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Seismic response of a ten story concrete building subjected to different earthquakes

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ABSTRACT

The purpose of this paper is to compare the response of a ten story concrete building in San Jose, California, under three different earthquakes. The strong-motion records of the instrumented building obtained during the 1984 Morgan Hill earthquake were used to calibrate a finite element model. Soil-structure interaction was included in the model by adding some translational springs to the foundation. The same model was subjected to 1986 Mount Lewis and 1989 Loma Prieta earthquakes. While for the first case a good match between the recorded data and analytical results was obtained, for the second one the match was not as good as expected. A modal identification analysis of the building was conducted for the three ground motions using both just output operational modal analysis (OMA) and input-output experimental modal analysis (EMA). It was demonstrated that for Loma Prieta, which presents higher amplitude shaking than the other two ground motions, the fundamental period for the transversal mode of the structure was higher than that obtained using the other two earthquakes. Consequently, the springs of the finite element model needed to be updated for Loma Prieta in order to capture the more flexible response of the building. After this adjustment, there was a good match between the recorded motions and analytical results. This study proves that the effects of soil-structure interaction becomes very important when a building is subjected to high levels of shaking. In some cases, a single model of a building with concrete shear walls may not be suitable to predict properly the behavior of the building under different ground motions.

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1. Introduction

The recorded response data from instrumented buildings can be especially helpful for a better understanding of the true behavior of the structures. The ground motion data obtained by sensors located in several different points of a building is used for the calibration and validation of its finite element model.

The dynamic response of a permanently instrumented ten-story commercial concrete shear wall building located in San Jose, California is studied. The building was instrumented in the 70's by the California Division of Mines and Geology – Strong Motion Instrumentation Program (CSMIP) in order to obtain strong motion and building response data. The instruments installed in several locations of the building recorded valuable data during April 24th 1984 Morgan Hill, March 31st 1986 Mount Lewis and 17th October 1989 Loma Prieta earthquakes. The recorded motions have been used to calibrate and update a computer finite element model of the structure.

This study comprises the following parts: investigation of the building's structural system, modal identification using the strong motion data collected at the building, calibration and updating of a computer model of the building, and comparison of the response of the building model subjected to the three different ground motions. This paper summarizes the important results obtained from a previous study by Martinez et al (2015) and focus on the additional results.

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2. Description of the Building and Instrumentation

2.1. Description of the building

The 10-story Great Western Saving building was built in 1964 and is located in San Jose, California. Its dimensions are 82 ft by 190 ft for its rectangular base (equal for every floor) and 102 ft for the elevation. Story heights are typically 12 ft, except from the ground floor and underground floor, which are 16 ft and 17 ft high respectively. The building is settled on a 90'x194'x5' reinforced concrete spread footing. The geology of the site is mainly alluvium, but parameters of the soil profile were not available for this study.

The lateral force resisting systems of the structure consists of moment frames in the longitudinal direction (NS-direction) and two concrete shear walls in the transversal direction (EW-direction). The building includes two elevator cores in the middle of the base plan, stairs joined to the shear-walls in both sides and two interior openings. An exterior view of the building is presented in Fig. 1.

Fig. 1. Ten story instrumented great western saving building in San Jose, California (adapted from CESMD).

2.2. Instrumentation of the building

The structure has 13 permanent force-balanced accelerometers which record accelerations at different locations of the building in different directions (vertical, longitudinal (SN) and transversal (EW)). Table 1 and Fig. 2 show the location of each sensor and the direction of the recorded data.

2.3. Recorded motions

The recorded motions for all the sensors during Morgan Hill, Mount Lewis and Loma Prieta earthquakes were obtained from CESMD (Center for Engineering Strong-Motion Data). Free field data in the vicinity of the building for the same ground motions was not available. Consequently, the mean of the channels of the basement for each direction is calculated and used as input ground motion for all the analysis performed in this study.

Acceleration time histories and the 5%damping acceleration spectra comparison of the three ground motions considered for this study are shown in Fig. 3 and 4 respectively. Mount Lewis presents the lowest peak accelerations (34 cm/sec^2) among the earthquakes, followed by Morgan Hill (59 cm/sec^2) and finally by Loma Prieta (97 cm/sec^2). Moreover, the acceleration spectra confirms that Loma Prieta produced significantly stronger ground shaking than the other two earthquakes, resulting in higher demands in the building. In addition, Loma Prieta has longer duration.

3. Modal Identification of the Structure

Modal identification of the structure was performed in Martinez et al. (2015) using ARTeMIS® computer program. Operational modal analysis (OMA) was conducted with the recorded ground motion data in different locations of the building as outputs. In addition, for this study input-output experimental modal analysis (EMA) for the three earthquakes is investigated and compared to the results obtained from the OMA.

This EMA uses as inputs (I) the recorded motions at the base and as outputs (O) the recorded motions at the fifth floor and at the roof. The measurements are converted from time domain to frequency domain using Fast Fourier transform algorithm and the transfer function (TF) is calculated as output divided by the input.

Transfer functions of the 5th floor and the roof for longitudinal and transversal direction are obtained for each of the seismic events. The obtained input-output EMA results for each of the events are compared in frequency domain to the spectral density results obtained from OMA. Fig. 5, 6 and 7 show in red and pink the TF-s obtained for the roof and 5th floor in transverse direction, and in dark and light blue in the longitudinal direction. These EMA results are plotted together with the OMA results, in which the identified natural frequencies are highlight as a black line.

The frequencies at which the first peaks occur in both longitudinal and transversal directions using EMA show good agreement with the natural frequencies obtained from ARTeMIS. The maximum deviation between the two different modal identification approaches is shown to happen during Mount Lewis event for the transversal direction with a 6% of error. It is also proved that the peaks of the TF-s at the two different levels of the building (5th floor and roof) for each direction occur at the same frequencies but with a higher amplitudes for the upper level.

For all of the earthquakes the first natural frequency representing the longitudinal direction of the building is around 1 Hz. However, the second natural frequency, which represents the first transversal mode, for Loma Prieta earthquake is lower than for Morgan Hill and Mount Lewis. The results of the comparison of both modal analysis approaches confirm that the dynamic characteristics of the building change depending on the ground motion. For Loma Prieta, the highest intensity earthquake, the structure behaves more flexible in the transversal direction.

	TIME DOMAIN		FREQUENCY DOMAIN	
INPUT	I (t)	⟶	I (w)	TF (w) = O(w) / I (w)
OUTPUT	O (t)	⟶	O (w)	

Table 1. Sensor number, location in the building and recorded direction of each accelerometer.

SENSOR NUMBER	LOCATION		MEASURED DIRECTION
	FLOOR	POSITION	
1	Basement	South West	Vertical
2	Basement	South East	Vertical
3	Roof	South Center	Transversal (EW)
4	Roof	North Center	Transversal (EW)
5	Roof	South Center	Longitudinal (SN)
6	5th Floor	South Center	Transversal (EW)
7	5th Floor	In the middle	Transversal (EW)
8	5th Floor	North Center	Transversal (EW)
9	5th Floor	South Center	Longitudinal (SN)
10	2nd Floor	South Center	Longitudinal (SN)
11	Basement	South Center	Transversal (EW)
12	Basement	North Center	Longitudinal (SN)
13	Basement	South Center	Longitudinal (SN)

4. Finite Element Modeling, Validation and Updating

4.1. Finite element model description

The design drawings of the building were used to develop a finite element model of the building using ETABS 2013 software. A linear elastic model of the structure supported by a flexible base was created. The base was designed as spreading concrete slab footing over a series of springs of finite stiffness. The foundation springs were modeled using the soil and foundation information available as specified in Gazetas (1983). The model includes structural, as well as, non-structural elements. Gravity frames, lateral load resisting frames, shear walls, interior core walls, openings and stairs were modeled too. For the reinforced concrete elements 80% of the modulus of elasticity, un-cracked moment of inertia and linear stress-strain reinforcement relationship was used. All the beam-column connection were designed as moment connections. A three dimensional view of the ETABS model is shown in Fig. 8.

4.2. Calibration of the model

A first manual calibration was performed using one of the low level of shaking earthquake (Morgan Hill).Structural properties and masses were modified manually until a "best match" between experimental and analytical results was obtained. The obtained first natural frequencies of the calibrated finite element in each direction were similar to the ones obtained through OMA and input-output EMA. In addition, recorded and analytical acceleration time histories and velocities and relative displacements (obtained by integration of accelerations) in all the channels during Morgan Hill event were compared. The calibration of the model was considered acceptable once a good correlation coefficient between the experimental and analytical results was obtained. However, a more accurate calibration could be performed using automatic modal updating tools.

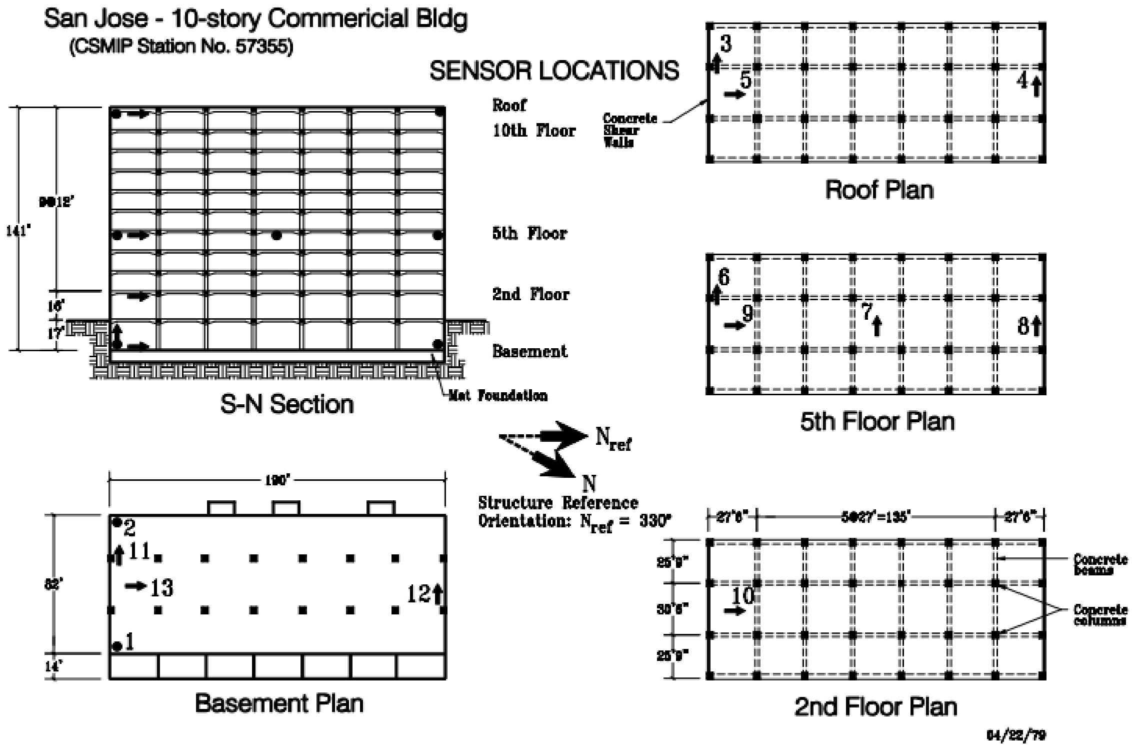

Fig. 2. Schematic map of instrumentation of the building (adapted from CESMD).

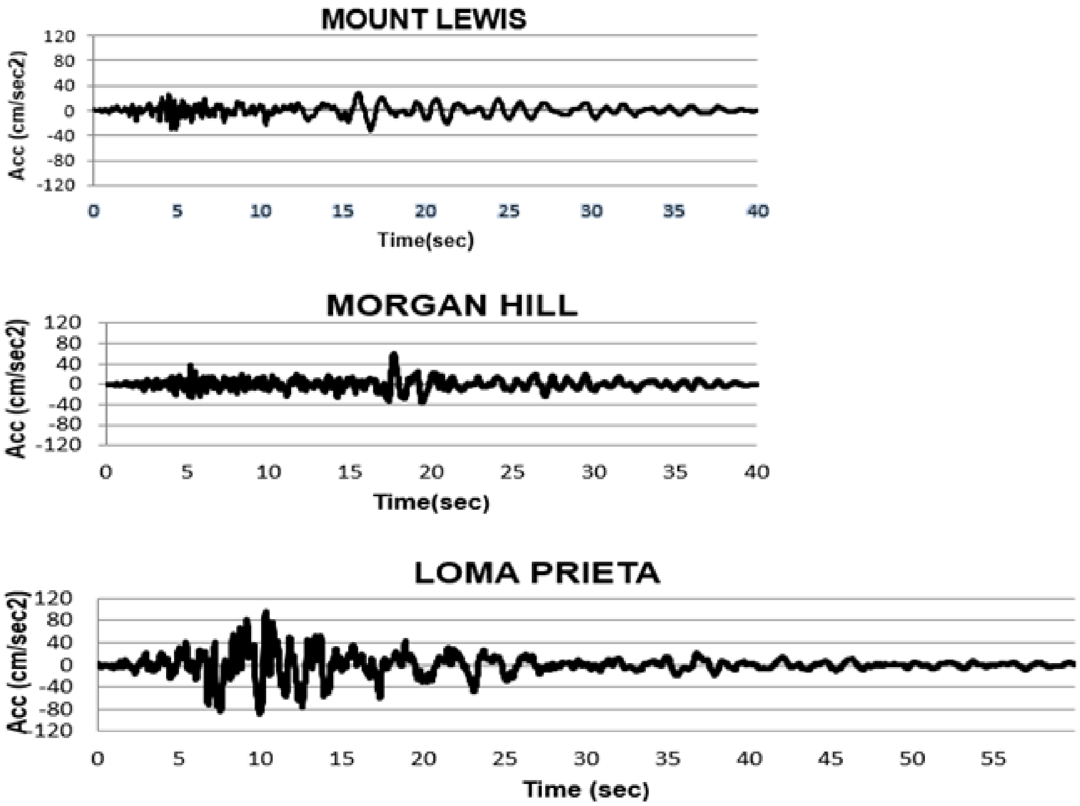

Fig. 3. Recorded acceleration time histories for Mount Lewis, Morgan Hill and Loma Prieta at the basement for EW direction.

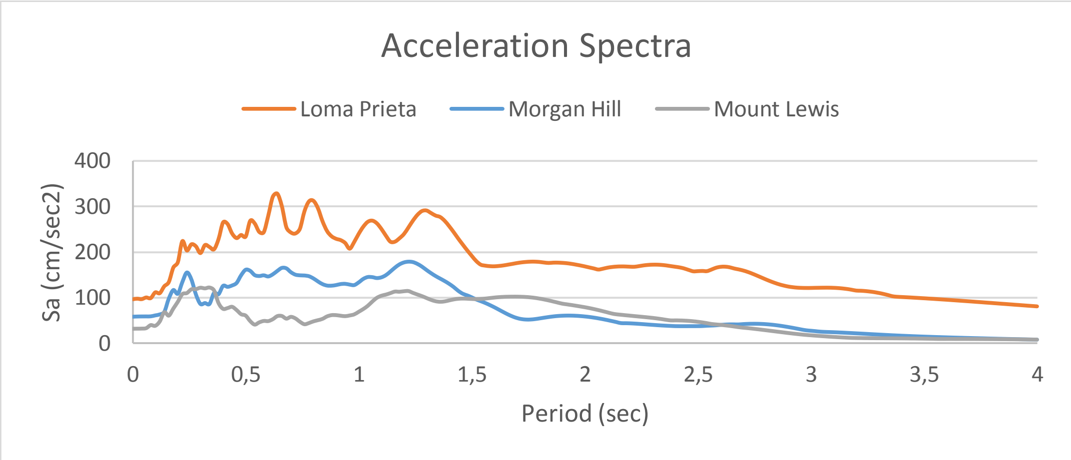

Fig. 4. - Comparison of acceleration spectra for Mount Lewis, Morgan Hill and Loma Prieta.

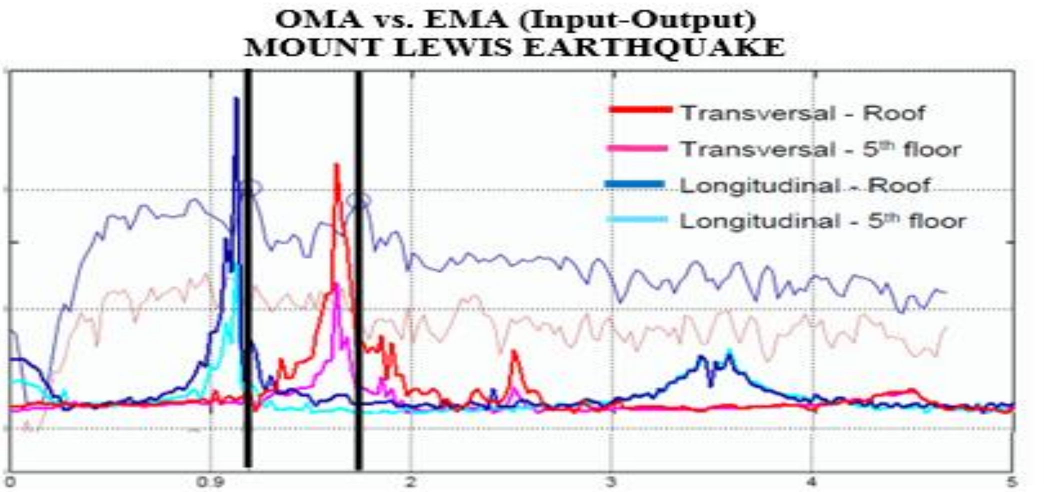

Fig. 5. OMA and input-output EMA results comparison in frequency domain for Mount Lewis.

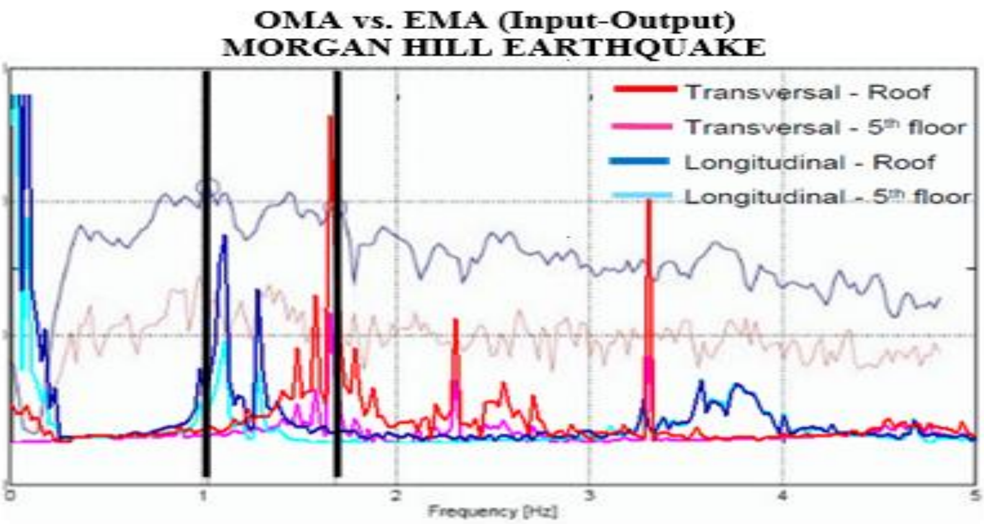

Fig. 6. OMA and input-output EMA results comparison in frequency domain for Morgan Hill.

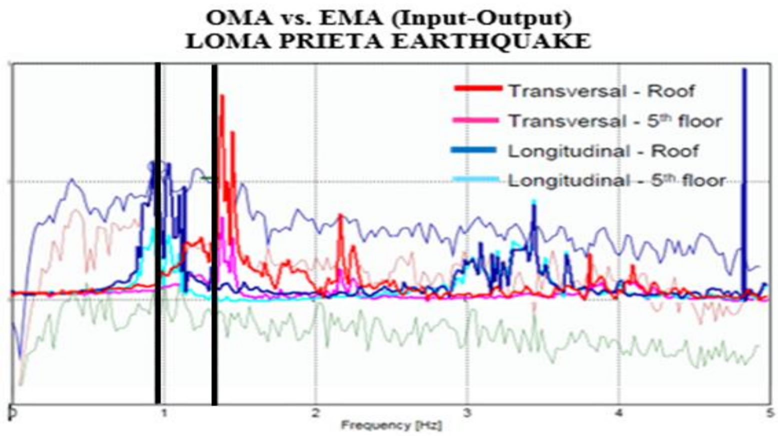

Fig. 7. OMA and input-output ema results comparison in frequency domain for Loma Prieta.

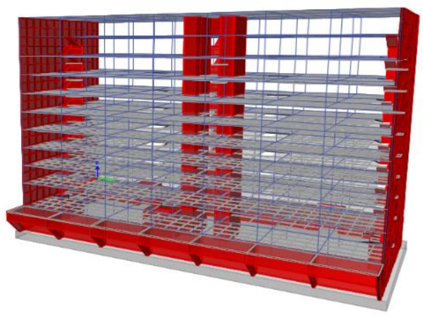

Fig. 8. 3D view of the ETABS model of the building.

4.3. Validation and updating of the model

In order to validate the model, time history analysis for the other two different earthquakes, one with a lower shaking (Mount Lewis) and the other one with a higher shaking (Loma Prieta) than Morgan Hill, were performed using the calibrated model. The same procedure used for Morgan Hill earthquake was followed. Whereas the model was performing well for Mount Lewis, the response of the model was not as good as expected for Loma Prieta. The results obtained for this last earthquake were not matching the experimental ones as desired.

The first and second natural frequencies, for the first calibrated ETABS model were compared to the ones obtained through modal analysis for each of the events. Both modal analysis techniques showed that the first natural frequency of the building occurs approximately at the same frequency of 1 Hz. However, the second natural frequency corresponding to the transversal mode of the structure slightly change depending on the earthquake. While for Morgan Hill, and consequently the calibrated FE model, this second natural frequency was shown to be 1.66 Hz, for Loma Prieta, the building responded more flexible with a natural frequency of 1.22 Hz. Therefore, a new FE model was created to capture better the less stiff response of the building under Loma Prieta earthquake.

No damage was detected in the building after any of the events. Consequently, none of the structural properties could have been changed. The increase of the flexibility of the building in the transversal direction, where the shear walls are acting as the lateral resisting system, for Loma Prieta event could be caused by the increase of the rocking effects. Hence, the first calibrated model was updated reducing the transversal stiffness of the springs from 0.1 $k/in/in^2$ to 0.02 $k/in/in^2$ and adding vertical springs in order to allow the building to rock. The natural frequencies of this second updated finite element model were compared to the ones obtained from the experimental data and a good match was obtained (see results in Table 2). The time histories and response spectra for acceleration, velocity and displacements obtained from the FE model for all of the channels were compared to the experimental data for each of the events. Good correlation coefficients between analytical and experimental results were obtained if the first calibrated model is used for Morgan Hill and Mount Lewis events and the more flexible updated model for Loma Prieta earthquake.

4.4. Results

The comparison between the experimental and analytical results is shown in this section. As mentioned in previous sections, natural frequencies, time histories and response spectra obtained from the FE model and the measured data are compared and good correlation is achieved.

4.4.1. Natural frequency comparison

The following table shows the natural frequencies obtained from both modal analysis techniques (OMA and input-output EMA) and compares them to the natural frequencies of both FE models (the first calibrated model and the more flexible updated model).

As mentioned in previous sections, a first longitudinal natural frequency of around 1 Hz was captured accurately by all the performed experimental modal analysis. Both FE models present the same natural frequency in that direction too. However, for the transversal direction either OMA or input-output EMA show a natural frequency decrease for Loma Prieta earthquake. The more flexible FE model matches this lower first transversal natural frequency of the structure (of around 1.25 Hz).

Table 2. First natural frequencies in longitudinal and transversal direction obtained from the experimental data and the FE models

EARTHQUAKE	Experimental				FE Model			
	OMA		Input-Output EMA		First Model		Flexible Model	
	$f_{1st\ longitudinal}$	$f_{1st\ transversal}$	$f_{1st\ longitudinal}$	$f_{1st\ transversal}$	$f_{1st\ longitudinal}$	$f_{1st\ transversal}$	$f_{1st\ longitudinal}$	$f_{1st\ transversal}$
Morgan Hill	1.03	1.66	1.1	1.65	1.06	1.66	1.07	1.28
Mount Lewis	1.07	1.56	1.12	1.65				
Loma Prieta	0.95	1.22	1.05	1.35				

4.4.2. Time history comparison

The first calibrated model was used to perform a time history analysis of the structure for Morgan Hill and Mount Lewis earthquakes, while the second updated model was used for Loma Prieta earthquake. The comparison between the absolute acceleration, velocity and relative displacement time histories for the recorded motions and the analytical motions show a good match in all the channels. The models captured the peaks, frequencies and values of the time histories quite accurately. The correlation coefficient (C.C.) between the experimental and analytical data was also calculated. The average of the C.C. for all the events was 85% with a minimum of 73%, which indicates a good correlation for practical purpose.

The relative displacements were obtained by subtracting the displacement at the basement to the total displacement of each channel. Therefore, the relative displacements account for the displacements due to the rocking and bending of the structure. Fig. 9 shows the comparison of the time histories of acceleration, velocity and relative displacement for two channels at the roof of the building, channel 5 (longitudinal) and 4 (transversal) for Morgan Hill earthquake.

4.4.3. Response Spectra Comparison

Acceleration, velocity and displacement spectra of the recorded measurements and the obtained from the finite element model were compared. 5% damping was considered for all the cases. Velocities and displacements for the measured data were obtained by integration of the recorded acceleration.

For all the events in all the channels good correlation was obtained in the studied period range of 0 to 4 sec. In all the cases, the highest error were obtained for both first natural periods of the structure; T = 1 sec / f = 1 Hz in longitudinal direction and T = 0.6 sec / f = 1.6 Hz (for Morgan Hill and Mount Lewis) and T = 0.77 sec / f = 1.2 Hz (for Loma Prieta) in transversal direction. For the rest period values, in which the structure is not excited that much, the FE model perfectly matches the response of the real building. The average of the maximum errors obtained at the peaks from the response spectra for each channel is computed; resulting in 11.4% for acceleration spectra and 15% for velocity and displacement spectra.

Figs. 8, 9 and 10 show the acceleration, velocity and displacement spectra obtained for Loma Prieta earthquake in the longitudinal direction. As explained above, the difference between the data measured by CSMIP and the FE model is higher at the main peak. Responses at the 5th floor and roof are plotted as well as the input in the basement.

5. Discussion of the Results

The results presented in the previous section showed that the response of the building under higher level of shakings can be captured by a proper modeling of the soil structure interaction (case of more flexible FE). Lower stiffness spring foundation will let the building to rock, increasing the horizontal motion of the structure and decreasing the natural frequencies. The following formulation shows the relation between the frequencies for a fixed system (w_{fix}) and a system accounting for SSI (w_{SSI}).

$$w_{SSI} = \frac{w_{fix}}{\sqrt{1+\frac{k_c}{k_h}+\frac{k_c * h^2}{k_r}}} \quad , \tag{1}$$

where h is the height of the structure, k_c the stiffness of the structure, k_h and k_r the translational and rotational stiffness of the structure respectively. In case of fixed base, k_c and k_r are equal to 0;hence, w_{fix} = w_{SSI}. However, if k_h and k_r are considered w_{SSI} will be reduced. Hence, it is proved that the net effect of accounting for SSI is a reduction of the fundamental frequency.

The importance of the proper design of the soil structure interaction in the model is fundamental to characterize the real response of the building. It also was shown that the intensity of shaking affects the soil-structure interaction, becoming softer and more important for stronger shaking (Loma Prieta case) than for lower shaking (Mount Lewis and Morgan Hill cases).

6. Conclusions

Modal identification of a ten-story concrete shear wall building located in San Jose, California, was performed using OMA and input-output EMA. The recorded motions during Morgan Hill, Mount Lewis and Loma Prieta earthquake at different levels and locations of the structure were used. It was demonstrated that for the stronger shaking record, Loma Prieta, the building presented a lower fundamental frequency in the direction of the shear walls than for the other two earthquakes.

A FE model of the building was manually calibrated using the recorded motions during one of the low intensity shaking earthquakes (Morgan Hill). The natural frequencies obtained from the FE model were compared to the ones obtained through both experimental modal analysis approaches. Acceleration, velocity and relative displacement time histories, as well as, response spectra for the measured and the data obtained from the FE model for different channels were also compared. Good match between the experimental and analytical results was obtained for the two low intensity earthquakes (Mount Lewis and Morgan Hill). Nevertheless, a new more flexible FE model needed to be created in order to capture correctly the more flexible transversal response of the structure during Loma Prieta earthquake. For this last model softer springs were added to the base allowing the structure to rock.

In conclusion, in some cases soil-structure interaction becomes important and cannot be neglected. The nonlinear behavior of the soil could significantly affect in the prediction of the response of certain buildings. Modeling a building without considering these effects may not be enough to capture properly the behavior of the building under different ground motions.

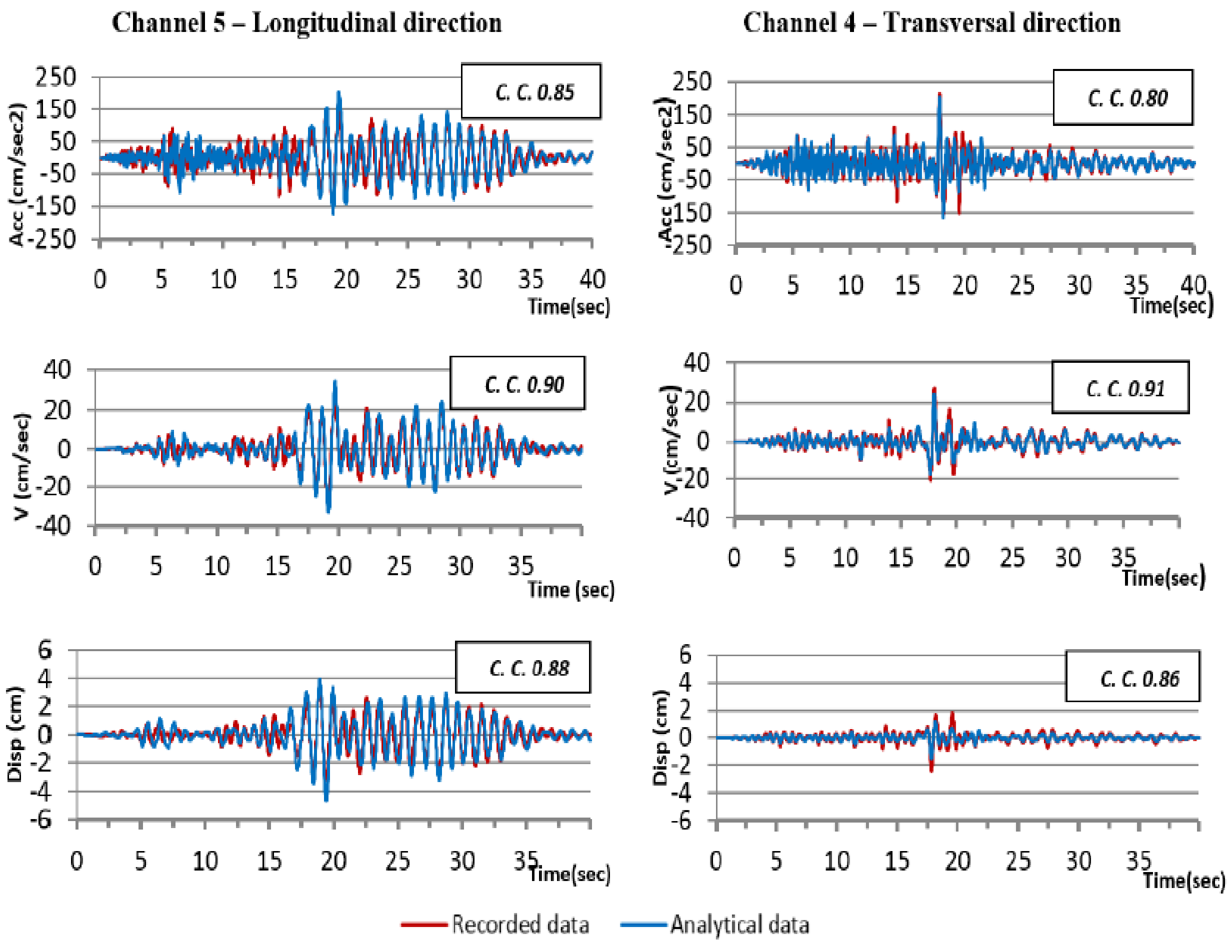

Fig. 9. Recorded and analytical acceleration, velocity and relative displacement time histories at channels 5 and 4 for Morgan Hill earthquake.

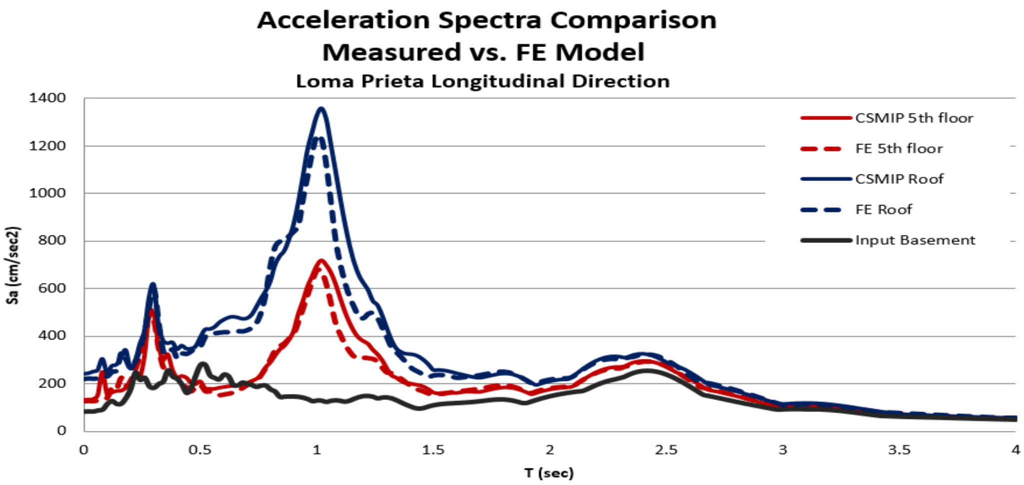

Fig. 10. Acceleration spectra comparison for loma prieta earthquake in the longitudinal direction of the structure.

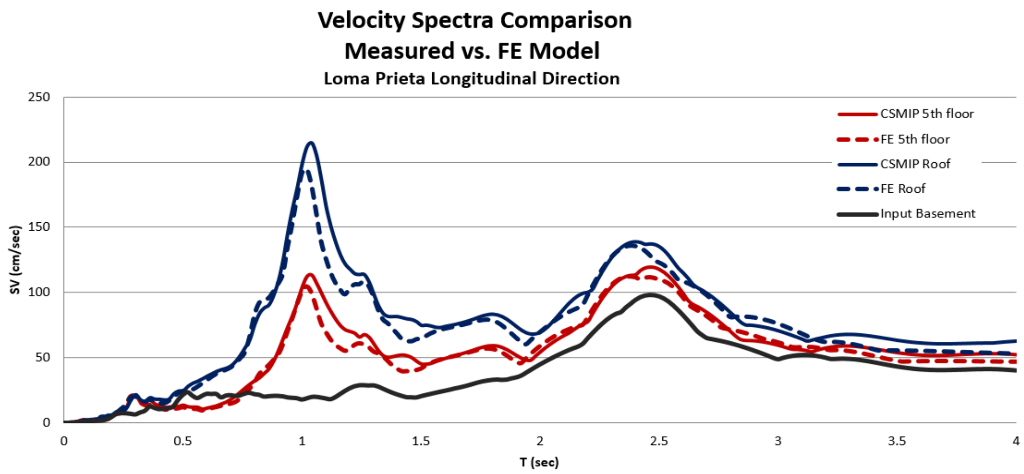

Fig. 11. Velocity spectra comparison for loma prieta earthquake in the longitudinal direction of the structure.

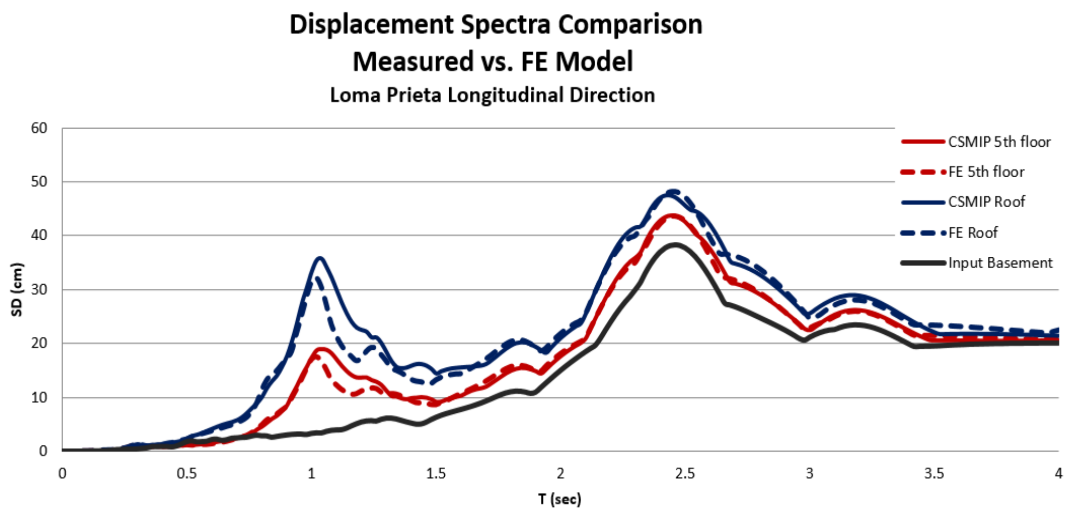

Fig. 12. Displacement spectra comparison for loma prieta earthquake in the longitudinal direction of the structure.

REFERENCES

CESMD (2016). Center of Engineering Strong Motion Data. http://www.strongmotioncenter.org. Downloaded on 10-01-2016.

Gazetas G (1983). Analysis of machine foundation vibrations: State of the art. *International Journal of Soil Dynamics and Earthquake Engineering*, 2(1), 2-42.

Martinez AV (2015). Modeling of a Building Subjected to Different Ground Motions. IMAC XXXIII, Springer Inc., Orlando, USA.