# Model Updating and Damage Detection of a 3D Printed Model Frame

Onur Ozturkoglu, Doga Altunevlek Gulsah Olgun and Ozgur Ozcelik

***Abstract*—**Finite element modelling is the one of most commonly used method for structural analysis. However, there are some discrepancies between experimentally identified and finite element solutions due to modelling assumptions. Therefore, initial finite element model needs to be calibrated according to experimental results. Damage can occur in structures due to earthquake, wind, fire, corrosion, fatigue etc. effects. Reliable damage detection is important for the utilization of the structure after damaging events. In this study, two story-one bay frame is numerically modelled with using finite elements and modal analysis is performed using this model. For calibrating the initial numerical model, shake table tests are conducted on the 3D printed model. Using natural vibration frequencies and mode shapes, initial finite element model of the 3D printed model is calibrated by varying modulus of elasticity within an optimization problem. It is assumed that modulus of elasticity is the uncertain parameter. After that a controlled damage is introduced on one of the first story columns and shake table tests are again performed on the damaged model. Finally using the same optimization based model updating technique, the introduced damage is detected.

***Keywords*—** Model updating, damage identification, finite element modeling, 3D printed model.

## I. Introduction

Modern and highly sophisticated finite-element (FE) procedures are available for structural analysis, yet practical application often reveals considerable discrepancy between analytical prediction and test results. The way to reduce this discrepancy is to modify the modelling assumptions and parameters until the correlation of analytical predictions and experimental results satisfies practical requirements. Classically, this is achieved by a trial and error approach, which is generally time consuming and may not be feasible in some cases. Thus, model updating procedures have been developed to update the parameters of analytical models using test data. In particular, modal information (natural frequencies and mode shapes) extracted from measured response data has found broad application as a target for model parameter updating.

Development of methodologies for accurate and reliable condition assessment of civil structures have also become increasingly important. System identification and damage detection techniques constitute a promising field with widespread applications in civil engineering. The system identification (SI) is classified as static SI [5]- [8], frequency domain SI [8-10] and time domain SI [9]-[10]. Even time and frequency domain SI algorithms utilize from the same data, transformation to frequency domain is widely used due to revealing nature of modal information. By using this process the numerical model of the system can be updated using the experimental results.

There is also great interest in the development of damage detection techniques through the model updating method. There are number of techniques based on changes in a structures modal properties. Cawley and Adams [11] utilized from changes in the natural frequencies together with a FE model in order to determine the local damage. Experiments conducted by Biswas et al. [12] on a highway bridge also showed that changes in the natural frequencies alone could be used to detect the damage. In recent years, many methods have been introduced to detect the location and extent of damage in structural systems [1]- [4]. Detecting actual structural damage due to earthquake, impacts or strong wind actions can provide important information on the operational state and structural safety of the structures concerned.

In this study an example to illustrate the mentioned concepts by using changes in structural and modal properties a 3D printed frames is used. Shake table tests were performed on the 3D printed model and system identification, model updating and damage detection procedures are applied to detect the introduced damage. This particular work has been done during a graduate class as a term project, and has been found very useful in teaching system and damage identification as well as basic structural dynamics concepts.

## II. Methodology

During the modeling process, an analyst must deal with uncertainties on how to correctly model the geometry, material properties, or boundary conditions. In general, inaccuracy comes with approximation. Thus, we can never be sure of the model until the results have been validated with experimental data.

In order to estimate the modal properties (related to mass, stiffness and damping) of the system experimentally, a system identification method is used. In this method, acceleration

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response is recorded in time domain. Then, the numerical model is updated according to the experimental data. In the model updating process there is an error function expressing differences between numerically calculated and experimentally identified modal data. Minimizing this error function with least square errors approach calibrates the design variables. For this purpose FEMtools software is used. In FEMtools optimization of the model is based on a cost effective approach and sensitivity based model updating. In model updating the key step of the accuracy is selection of the parameter to be updated. In order to see if selected modal parameters are sensitive to changes of at least some of selected model parameter, sensitivity analysis is conducted.

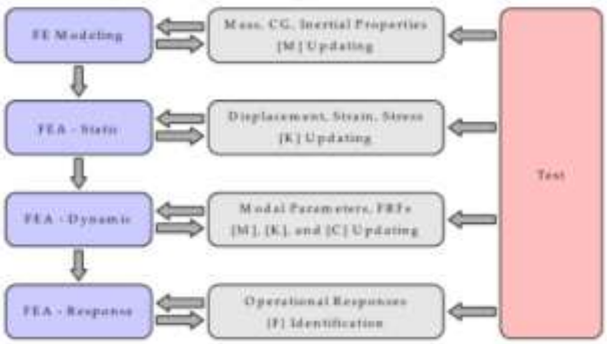


Fig. 1 The optimal updating sequence

The operational model analysis (OMA) requires a good deal of expertise and lot of instrumentation. Noise sources or any other factors can be various and are not always under control. However, the technological breakthroughs of the last few decades made OMA very popular. It has come along from single channel systems to multi-channel configurations with powerful software featuring like graphics and animation. In our study, Artemis software is used for this purpose. For finite element model (FEM), SAP2000 software is used.

This useful procedure can also be used in structural damage identification. An updated FE model using the modal data corresponding to a damage state reflects the observed dynamic characteristics of real damaged structure. When this model is compared against a reference model of the real damaged structure, structural damages can be detected.

The major phases in damage identification are

- Identifying the existence of damage (correlation analysis)
- Identifying the location of the damage (error localization, sensitivity analysis)

Estimating the magnitude of the damage (model updating)

## III. Case Study

### A. Model Properties

#### 1) Geometrical Properties

A 3D printer model 'Ultimaker 2' is used to print the 3D frame. The printer uses PLA filament as material and maximum length is 90 meter for one 3D model. Dimensions of a model cannot exceed 20 cm for all x, y, and z dimensions.

Using these information, initial SAP2000 model is generated. For SI and FEM updating; two story-one bay frame is conceived. Modal analysis is performed with analytical model. After deciding model dimensions, 3D drawing of model is prepared by using AutoCAD for 3D printer input (Figure 2-3). 3D model is printed at DEPARK laboratory and it took 45 hours (Figure 4) to finalize printing. Due to the tolerance limits of the 3D printer used, the printed model was a little different from the first numerical model. SAP2000 model is revised according to measurement of the real 3D printed model. Final dimensions are shown below.

- Max height of the model (with base) = 196 mm
- Max length of the model = 196 mm
- Max width of the model = 97 mm
- Column section sizes = 5 mm (in plane) x 20 mm (out of plane)
- Slab section sizes = 97 mm x 10 mm
- Base section sizes = 46 mm x 10 mm
- Base holes diameter = 14 mm

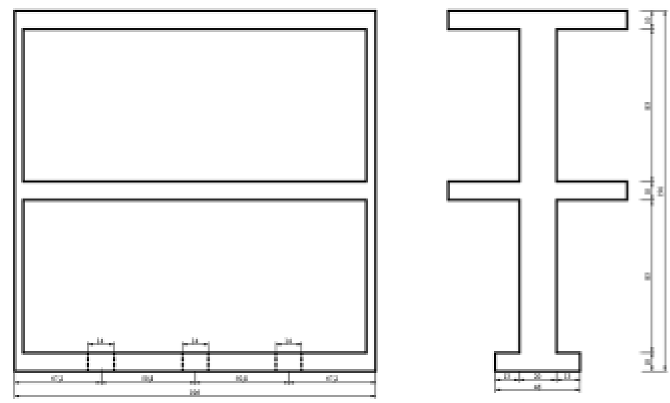

Fig. 2 Dimension of the model (mm).

The computer model is printed by the 3D printer and the physical model given in Figure 4 is obtained.

Fig 3. 3D solid model

Fig. 4. Experimental model printed with 3D printing technology

*2) Material Property*

The material used in 3D printing is called PLA filament. The weight per unit volume of this material is measured in laboratory as 1.2262 g/cm$^3$ and the Young’s modulus is 3.5 GPa.

*B. Calibration of Initial Model*

*1) Analysis Procedure*

1. Pre-processing

- SAP2000 software is used in order to develop the FE model of system and Artemis software is used to evaluate the 3D printed experimental model
- The FE model in SAP2000 and OMA model in Artemis are integrated by FEMtools
- Modifying and visualizing the information stored in the FEMtools internal database is extracted
- Analysis
- In case of static analysis, compute displacement shapes
- In case of dynamic analysis, compute or import modes and/or FRFs
- Database transformations
- Error localization and selection of responses and parameters
- Correlation analysis
- Sensitivity analysis
- Model updating
- Post-Processing
- Visualization and interpretation of results
- Exporting the updated FE model for further analysis

*2) Experimental Setup*

For operational modal analysis, the vibration data is obtained using accelerometers. Accelerometers used for the dynamic tests are, a tri-axial accelerometer for the base and two uni-axial accelerometers for each story (both along in plane and out of plane directions); total of five accelerometers having +/- 5g amplitude and 0.5 – 3000 Hz frequency range are used. Accelerometers used for the tests are shown in Figure 5.

Fig 5. Accelerometers used for shake table tests

The 3D printed model is fastened to the shaking table using 3 bolts and accelerometers are attached on the base and on each story. Figure 6 shows a test setup.

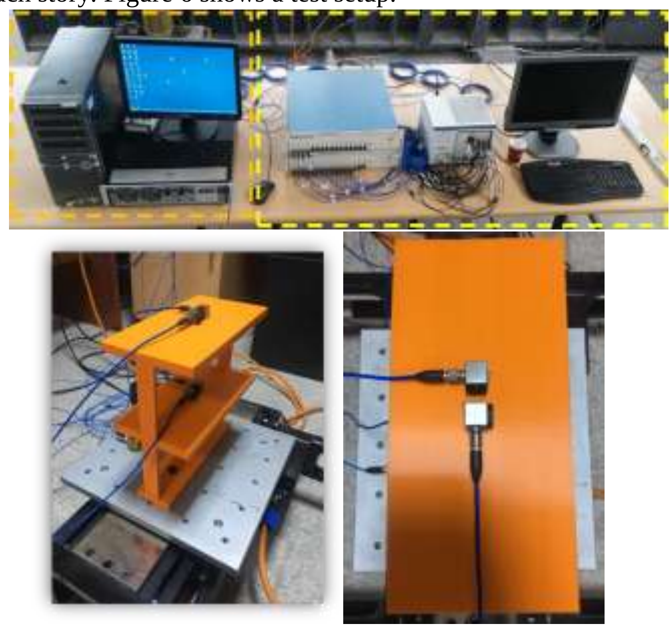

Fig. 6. Experimental setup

*3) Selection of Reference Responses and Parameters for Reference Model*

In our study, the 3D frame system is updated using a modal-based approach. Because, from the many types of results available, the modal parameters are the ones contain the most relevant information about the dynamic characteristics of the frame and can easily be compared against test data. Responses from various types of analysis can be selected as references for correlation analysis, sensitivity analysis and model updating. For model updating, target values have to be specified. For analysis parameters are also required for sensitivity analysis, model updating. They include all physical properties of the elements. In our study frequencies and Modal Assurance Criterion (MAC) values are used as responses. As to parameters to be changed for updating, only Young’s modulus is selected globally which means this value is updated equally for each column by the program. Because according to the sensitivity analysis conducted prior to the updating, the columns of the first floor turn out to be more sensitive to 1st natural frequency when compared to the 2nd floor columns while for the 2nd mode opposite is true. This updated model is called the reference model (i.e., the model representing the undamaged state of the 3D printed model). The selected parameters and responses are given in Table 1.

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TABLE I
PARAMETERS AND RESPONSES

| **Parameter** | **1** | **2** | **3** | **4** |
|---|---|---|---|---|
| | Left column in 1st story | Left column in 2nd story | Right column in 3rd story | Right column in 4th story |
| **Response** | **1** | **2** | **3** | **4** |
| | 1st natural frequency | 2nd natural frequency | 1st mode MAC | 2nd mode MAC |

*4) Model Updating of Reference Model*

The modal results obtained from FE model by using SAP2000 software is given in Table 2.

TABLE II
PARAMETERS AND RESPONSES MODAL RESULTS OF FE MODEL

| | **Frequency (Hertz)** | **Period (s)** | **in/out of plane** |
|---|---|---|---|
| **Mode 1** | 28.8412 | 0.0347 | in plane |
| **Mode 2** | 31.7541 | 0.0315 | out of plane |
| **Mode 3** | 71.4526 | 0.0140 | out of plane |
| **Mode 4** | 71.6499 | 0.0140 | In plane |

For experimental model, four acceleration records are taken from the tests consisting of two white noise and two ambient excitations. The data recorded is then filtered and de-trended using MATLAB. After this step, the model is defined in Artemis and the records are uploaded to the program (Figure 7). Each record is assigned to the related degree of freedoms. Uploaded data is then processed by using SSI-UPC method available in Artemis (Figure 8). It is seen that modal properties of four records are close enough. The comparison of modal property of physical model and analytical model are given in Table 3.

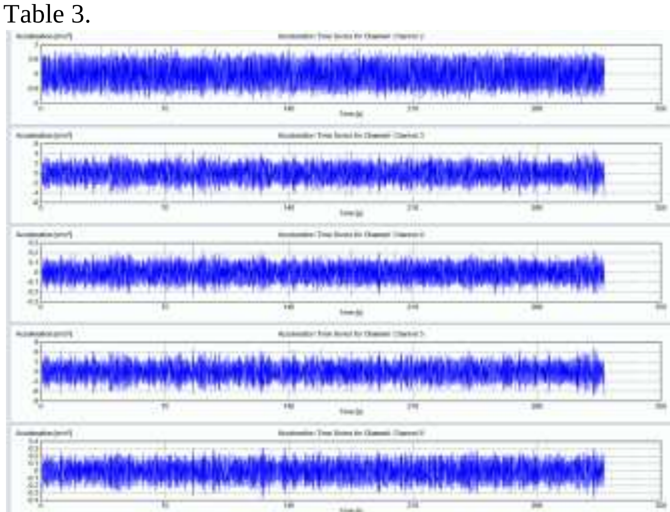

Fig. 7. An example of a data set from one of the tests

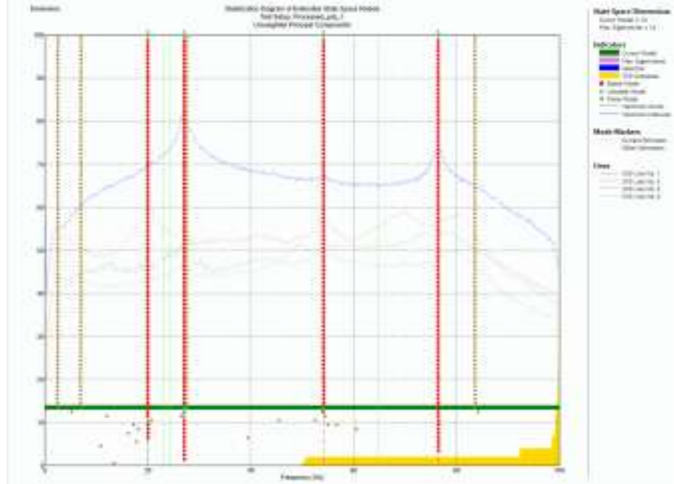

Fig. 8. Stabilization diagram

TABLE III
COMPARISON OF MODAL DATA (EXPERIMENTAL VS. NUMERICAL)

| | **Frequency (Hertz)** | **Period (s)** | **in/out of plane** |
|---|---|---|---|
| | **Numerical Result** | | |
| **Mode 1** | 28.841 | 0.0347 | in plane |
| **Mode 2** | 71.6499 | 0.0140 | In plane |
| | **Experimental Results** | | |
| **Mode 1** | 30.238 | 0.0330 | in plane |
| **Mode 2** | 76.793 | 0.0130 | In plane |

Since modelling assumptions and material properties are unknown numerical model can be different from experimental (real) model. Therefore, numerical model needs to be calibrated using the experimentally identified modal data. In this case two models give very close results, because of relative simplicity of the 3D printed experimental model. Nonetheless, analytical model is calibrated using FEMtools software.

Calibration process is completed with two iteration steps and elastic modulus of the model is increased about 12.38%. Elastic modulus of the initial model was 3500 MPa and elastic modulus of the calibrated model updated to be 3933 MPa. Figure 9 shows parameter changes with respect to the iteration number.

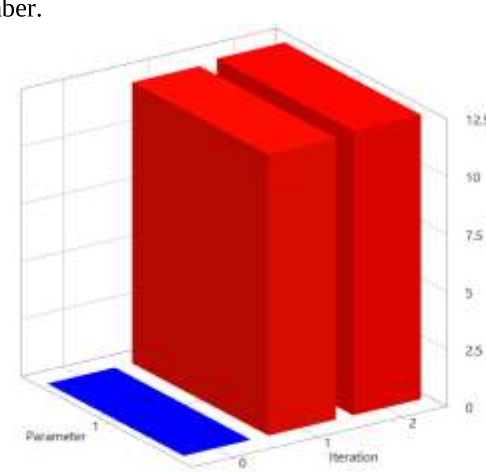


Fig. 9. Parameter changes

### *C. Damage Indentification*

After calibration of the initial mode and obtaining the reference model, one of the first story columns is damaged at the bottom using a honing machine (Figure 10).

Fig. 10. Introduced damaged on one of the columns

Acceleration records are taken from the damaged model and the records are filtered and de-trended as was done in first step. Filtered records are uploaded to Artemis® and the system is re-analyzed. Modal parameters of the damaged model and the reference model are shown in Table 4 together.

TABLE IV
MODAL PROPERTIES FOR REFERENCE NUMERICAL (UNDAMAGED) AND TEST RESULTS (DAMAGED)

| | Frequency (Hertz) | Period (s) | in/out of plane |
|---|---|---|---|
| | **Numerical Result (undamaged)** | | |
| **Mode 1** | 30.575 | 0.0327 | in plane |
| **Mode 2** | 75.957 | 0.0131 | In plane |
| | **Experimental Results (damaged)** | | |
| **Mode 1** | 27.048 | 0.0369 | in plane |
| **Mode 2** | 75.451 | 0.0132 | In plane |

Using frequencies in Table 4 and MAC values of modes (numerical and experimental), FEM updating is performed using FEMtools. Elastic moduli of four columns are again set as the updating parameters. Note that beams are assumed to have no damage by definition. After 8 iterations, elastic moduli of the first story columns decreased about 32%. Elastic moduli of the second story columns remained the same because there was no damage at the second floor columns in the experimental model. Parameter changes are shown in Figure 11, 12 and 13. Here parameters 1 and 3 are the first story columns’ elastic moduli while parameters 2 and 4 are the second story columns’ elastic moduli. Response tracking and MAC matrix are shown in Figure 14 and 15, respectively.

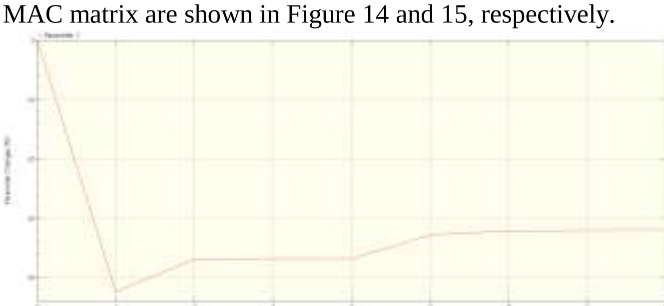

Fig. 11. First story column’ elastic moduli change

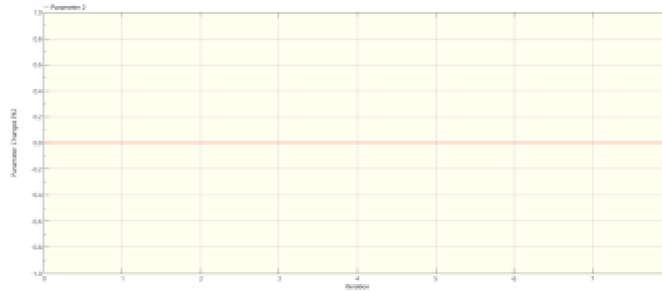

Fig. 12. Second story column’ elastic moduli change

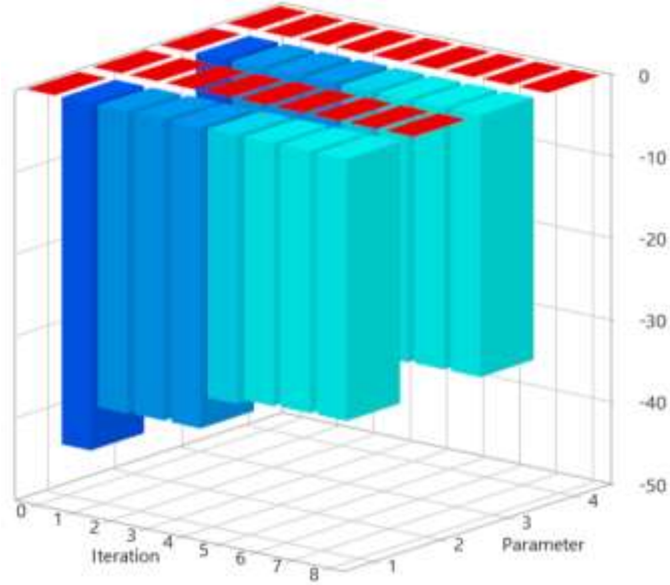


Fig. 13. Matrix of parameter change

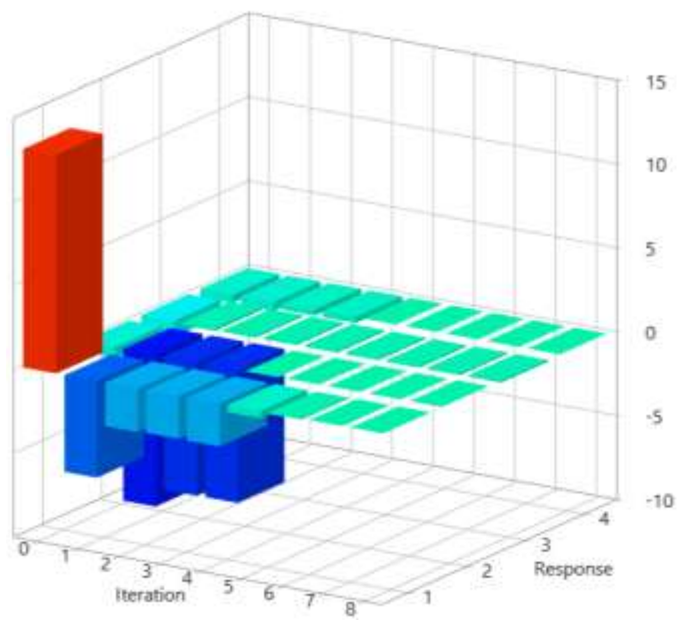


Fig 14. Response tracking matrix

Both the numerical and experimental data are now complete and the mode shapes can be paired using the MAC matrix. MAC is the squared cosine of the angle between two mode shapes, and used for mode shape comparisons.

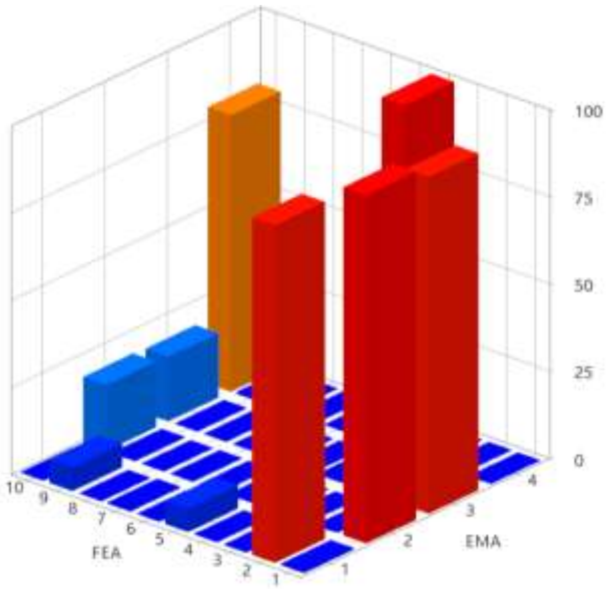


Fig. 15. Modal Assurance Criteria (MAC) mat

### *D.Discussion*

The following conclusions can be made as a result of the presented experimental work:

In first phase of this study it is seen that the modal properties of the numerical and experimental models are different because of geometrical, mechanical, and possibly boundary conditions modeling assumptions. This means that the initial numerical model must be calibrated using experimental data to obtain a reference model which is more representative of the real structure. This reference model is also used for damage detection purpose.

The study shows how sensitivity analysis can be used to find sensitive areas in a structure. This information can, for example, be used to find optimal ways to change the structure in order to obtain certain desirable frequency shifts.

In the second part of the study (damage identification), the decrease in elasticity moduli is observed in the first floor columns as was the damage scenario used. This indicates that the model parameter updating occur in the area where damage is introduced.

It is also observed that the decrease in elasticity moduli of the 1st story columns occurred symmetrically in both columns while the physical model is only damaged in one column. The reason for this may be due to using only two modes as response quantities, and therefore a unique solution does not exist (under-determinate problem meaning that the number of model parameters to be updated is larger than the size of the cost function to be minimized). In other words, in order to converge to the real solution, the size of the cost function must be increased by using more response parameters.

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