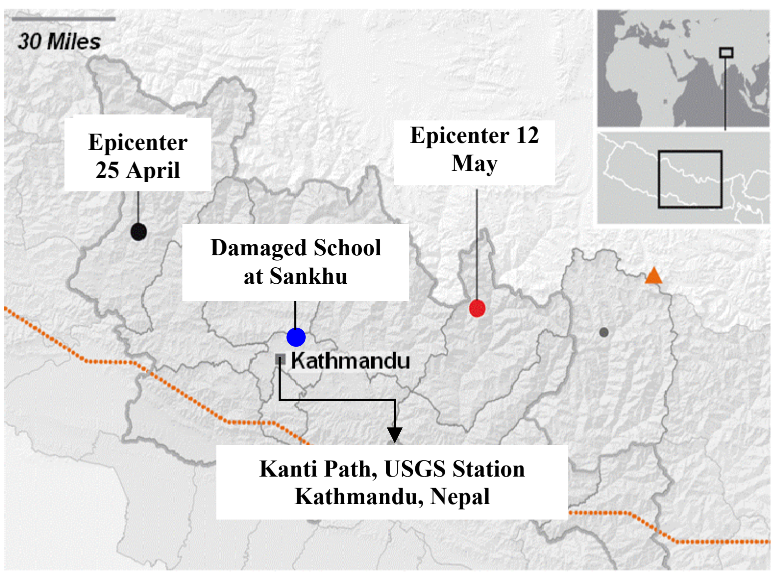
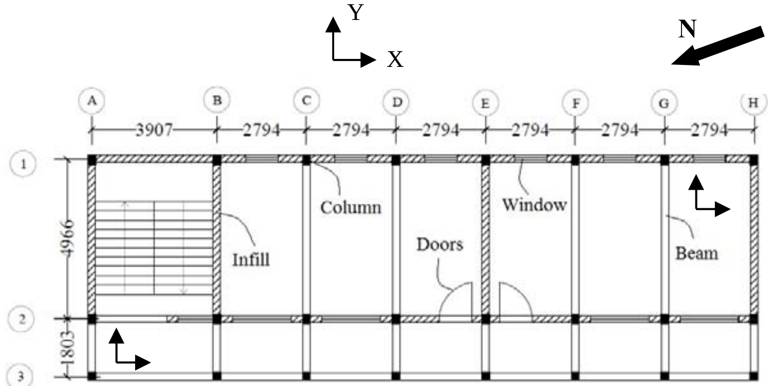


Fig. 1 – Location of the school building and epicenters of the main earthquake and aftershock (Credit: Dr. Andre Barbosa, Oregon State University)

The focus of this paper is FE model updating of a four-story infilled reinforced concrete school building, located in Sankhu, Nepal, which was severely damaged during the Gorkha earthquake. Modal parameters of the building are identified from post-earthquake ambient vibration recordings. An initial finite element model is created based on the in-situ inspections as well as the gathered primary design information. The intensely damaged structural elements are removed from the initial model to represent the damaged state of the building after experiencing the earthquake. Similar structural components are grouped together to reduce the number of updating parameters, and a global optimization approach is employed in the model updating process. The elasticity modulus of structural elements are updated in order to fit the model estimated modal properties to those extracted from ambient measurements. The changes in the updating parameters can represent the seismic damage in different structural components. These changes are compared to the observed damage after the earthquake and its aftershocks.

2. Description of the Building and Observed Damage

The four-story school building located in Sankhu, Nepal has a masonry-infilled reinforced concrete frame structural system with seven bays in the north-south direction and two bays in the west-east direction as displayed in Fig. 2. There is a balcony in the west side of the building which is serving as a corridor and supported by bare RC columns. In the east side of the building, most of the infill walls have wide and relatively short windows, while in the west side of the building, the walls have either larger windows or doors. As it can be seen from plan view of the structure (Fig. 2b), there is a staircase located in the north end of the building which develops some torsional irregularity in the structure.



(a) (b)

Fig. 2 – The case study school building at Nepal: (a) west view, (b) typical plan view

The building was intensely damaged due to the Gorkha earthquake and its main aftershocks. As it is presented in Fig. 3, major damage was observed in different structural components, specifically in the first story of the building during the post-earthquake assessment of the structure. Shear failure was observed in the columns of the first story towards the south side of the building, which can be attributed to the torsion induced by the irregularity due to the staircase on the north side (Fig. 3b and Fig. 3c). The damaged columns revealed improper reinforcement detailing and also inadequate spacing of stirrups along the column. Extensive damage was also observed in the beam-column connections, and in some cases, the infill panels were found to be separated from the bounding RC elements.

(a) (b) (c)

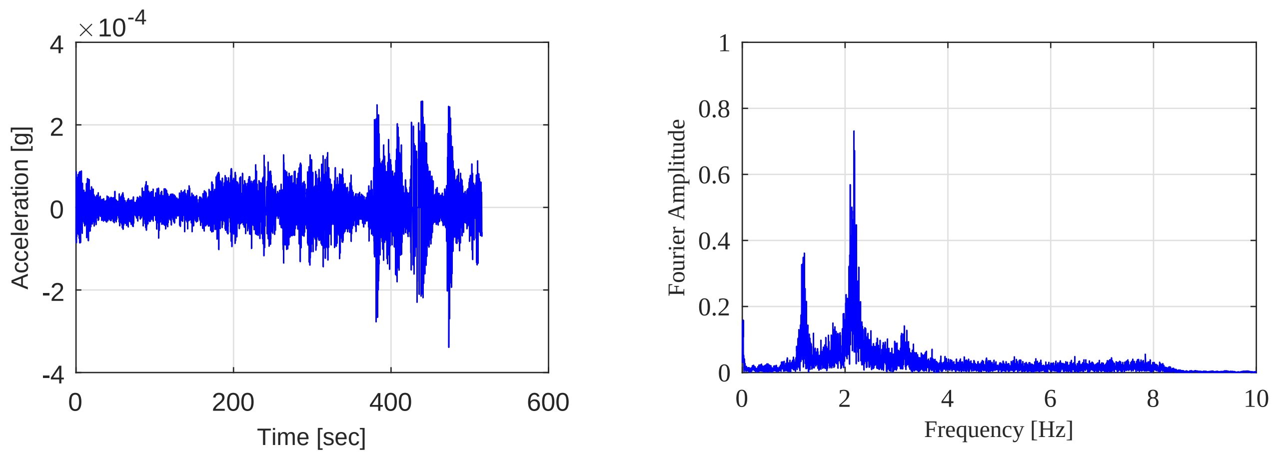
Fig. 3 – Damaged components at the first story of the building due to the Gorkha earthquake: (a) infill wall H12, (b) column G1, (c) column H1

3. System Identification

3.1 Ambient measurements and data processing

The ambient acceleration response measured through two experiment setups is used for system identification of the building. In the first experiment setup, a total of 54 minutes of ambient acceleration response was recorded. The sampling rate of 2048 Hz is used for acceleration measurements. In this setup, 12 accelerometers were installed at three floor levels: roof, 4^{th} floor, and 3^{rd} floor. At each floor level, 4 accelerometers were installed at two opposite corners of the building, namely north-west and south-east corners, to measure the acceleration response at two perpendicular directions, defined as X and Y directions (see Fig. 2b). In the second experiment setup, accelerometers were installed at the 3^{rd}, 2^{nd}, and the 1^{st} floor levels. In this setup, a total of 45 minutes of ambient acceleration data was acquired.

In the application of system identification, every 9 minutes of data are used for estimation of modal parameters, resulting in 6 sets of modal parameters for the first experiment setup and 5 sets of modal parameters for the second experiment setup. The acceleration time histories of each data set were filtered in the frequency range of 1.0 - 8.0 Hz using a Finite Impulse Response (FIR) filter of order 4096. The filtered response was down-sampled to 256 Hz to increase the computational efficiency. Fig. 4a shows a sample filtered time-history measured at the north-west corner of the third floor during the first experiment setup, while Fig. 4b displays the Fourier Amplitude Spectrum of the same record.



(a) (b)

Fig. 4 – Filtered and down-sampled ambient measurement: (a) acceleration time history, (b) Fourier amplitude spectrum

3.2 NExT-ERA method for system identification

The Natural Excitation Technique combined with the Eigensystem Realization Algorithm (NExT-ERA) [9, 10] is employed to identify the natural frequencies, damping ratios, and mode shapes of the structure from the ambient vibration measurements. The NExT-ERA method is an output-only parametric system identification approach which estimates the modal parameters of a linear dynamic system from its measured response to a broadband excitation. This method has been successfully applied for system identification of civil structures when the input excitation measurements are not available [10-12].

In order to employ the NExT-ERA method for system identification of the building, the auto-correlation and cross-correlation of the filtered ambient data were estimated as the inverse Fourier transformation of power spectral density and cross spectral density functions of the data. The spectral density functions were computed using equal length Hanning windows with 50 percent overlap based on the Welch method [13]. Two reference channels were used in the system identification to account for motions in both X and Y directions. In the first experiment setup, the acceleration measurements in the X-direction of the 3rd story and Y-direction of the 2nd story, both at south-east corner, were assumed to be the reference channels. In the second experiment setup, the acceleration measurements in the X-direction of the 1st story and Y-direction of the 2nd story, both at the same corner, were used as the reference channels. The estimated auto correlation and cross correlation are then used to establish a block Hankel matrix of size (12×400)×(400×2) for Eigensystem Realization Algorithm. This algorithm is based on the singular value decomposition of Hankel matrix to estimate the underlying state-space matrices from which the modal parameters of the system are identified [14]. A stabilization diagram is used to select an appropriate system order for identification of the stable modes. In the stabilization diagram, a mode is considered stable if the identified natural frequencies do not vary at increasing system orders. A sample stabilization diagram is illustrated in Fig. 5. The implemented system identification approach is applied to all data sets from the two experiment setups resulting in 11 sets of identified modal parameters. The first three stable vibration modes are reported in this study. The average of identified natural frequencies and damping ratios, along with their corresponding Coefficient of Variation (CoV), are reported in Table 1 for each setup separately. It is observed that the identified natural frequencies exhibit little variability (i.e., low CoV values) at each experiment setup, and the results from the two experiment setups are also very consistent. However, the identified damping ratios demonstrate a larger level of variability, either at each experiment setup (i.e., low CoV values at each experiment), or across the two setups.

The identified mode shapes from the two setups are combine to form the mode shapes of building along its full height. To achieve this, the average mode shapes of each setup are normalized to a common component on the 3rd story, namely the X component at north-west corner on the 3rd story. The combined mode shapes initially had 20 components, however, the size of mode shape vectors are reduced to 11 components after removing the measurements from noisy channels.

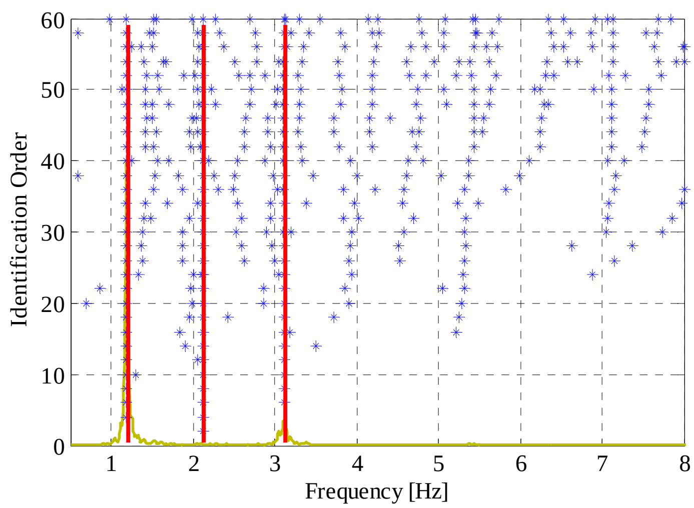


Fig. 5 – A simple stabilization diagram for identification of natural frequencies

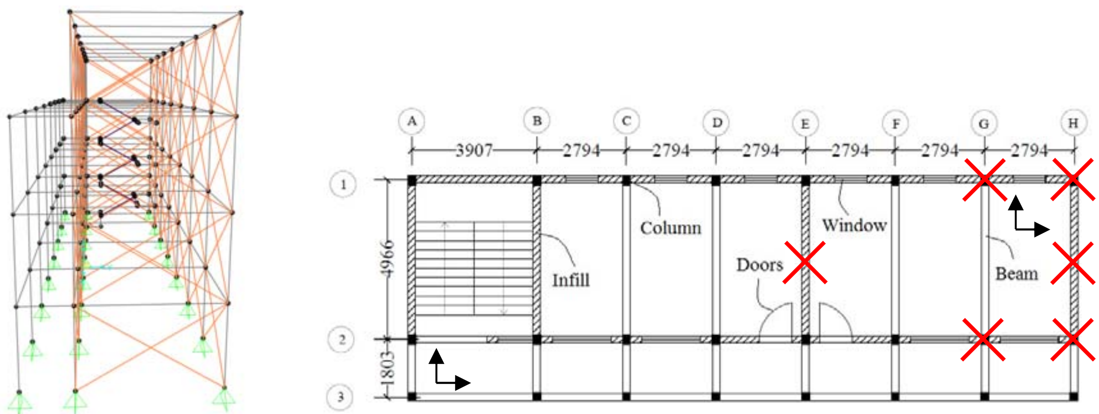
Table 1 - Statistical properties of identified modal parameters of the building

Experiment setup	Mode	Natural frequency [Hz]		Damping ratio [%]	
		Mean	CoV [%]	Mean	CoV [%]
A	1	1.18	0.7	2.2	15.3
	2	2.16	1.1	2.2	17.6
	3	3.15	1.1	3.0	36.2
B	1	1.19	0.5	1.8	32.5
	2	2.14	2.0	1.5	42.0
	3	3.19	0.6	2.4	18.4

4. Initial Finite Element Model

A nonlinear finite element model of the school building at Sankhu, has been developed in the structural analysis software, OpenSEES [15] adopting beam-column elements for the RC frame and strut elements for the infill panels [16, 17]. The geometry of the model is based on in-situ measurements and the material properties are according to the tests reported in [18]. The compressive strength is considered as 1.40 ksi and 0.50 ksi, while the elastic modulus as 2022 ksi and 370 ksi for concrete and masonry, respectively. Simplified curves [17] representing the lateral force- drift behavior are developed for every single-story, single-bay sub-assemblies in the building based on a detailed parametric study [19].

Although the model can simulate the nonlinear response of the building, it is only considered at its linear range in this study. The initial stiffness of both the RC members and infills are reduced to 40% of the nominal values to account for the cracked section condition prior to the earthquake [20]. In addition, the fully damaged components are removed since they are not expected to affect the structural response to ambient excitation that is considered here. The removed elements correspond to the infill panels (H12 and E12) and the RC columns (H1, H2, G1 and G2) of the first story that were severely damaged as indicated in Fig. 6.



(a) (b)

Fig. 6 – Initial finite element model: (a) diagonal strut model, (b) removed structural components

The natural frequencies and mode shapes of the model are compared with the identified modal parameters from the ambient vibration recordings in Table 2. The comparison indicates that the numerically obtained frequencies are relatively close to the identified frequencies for the first three modes. In all cases, the frequencies estimated from the model are higher than the identified frequencies. This may be because the initial FE model does not account for the partial damage in the structural members except for those which were fully removed. The model updating results can provide a measure of damage (as loss of stiffness) in the updated elements. The Modal Assurance Criterion (MAC) values comparing the mode shapes obtained from the FE model and the identified mode shapes are also reported in Table 2. The average MAC value is 0.96 indicating very good agreement between the model estimated and the experimentally identified mode shapes. Fig. 7 plots the modes shapes of the building obtained from the FE model.

Table 2 – Comparison of modal parameters of model with identification data

Mode	Natural Frequencies [Hz]		Normalized Freq. Error [%]	MAC
	System ID	Model		
1	1.19	1.30	9.5	1.00
2	2.15	2.69	25.2	0.95
3	3.17	3.39	6.9	0.95
Avg.	-	-	13.8	0.96

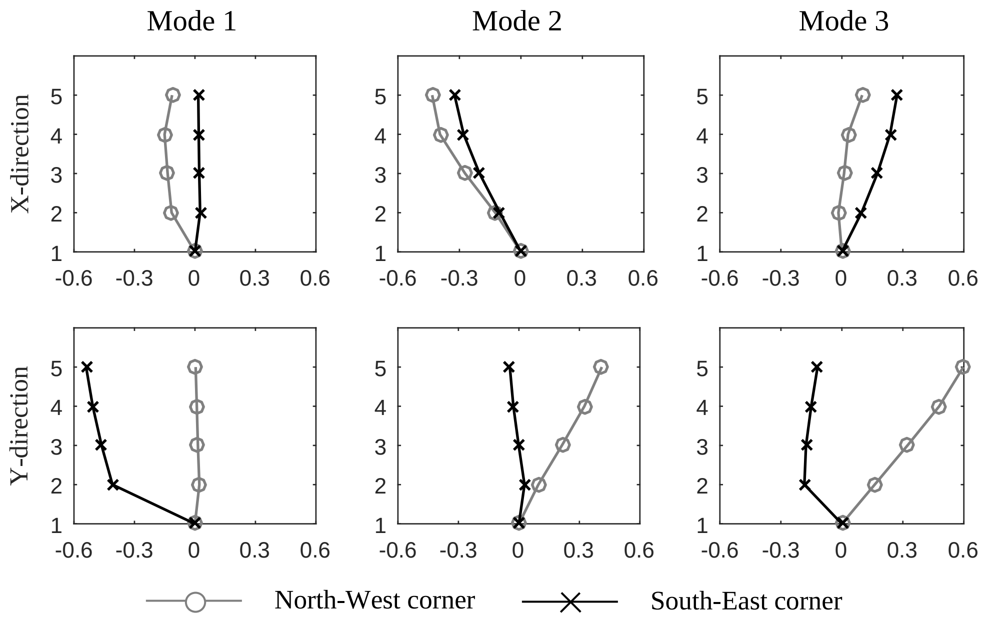


Fig. 7 – Mode shapes of the building from FE model

5. Finite Element Model Updating

5.1 Model updating process

The first step in implementing the model updating is to determine the updating parameters. The type (geometric and/or material properties) and the number of updating parameters play significant roles in the performance of model updating process. In this study, only material properties are used as updating parameters, and since the initial FE model is used here only in its linear range of response, the elastic modulus (*E*) of different structural components are updated. Thus, the updating parameter for the k^{th} structural component is defined as

$$\theta_k = \frac{E_k^{updated}}{E_k^{initial}} \tag{1}$$

Considering the large number and variety of structural components in the model, the components which have similar material properties or have comparable effect on structural response are grouped together to reduce the number of updating parameters. In this study, moduli of elasticity of infill walls are selected as the updating structural components because their stiffness is estimated with high level of uncertainty in the initial FE model. Furthermore, the severely damaged columns and walls have been manually removed in the initial model; however, some infill walls particularly on the first and second stories have experienced slight to moderate damage. The model updating process can be used to determine the extent of damage as the loss of stiffness or elasticity moduli. As it is shown in Fig. 8, there are 7 types (type A to type G) of infill walls on each story of the building. It is not practical to consider each types of the walls at each story as an individual updating component. Therefore, for the first and second stories, the walls on the west side of the building are grouped together at each story, the walls on the east side of the building are grouped in a similar way, and the infill walls in east-west direction are grouped together (Fig. 8). Since the structural components on the upper stories have less impact on the response of the structure, all the walls on the third and fourth stories are grouped together for each story. Finally, one updating parameter is considered for all the concrete columns and beams in the building, resulting in nine groups of structural components in the model updating process. The updating parameters consist of: all the columns and beams in the building (1 parameter), infill walls on the first story (3 parameters), infill walls on the second story (3 parameters), all the infill walls on the third story (1 parameter), and all the infill walls on the fourth story (1 parameter).

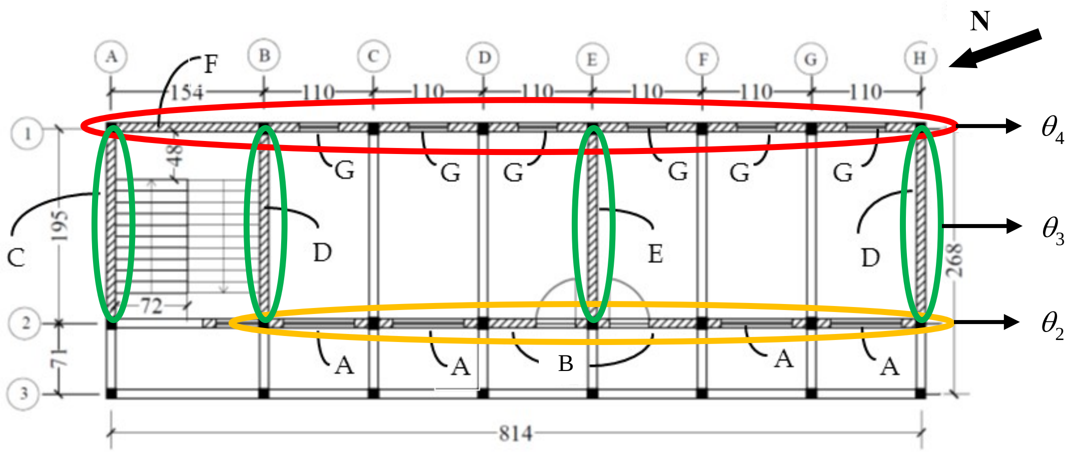


Fig. 8 – Updating groups of infill wall components on the first story

After a sensitivity study of modal parameters to the updating parameters in the initial FE model, the model updating is implemented as an optimization process which minimizes the difference between model-predicted natural frequencies and mode shapes with their experimentally identified counterparts for the first three vibration modes. Genetic Algorithm (GA) is used as a global optimization method [21] to minimize the objective function which can be expressed as

$$G(\boldsymbol{\theta}) = \mathbf{r}(\boldsymbol{\theta})^T \mathbf{W}\mathbf{r}(\boldsymbol{\theta}) + \alpha \left\|1 - \boldsymbol{\theta}\right\|^2 \tag{2}$$

where $\boldsymbol{\theta}$ is the vector of updating parameters, $\mathbf{W}$ refers to a diagonal weighting matrix, α is the regularization factor, and $\mathbf{r}(\boldsymbol{\theta})$ denotes the residual vector between the model predicted and identified natural frequencies and mode shape components.

$$\mathbf{r}(\boldsymbol{\theta}) = \begin{bmatrix} \mathbf{r}^f(\boldsymbol{\theta}) \\ \mathbf{r}^s(\boldsymbol{\theta}) \end{bmatrix} \tag{3}$$

in which

$$\mathbf{r}^f(\boldsymbol{\theta}) = \left[\frac{f_i(\boldsymbol{\theta}) - \tilde{f}_i}{\tilde{f}_i}\right], \quad \mathbf{r}^s(\boldsymbol{\theta}) = \left[\frac{\boldsymbol{\Phi}_i^l(\boldsymbol{\theta})}{\boldsymbol{\Phi}_i^r(\boldsymbol{\theta})} - \frac{\tilde{\boldsymbol{\Phi}}_i^l}{\tilde{\boldsymbol{\Phi}}_i^r}\right] \quad l \neq r, \quad i \in \{1,2,3\} \tag{4}$$

where $\mathbf{r}^f(\boldsymbol{\theta})$ and $\mathbf{r}^s(\boldsymbol{\theta})$ are natural frequency and mode shape residuals, respectively, $f_i(\boldsymbol{\theta})$ and $\tilde{f}_i$ denote model-predicted and identified natural frequencies of the i^{th} mode, and $\boldsymbol{\Phi}_i(\boldsymbol{\theta})$ and $\tilde{\boldsymbol{\Phi}}_i$ represent the model-predicted and identified mode shape vectors, respectively.

To study the impact of the regularization factor, the model updating is initially performed without applying a regularization factor (i.e., $\alpha = 0$), and also using three different regularization factors of 0.01, 0.02, and 0.05. The updated FE models from these four cases are called Model R0, Model R1, Model R2, and Model R3, respectively.

5.2 Discussion of results

The natural frequencies of the first three vibration modes for the four updated FE models are compared to the quantities from system identification and initial FE model in Table 3. It is observed that frequencies from all the updated models match the identified natural frequencies. The MAC values between models estimated and experimentally identified mode shapes are also provided in Table 3. It can be seen that all the MAC values (three vibration modes for each updated model) are higher than 0.99 which indicates excellent match between mode shapes of the updated FE models and their identified counterparts. Note that this accuracy is only achieved after removing data from the noisy sensors. Another interesting observation is that increasing the regularization weight will not deteriorate the goodness-of-fit of updated models.

Table 3 – Comparison of modal parameters of updated models with identification data

		System ID	**Initial model**	**Model R0**	**Model R1**	**Model R2**	**Model R3**
Freq. [Hz]	Mode 1	1.19	1.30	1.19	1.19	1.19	1.19
	Mode 2	2.15	2.69	2.15	2.15	2.15	2.15
	Mode 3	3.17	3.39	3.17	3.17	3.17	3.17
MAC	Mode 1	-	1.00	1.00	1.00	1.00	1.00
	Mode 2	-	0.95	0.99	0.99	0.99	0.99
	Mode 3	-	0.95	0.99	0.99	0.99	0.99
	Avg.	-	0.96	0.99	0.99	0.99	0.99

The updated parameters (i.e., updated-to-initial ratios of the elasticity moduli) for the four updated FE models are listed in Table 4. It is observed that updated parameters of Model R0, which is updated with no regularization factor, can be very different from those of the other three models, while Model R1-R3 which are updated using regularization factors of 0.01, 0.02, and 0.05, respectively, have relatively close updated parameters. Particularly, considering the updated parameters for the walls of the fourth story (θ_9), it is observed that without applying a regularization factor, an updated parameter of 2.20 is obtained indicating that the elasticity moduli of all the walls on the fourth story should increase by 120%. This effect does not seem to be realistic considering the low impact of walls of the top story on the structural response. However, it can be seen that by increasing the regularization factors, the updating parameter becomes closer to 1.00, especially for Model R2 and Model R3, which is more realistic based on the observed damage. The average change of updated parameters for each model is computed and reported in Table 4.

$$\Delta\theta_{avg} = \frac{\sum_{k=1}^{9} \left|1-\theta_k\right|}{9} \tag{5}$$

As expected, the average change of updating parameters decrease as the regularization factor is increased. It can also be seen that the regularization factors of 0.02 and 0.05 provide very similar updating parameters in Model R2 and Model R3 with average change of 0.26 and 0.24, respectively. Hence, either of these two models is recommended to be used as the final updated model. In this study, Model R3 is selected as the final updated FE model.

Table 4 – Updated stiffness parameters in calibrated FE models

Updating parameter	Structural component	Initial elasticity modulus [ksi]	Updated ratio of elasticity modulus			
			Model R0	Model R1	Model R2	Model R3
θ_1	Columns and beams	467	1.20	1.15	1.15	1.18
θ_2	1st story (frame A) 1st story (frame B)	250 294	0.29	0.28	0.28	0.28
θ_3	1st story (frames C, D, and E)	417	0.87	1.04	1.06	0.99
θ_4	1st story (frames F and G)	313	0.28	0.37	0.30	0.27
θ_5	2nd story (frame A) 2nd story (frame B)	250 294	0.36	0.66	0.96	0.98
θ_6	2nd story (frames C, D, and E)	417	0.73	0.74	0.81	0.78
θ_7	2nd story (frames F and G)	313	0.92	0.46	0.67	0.78
θ_8	3rd story (frame A) 3rd story (frame B) 3rd story (frames C, D, and E) 3rd story (frames F and G)	250 294 417 313	1.16	1.21	0.88	1.04
θ_9	4th story (frame A) 4th story (frame B) 4th story (frames C, D, and E) 4th story (frames F and G)	250 294 417 313	2.20	0.85	1.02	1.00
$\Delta\theta_{avg}$	Average change of updated parameters		0.46	0.34	0.26	0.24

From the updated parameters of Model R3, it is observed that updated elasticity moduli of the frames A and B on the first floor (corresponding to θ_2) and the frames F and G on the same floor (corresponding to θ_4) are significantly reduced compared to the initial FE model with factors of 0.28 and 0.27, respectively. Since a 60% reduction has been considered for the initial stiffness of the RC member and infill panels to account for the cracked cross sections, the low updating factors can potentially reflect the induced damage due to the earthquake. Fig. 9 shows one of the frames of type A and the frame type F on the first floor. The separation of infill wall A from the beam-column system and the major cracks on the wall F clearly indicate some reduction of the effective stiffness for those elements. Hence, the model updating can provide an average measure of induced damage in the updated structural components. The model updating results also indicate minor damage for the frames of types C, D, E, F, and G on the second story (corresponding to θ_6 and θ_7), while the results suggest underestimated stiffness values for columns and beams in the initial FE model (i.e., updated parameter θ_1 is higher than 1.0). For all the other groups of structural components, the updated parameters are close to 1.0 indicating that these elements most likely have not experienced major damage during the earthquake.

(a)

(b)

Fig. 9 – Damaged infill wall components on the first story: (a) frame A, (b) frame F

6. Conclusions

The paper presents finite element model updating of a four-story masonry-infilled reinforced concrete frame building based on its post-earthquake ambient vibration data. The building which is located in Sankhu, Nepal, was intensely damaged during 2015 Gorkha earthquake. Modal properties of the building are extracted through ambient measurements performed after the earthquake, and an initial FE model is created based on the design layouts and site inspections. The severely damaged structural components are eliminated from the initial model. The elasticity modulus of structural elements are updated in order to match the modal parameters of the FE model to those identified from ambient recordings. Different structural components are grouped together to reduce the number of updating parameters. The updated FE models provide very good agreement with the system identification data. Furthermore, the updated parameters indicate moderate damage in certain infilled walls, particularly on the first and second stories of the building. The updating results do not show considerable change in the stiffness of components on the third and fourth floors, representing no significant damage in those stories, which is consistent with the field observations. The estimated loss of stiffness in different structural components also allows for calibrating the nonlinear FE model. In this case, the hysteretic models can be calibrated so that the loss of stiffness of different components match the identified loss of stiffness. Such calibrated models of the building can then be employed for more detailed seismic performance assessment and response prediction of the building.

7. Acknowledgements

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