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STRUCTURAL DAMAGE DETECTION THROUGH FORCED VIBRATION TESTING

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Abstract

Existing methods of evaluating buildings after a seismic event often rely on demolition of architectural elements such as cladding, partitions, and ceilings in order to inspect structural members. Evaluations are done by visual inspection with no quantitative data. Current research focuses on the application of Forced Vibration Testing (FVT) for assessment of buildings after a seismic event. This non-destructive method involves temporary instrumentation to record building behavior.

This paper describes the use of FVT to detect simulated earthquake damage in an experimental one-story steel structure spanning a forty-eight foot ravine. The structure serves as a dynamic earthquake field laboratory and is outfitted with detachable braces that can be used to simulate damage. It is assumed that an intact structure is represented when all braces are engaged. Damage is simulated by removing one or more braces.

FVT, based on a 30 lb linear mass shaker and sensitive accelerometers, has successfully been used to register building dynamic properties such as natural frequency, mode shapes and damping in a wide range of structures ranging from a two-story laboratory structure to an 180,000 square-foot 5-story reinforced concrete library.

The paper demonstrates how FVT can be applied to positively identify structural damage in the experimental structure by comparison of experimental mode shapes with theoretical mode shapes from computer models. The modal assurance criterion (MAC) allows for a quantitative comparison of two mode shapes. Experimental mode shapes for a building configuration with a particular brace configuration can be compared to the theoretical mode shapes from a suite of computer models with a variety of different brace configurations. It is shown that the MAC criterion provides a confidence metric that can positively identify the correct theoretical model and thus reveal the location of structural damage.

Keywords: damage detection; forced vibration testing; mode shape analysis; MAC; system identification

1. Introduction

The goal of this research is to identify simulated damage in an experimental building on the California Polytechnic State University, San Luis Obispo campus. The one-story bridge-like structure spans a seasonal creek. At a distance it resembles a bridge truss thus referred to as the 'Bridge House'. In 2011 it was designated as a Dynamic Structural Experimental Laboratory. Removable braces were added to the structure for damage simulation. An "engaged" brace acts as an undamaged brace, and a "dis-engaged" brace resembles a brace that has ruptured. A dis-engaged brace lowers the lateral stiffness of the building, and changes its dynamic response. By dis-engaging various braces, a series of brace configurations can be established that represents a damaged building after a seismic event. Each brace configuration has a unique dynamic response.

Dynamic excitation of the Bridge House was done with a linear mass shaker installed at the roof. The shaker output is up to 30 lb in the 1 Hz to 20 Hz frequency range. When the shaker frequency coincides with the buildings natural frequency, and the structure reaches its steady state, the frequency, modes shape and acceleration amplitudes are recorded. A series of accelerometers were placed strategically on the roof and the floor to record the dynamic response.

Two computer models were built - a rudimentary model and a detailed model. Each model was executed for different configurations of braces and theoretical natural frequencies and mode shapes were computed. Correlation between the experimental and theoretical data was established quantitatively using the Modal Assurance Criterion (MAC) [1]. A MAC analysis allows for the comparison of one set of mode shapes to a second set of mode shapes. In this case the sets of mode shapes were experimental and computer generated. This comparison reveals the correlation between the two sets of data. A MAC analysis along with logical inspections of the data greatly increase the ability to predict which computer model best matches the structure in a given brace configuration.

Examples of recent related research on modal property based damage detection and system identification using vibration measurements may be found in e.g. [2,3].

2. Bridge House

Fig. 1 shows the Bridge House. The foot print is 48 ft by 24 ft and the floor to roof height is 10 ft. The lateral and gravity force resisting system in the East-West direction (across the creek) is a Pratt truss. In the North-South direction, the lateral force resisting system is composed of a hybrid Vierendeel truss and brace frame system. The braces on the East and West faces (Fig. 2) are detachable and facilitate dynamic testing of the building in multiple configurations. Additionally, all interior beams and columns constitute moment frames.

(a) S-W Perspective

(b) West Face

Fig. 1—Bridge House

The roof is composed of insulated corrugated steel decking and the floor is a concrete slab. The Bridge House is supported by four concrete pedestals, one in each corner, as shown in Fig. 2. The height of each pedestal and embedment into the soil varies. The soil and pedestal properties significantly contribute to the building response.

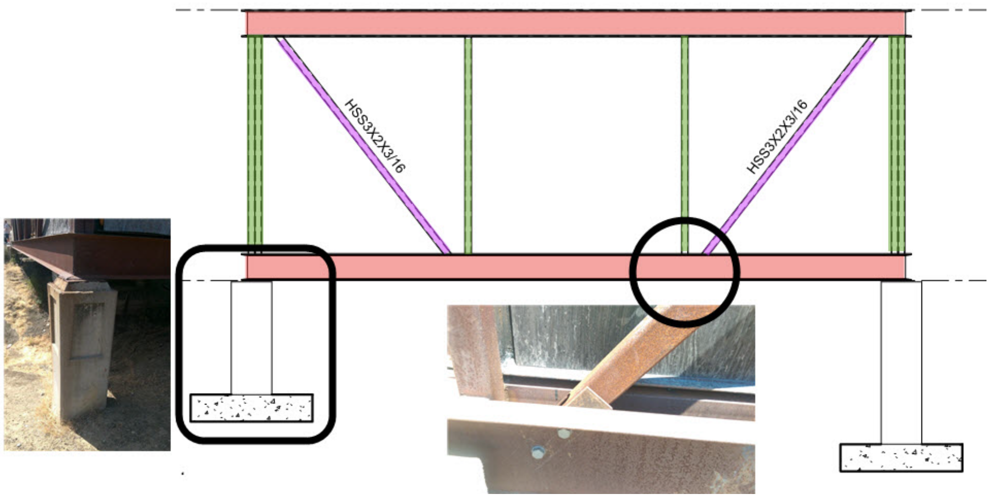


Fig. 2—West face, framing and pedestals

3. FVT Testing

Four brace configurations were investigated as indicated in Fig. 3. Red lines indicate engaged (undamaged) braces. 'All On' represents the structure in its intended state. 'All Off' (None) represents the structure with complete failure of the E-W lateral system. 'West Only' and 'East Only' represent complete failure of the West or East brace lines. The roof was subjected to mass shaker loading in the center in the N-S direction. Accelerations were measured in the N-S direction at 7 locations (at each beam) and at each end of the floor slab. Previous investigations had shown the roof acts as a semi-rigid diaphragm and the floor acts as a rigid diaphragm [4].

Fig. 4 shows the results of a frequency sweep for each brace configuration. Only the first mode in the N-S direction was measured. The peaks represent the resonant frequency and are listed in Table 1. The modal damping ratios based on the half-bandwidth method [5] are also indicated.

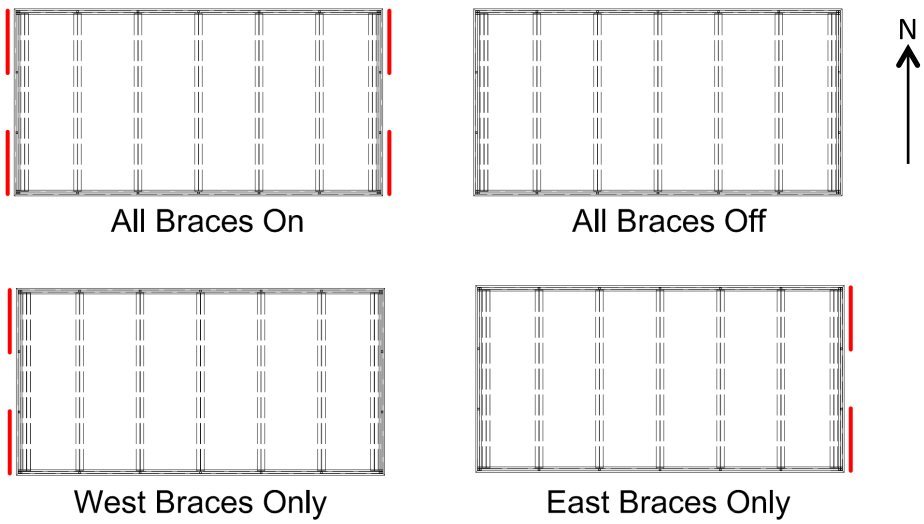


Fig. 3—Plan view, experimental brace configurations

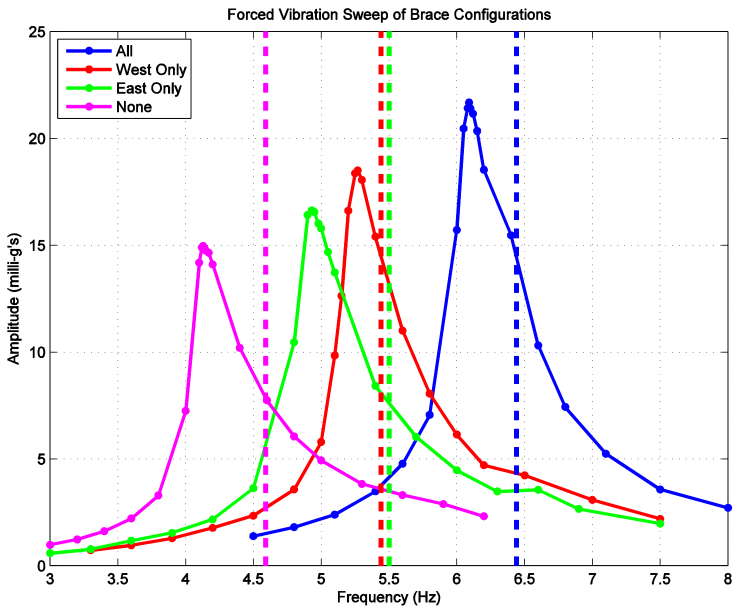


Fig. 4—Forcing frequency vs. acceleration amplitude plot, analytical frequencies in dashed line.

Table 1—Experimental and analytical (model) frequencies

Brace Configuration	Experimental Frequency (Hz)	Damping Ratio (%)	Analytical Frequency (Hz)	Ratio Analytical /Experimental
All Braces On	6.09	4.04	6.44	1.06
West Only	5.27	3.03	5.44	1.03
East Only	4.93	3.95	5.50	1.16
No Braces	4.13	2.99	4.59	1.11

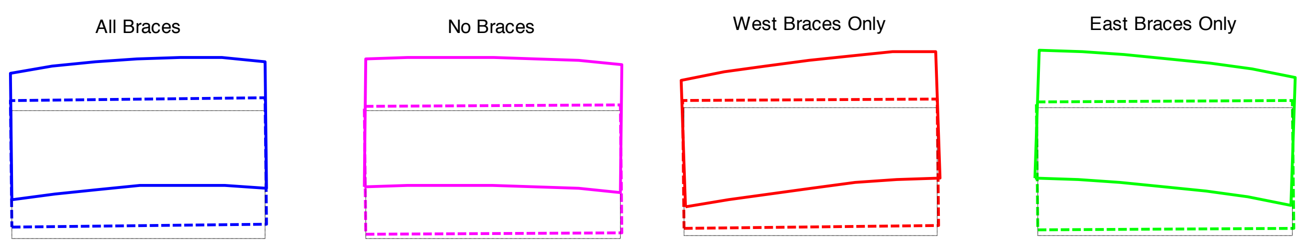


Fig. 5—Normalized mode shapes (reference grey, floor dashed, roof solid).

Fig. 5 shows the measured normalized mode shapes. All Brace and No Brace configurations appear to have mostly translational character. No Brace configuration clearly shows less displacement of the roof relative to the floor, than the All Brace configuration. East Only and West Only configurations clearly exhibit torsional response due to the asymmetric lateral systems. It is also seen that the foundations contribute significantly to the mode shapes and should be considered in the analytical models. Lastly, Fig. 5 shows that the roof is semi-rigid. This is particularly evident for the All Brace configuration. All measurements were taken in the early morning before sunrise because previous research [4] had shown significant frequency shift throughout the day linked to thermal effects.

The substructure stiffness was determined experimentally by system identification. At resonance and at the steady state, the displacements and inertia forces can be calculated from the measured accelerations, a_i, and the lumped structure mass, m_i, at each accelerometer position. The total shear, V, transmitted to the foundations at each end of the structure was based on equilibrium and found by summing the story forces at the roof and the floor using Newton's Second Law, $F_i = m_i a_i$. At steady state response, the displacements d_i may be determined by $d_i = a_i/\omega^2$ where $\omega = 2\pi f$ is the circular frequency and f is the natural frequency [5]. The foundation stiffness was calculated as $K = V/d$, where V is the total shear and d the floor displacement at the east or west end foundations. Representative stiffness of the foundations was 600 kip/in and 300 kips/in for the West and East foundations, respectively.

4. Analytical Model

Analytical models were made using SAP2000 [6]. All structural steel sections were modeled as frame elements, and the roof and diaphragm were modeled as shells. The model thickness of the roof shell was taken as 1/2 of the thickness of the corrugated metal decking. Two models were created: (a) a simple and rudimentary model (termed 'crude' model) and (2) a highly detailed model (termed 'baseline' model).

Fig. 4 shows the analytical model natural frequencies in dashed line. Table 1 shows both the experimental and analytical frequencies. Fig. 7 shows the analytical mode shapes for the baseline model along with a comparison to the experimental mode shapes.

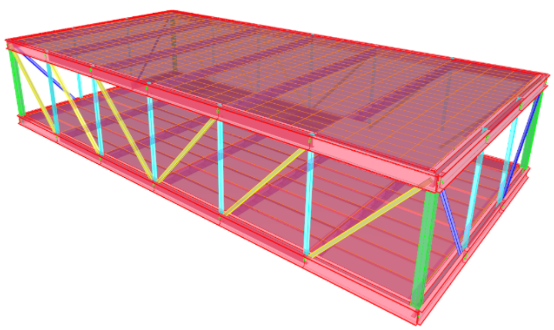


Fig. 6—Analytical Model, reference model (foundation springs not shown)

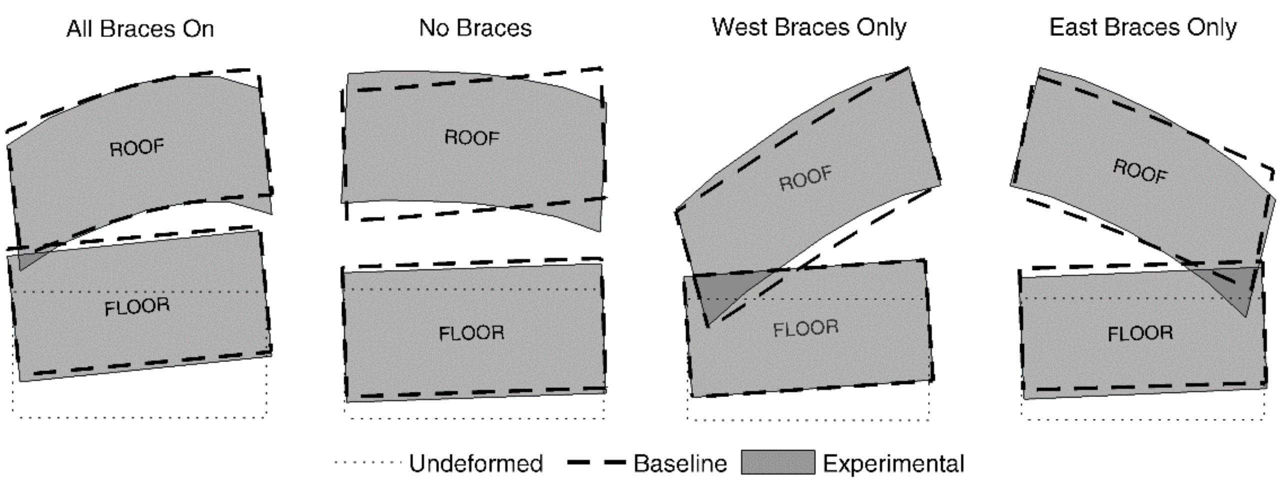


Fig. 7—Analytical (baseline) and experimental mode shapes, comparison

5. Damage Detection

The goal is to identify the analytical model that best matches a given experimental data set (frequency and modes shape), for example the West Only brace configuration. The identified analytical model then reveals the state of the structure. Three complementary approaches are presented here:

a. Frequency comparison
b. Visual comparison of mode shapes
c. MAC comparison of mode shapes

5.1 Frequency Comparison

Fig. 4 and Table 1 compares the frequencies from all experiments and analytical models. It is clear from the analytical to experimental frequency ratios that the model captures the experimental frequencies well. However, if one only plots the West Only experimental response along with the theoretical frequencies (vertical dashed lines), it will be impossible to select the correct model because both West Only and East Only models would be reasonable picks for the true state of the structure. Previous research has also shown that comparing experimental natural frequencies to theoretical natural frequencies has limitations [7,8].

5.2 Visual Comparison

Visual comparison of all analytical and experimental mode shapes was done in Fig. 7. This type of comparison is only possible for a structure like the Bridge House where multiple states of damage can be simulated. Looking at Fig. 7, it is clear that pairing the West Only experimental results with any other analytical model than the West Only one would be incorrect because of the torsional response of the roof. An identical conclusion can be made for the East Only case. However, the analytical mode shapes for All Braces and No Braces are somewhat similar because they are normalized to the same roof peak amplitude. The ratio of floor to roof displacement would however help assign the correct No Brace/All Brace models to the correct experiment. As suggested above, this would not be possible in a post seismic event as only one experimental brace configuration would exist. A likelier example of visual inspection after an earthquake is the blind visual inspection.

A blind visual comparison consists of comparing the mode shape of one experimental brace configuration to the mode shapes of four brace configurations from a computer model. This is the methodology that would be used after a seismic event. In Fig. 8, the experimental results for the All Braces On configuration are plotted with the results from the analytical model. It is clear that the All Braces On analytical mode shape best matches the Al Braces On experimental mode shape. Blind visual comparison done for the No Braces configuration is slightly harder to synthesize (Fig. 9). A reasonable conclusion is that the No Braces analytical mode shape resembles the Experimental Results the most, thus a positive identification. The roof motion is clearly not accurately captured, however the roof motion for the other analytical mode shapes is even less accurate.

5.3 MAC Comparison

The Modal Assurance Criterion (MAC) is a qualitative method that compares a suite of vectors against a second suite of vectors of similar length, such as a mode shape. The MAC results in a matrix that is populated with numbers from 0 to 1. Each cell in the matrix represents the comparison of two vectors. A value of 0 indicates that the compared vectors have no correlation, a value of 0.5 indicates random correlation, and a value of 1 indicates a full correlation [1]. For the purpose of this research, the MAC has been modified to include normalization with respect to the mass distribution:

$$MAC_{ij} = \frac{\left(\phi_i{}^T M \phi_j\right)^2}{\left(\phi_i{}^T M \phi_i\right)\left(\phi_j{}^T M \phi_j\right)} \quad (1)$$

where ϕ_i and ϕ_j are the mode shape vectors being compared, and M is the mass matrix defined by the tributary mass relevant to the acceleration measurement arrangement.

The first application of the MAC is to identify if the experimental mode shapes representing the brace configurations are similar or different. This is done by comparing all experimental mode shapes against themselves. This is illustrated in Fig. 10(a) and reveals ones in the diagonal as expected but also that there seems to be a high degree of correlation between the mode shapes. Nevertheless, the off-diagonal numbers are consistently less than one. Similarly, there is significant correlation between the analytical mode shapes.

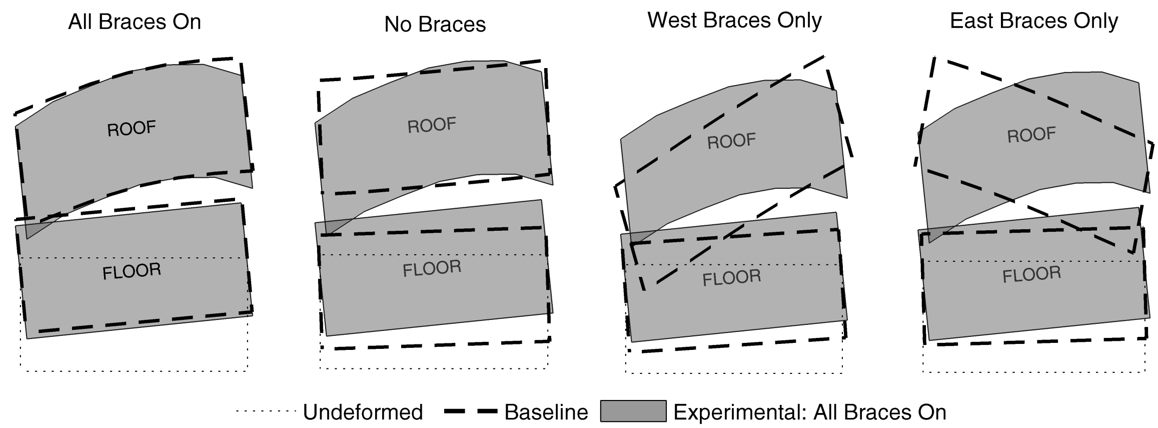


Fig. 8—All 4 analytical mode shapes (baseline) and the All Brace experimental mode shapes

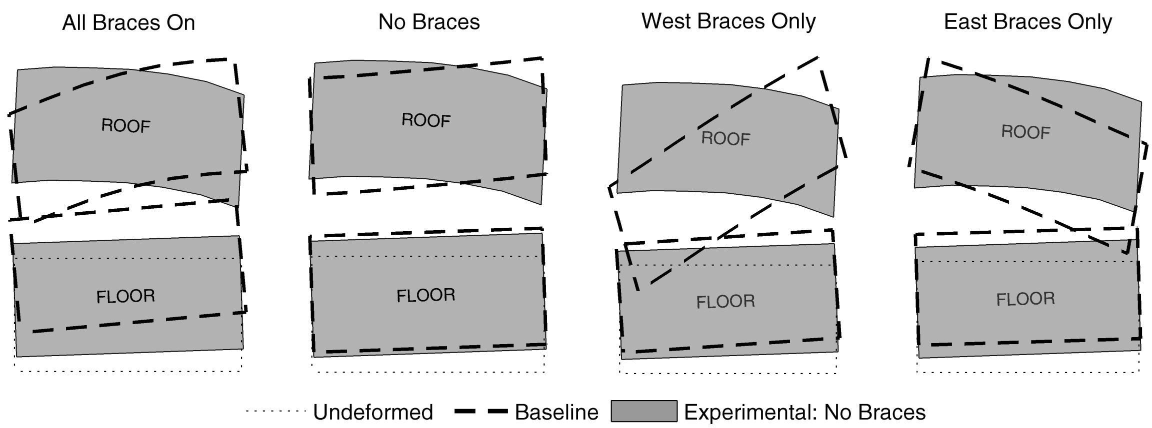
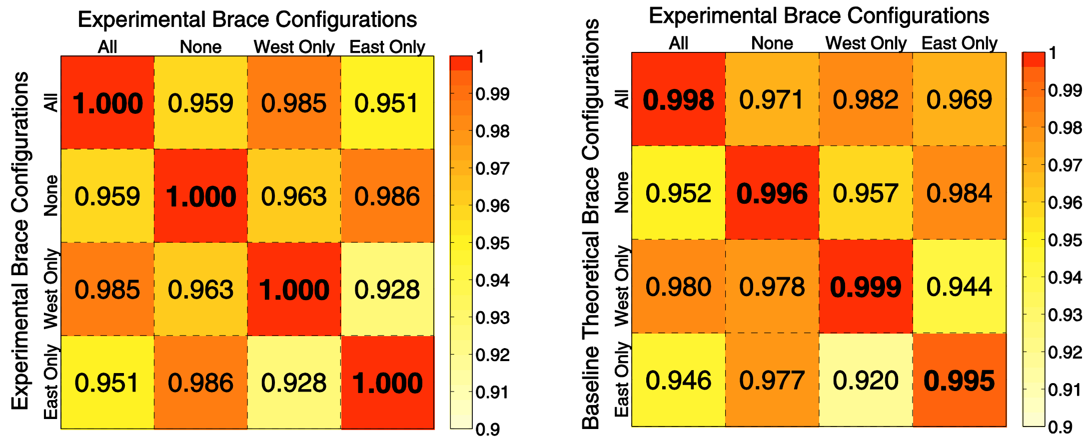


Fig. 9—All 4 analytical mode shapes (baseline) and the No Brace experimental mode shapes

Fig. 10(b) shows the MAC for the analytical modes shapes compared to the experimental mode shapes. As expected, there is high correlation between all analytical and experimental mode shapes. In this Fig., the analytical and experimental mode shape vectors were arranged in the same order. Therefore, one expects to see the highest correlation numbers in the diagonal. Fig. 10(b) clearly illustrates that this is the case. When each column, that represents the correlation between one experiment and all of the analytical models, is scanned, it is clear that the highest MAC number consistently occurs in the row that identifies the correct analytical mode shape. It is concluded that the MAC analysis provides 100% certainty of which model belongs to which experiment, such that the model reveals the likely state of the structure after an extreme load event occurs, such as strong seismic ground motion.

6. Analytical model robustness

Early in the research a rudimentary analytical model was made. It reflected simplified assumptions for the main lateral system, notably a rigid floor, flexible roof and an estimate of the foundation stiffness based on the pedestal geometry and likely soil properties [4]. Fig. 11 shows the responses of the crude model (labeled 'Theoretical'), the baseline model and the experimental results. It is clear that the crude model does not capture the roof displacement as well as the baseline model, particularly the All Brace case. The No Brace case and the East Brace and West Brace cases show generally correct tendencies.



(a) experimental vs. experimental (b) baseline analytical vs. experimental

Fig. 10—MAC comparisons

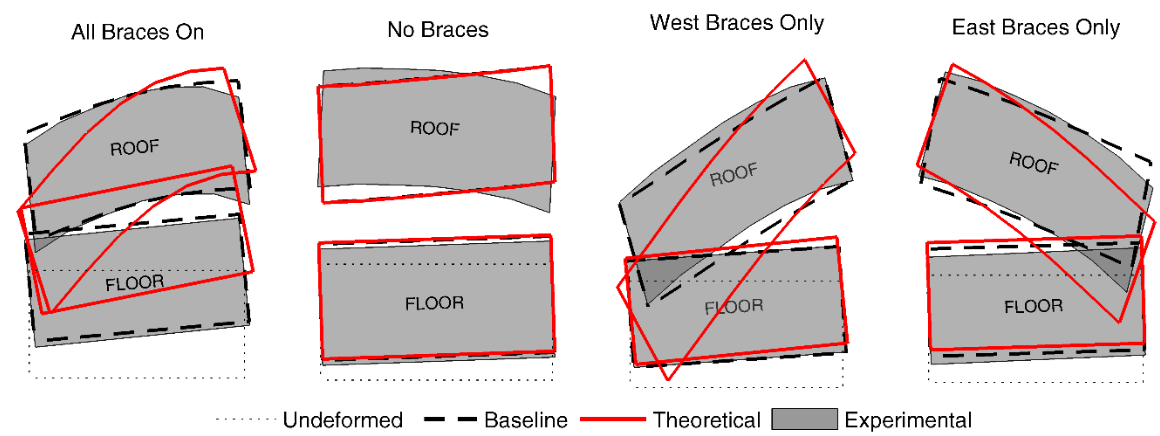


Fig. 11—Modes shape comparison, Crude model (Theoretical), Baseline model, Experimental

Fig. 12 shows the results of a MAC mode shape comparison of the crude model (Theoretical) and the experiment. Investigating each individual experimental brace configuration (each column), it is clear that the largest value occurs in the position that corresponds to the 'correct' analytical model. While the largest values are found on the diagonal for the crude model, these values were further from unity when compared to the MAC values from mode shape comparison of the detailed model (Baseline) and the experiment. This suggests that the crude model had less correlation to the experiment than the Baseline model. Nevertheless, the rudimentary model did suffice in this case for MAC comparison and correct identification of damage.

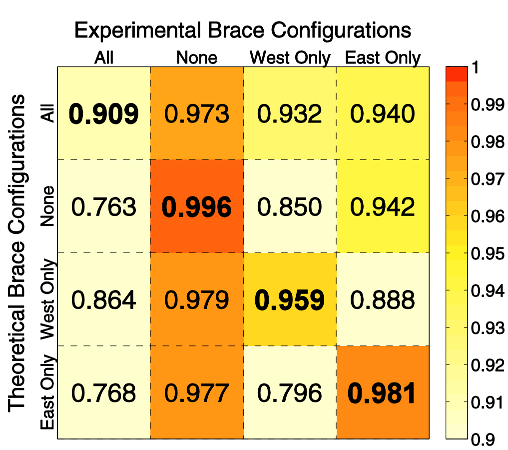


Fig. 12—MAC comparisons, crude model vs. experiment

7. Conclusion

FVT was used to record the response (1st fundamental natural frequency and mode shape) of a structure with four brace configurations. A series of analytical models were created to reflect the four structural configurations. Both rudimentary models and detailed models were created. Frequency comparison, visual inspection of the mode shapes, and the Modal Assurance Criterion (MAC) were used to compare experimental and analytical results.

Comparison of experimental and analytical frequencies alone did not allow for identifying the correct analytical model. It is generally possible to create a computer model that accurately predicts the natural frequency of a real structure. Unfortunately, structural changes due to damage tend to result in only slight changes in natural frequencies.

Visual inspection of all experimental and analytical mode shapes together allows for pairing the correct model to the actual experiment. Unfortunately, only one experimental dataset is available in a realistic scenario, which makes such comparison impossible. Blind visual inspection allows comparison of one experimental mode shape to the mode shapes from a suite of analytical models. Such comparison led to positive identification (engineering judgement) of the correct analytical model. However, this is not necessarily the case in a realistic scenario where a conclusion preferably should be based on some metric.

A far better approach is to use the MAC criterion for identification of the analytical that most likely represents the state of the actual structure. Applying the MAC criterion to the experimental mode shapes indicated that all experimental brace configurations produced similar mode shapes. Despite significant correlation between the experimental mode shapes, the MAC was successfully used to identify the correct analytical model. The MAC value corresponding to the correct pairing of the experimental and analytical mode shapes was in all cases distinctly higher than the remaining MAC numbers.

Studies showed that a model of lesser level of detail and accuracy than the baseline model was sufficient for MAC analysis and resulted in correctly predicted brace configurations.

In conclusion, the paper demonstrates how forced vibration testing (FVT) can be applied successfully to identify structural damage. With the MAC, an experimental mode shape for a building configuration with a particular brace configuration was compared to the theoretical mode shapes from a suite of computer models with a variety of different brace configurations. It was shown that the MAC criterion positively identified the correct theoretical model and thus revealed the extent of structural damage.

It is expected that the proposed method can be extended to more complex real-world structures with more complex damage and failure mechanisms. For example, a multi-story building with RC moment frames and/or shear wall as lateral system subjected to strong ground motion potentially will exhibit significant stiffness degradation due to damage (not necessarily failure) and thus alter the mode shapes sufficiently to allow for identifying damage as described above. This could reveal damage, for example, in a certain direction of motion or in a certain floor.

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