PERIOD VARIATIONS IN A SHEAR WALL BUILDING DUE TO EARTHQUAKE SHAKING

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The article presents the study of modal parameter variations of a 9 story, shear wall building during several seismic events, including the Mw=8.8, 2010 Chile Earthquake. The building, located at the Faculty of Engineering at the University of Chile, was built in 1962 and has been instrumented with a continuous monitoring network since March 2009. The network includes 8 accelerometers, located at three different levels of the building, 3 soil humidity sensors beneath its foundation and a nearby weather station. The main purpose of the system is to monitor and correlate the dynamic behavior of the building for different ambient conditions and shaking levels.

This study is based on the seismic records obtained for the building during the Mw=8.8 Chile Earthquake and 30 of its aftershocks, in addition to the events recorded before the main-shock.

A study of the variation in the modal parameters of the building during each seismic event is performed, using a parametric Multiple Input Multiple Output (MIMO) identification technique. Medium and low level earthquakes caused only transient variations in the modal parameters of the building, which disappear after the strong shaking has ended. In the case of the large 2010 Earthquake, despite the low structural damage detected after the event (only minor cracks in shear walls and non-structural elements), significant and permanent changes in the modal parameters are observed, with modal periods increasing up to 41% during the main-shock, showing a permanent average increase of 14% for the first six modes after the event.

Finally, the correlation between the identified modal parameters and the severity of shaking is also determined.

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The article presents the study of modal parameter variations of a 9 story, shear wall building during several seismic events, including the Mw=8.8 2010 Chile Earthquake. The building, constructed in 1962, has been instrumented with a continuous monitoring network since March 2009. The network includes 8 accelerometers and 3 soil humidity sensors beneath the foundation. The main purpose of the system is to monitor and correlate the dynamic behavior of the building for different ambient conditions and shaking levels.

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1 INTRODUCTION

For the last 2 decades, several structural health monitoring studies have analyzed the variations in the modal parameters of structures. These parameters, such as periods, damping ratios and mode shapes, represent the dynamic behavior of a structure, so any appreciable change in their values could indicate an abnormal behavior or damage to the structure.

Previous studies have shown variations of the modal parameters for different levels of structural damage after high intensity earthquakes. For instance, modal frequencies have shown permanent variations from 11% for small degree damage, Clinton, Bradford, Heaton & Favela (2006), to more than 30% for structures with severe damage, Todorovska & Trifunac (2008).

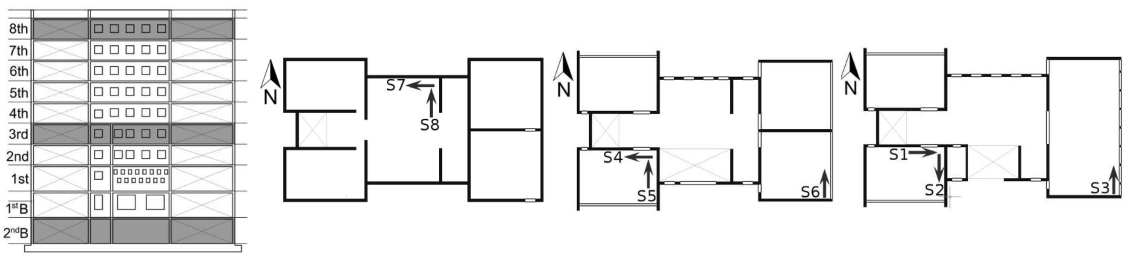
As part of a research project, the Torre Central Building, located at the School of Engineering at the University of Chile, contains a continuous structural monitoring network since March 2009. As a result, in this building not only we have recorded the Mw=8.8 February 27th, 2010 Chile Earthquake but also several low and medium level earthquakes. This situation allows to evaluate the variations of the modal parameters of the building during events of different intensity of shaking.

2 BUILDING DESCRIPTION AND SENSOR LAYOUT

The Torre Central Building, located at the School of Engineering at the University of Chile, is a 9 story and 2 underground levels reinforced concrete shear wall building, Figure 1. The structure, built in 1962, is 30 meters high; with a nearly rectangular floor shape of 30 x 19 meters and a total plan area of 4600 square meters. The typical wall thickness is 0.35 meters, with an average wall area to plan area ratio of 7.7%. All floor slabs are 0.25 meters thick. The foundation soil is dense gravel, corresponding to a soil class C according to the ASCE7-10 code. Since its construction, the office building has experienced several structural and non-structural renovations, such as wall openings, a new steel façade, the addition of non-structural elements (partition walls, ceilings), etc.

In March 2009 a continuous monitoring network was installed in the building, Yanez (2009). The main purpose of the system is to monitor and correlate the dynamic behavior of the structure for different ambient conditions and shaking levels. The monitoring network comprises an array of eight accelerometers on the building and three soil-humidity sensors beneath its foundation. The network is also connected to a nearby weather station. The accelerometers were located at three different levels: two at the base and three on both 3rd and 8th floors, Figure 2.The monitoring system was set to record with a sampling rate of 200 Hz.

Figure 1. Torre Central Building, general views.

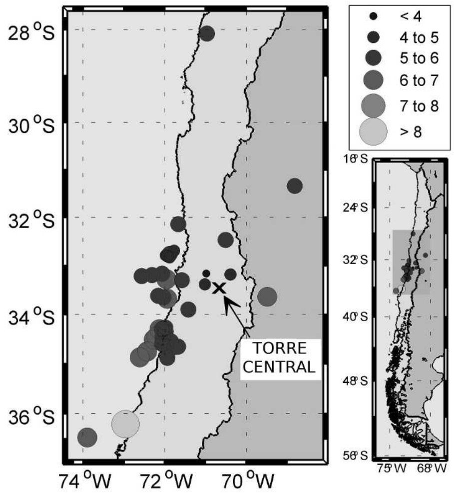


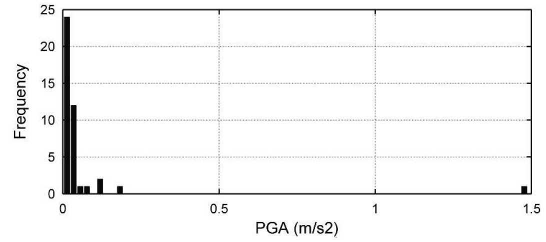
(a) Instrumented stories (b) Second Basement. (c) Third Floor. (d) Eighth Floor.

Figure 2. Torre Central Building. Sensor Layout.

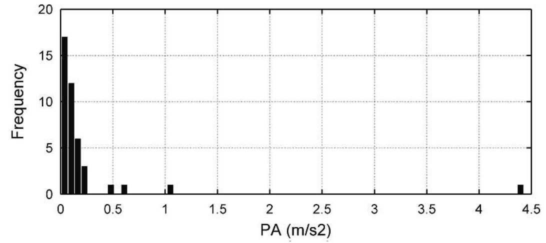
3 DESCRIPTION OF SEISMIC RECORDS

For this study, a total a 42 seismic events were recorded in the building, between September 2009 and May 2010. These records include the Mw 8.8 event, 30 of its aftershocks, and 11 earthquakes preceding the main-shock. The magnitude of the seismic events ranged between 3.9 and 8.8. Recorded Peak Ground Accelerations (PGA) ranged between 0.003 m/s2 and 1.5 m/s2, meanwhile recorded Peak Accelerations in the structure (PA) ranged from 0.008 to 4.4 m/s2.





(b) Histogram of Peak Ground Accelerations



(a) Earthquake epicenters - magnitudes (c) Histogram of Peak Accelerations

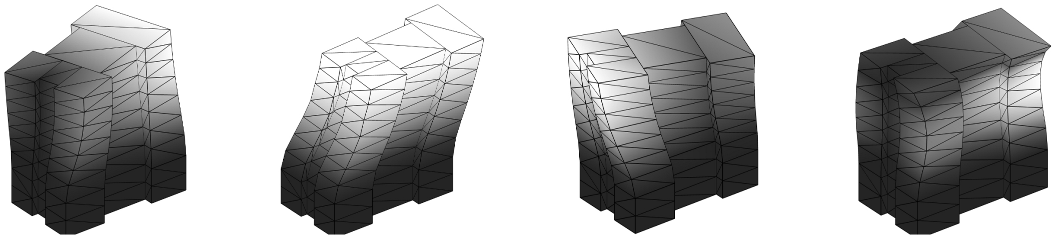
Figure 3. Properties of seismic events.

4 AMBIENT VIBRATIONS RECORDS ANALYSIS

Besides strong motion records, the monitoring system in the building is also continuously recording ambient vibration records. As part of additional studies on the building, these records have been analyzed using a Stochastic Subspace Identification Technique (SSI, Van Overshee & De Moor (1996)). The results of such analysis show the permanent increase in the modal periods of the structure after the Mw 8.8 seismic event, with an average of 14% for the first 6 modes, Table 1. Modal damping ratios display greater relative differences, but they fall within the expected error in the identification results for this parameter. Mode shapes, Figure 4, show only small variations after the main-shock as can be seen from its MAC values, Figure 5.

Table 1. Modal parameters before and after the earthquake. Ambient vibrations analysis.

	Before Earthquake		After Earthquake		Difference (%)	
Mode	Period (sec)	Damping (%)	Period (sec)	Damping (%)	Period	Damping
1	0.45	0.7	0.53	0.7	18.6	0.0
2	0.38	0.7	0.44	0.7	14.0	0.0
3	0.34	0.7	0.37	0.8	10.9	14.3
4	0.16	1.2	0.18	0.9	15.5	25.0
5	0.13	1.5	0.15	1.3	12.1	13.3
6	0.13	0.9	0.14	1.0	12.4	11.1



(a) Mode 1 (b) Mode 2 (c) Mode 3 (d) Mode 4

Figure 4. Identified mode shapes from ambient vibrations records [1].

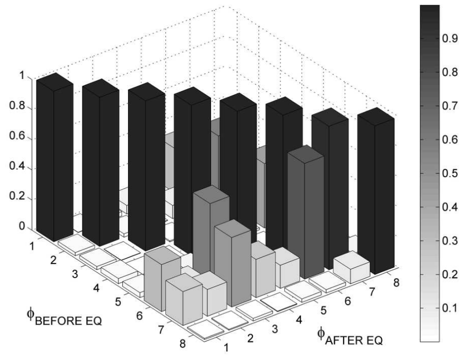


Figure 5. MAC values. Mode shapes before and after the large 2010 Earthquake.

5 SEISMIC RECORDS ANALYSIS

5.1 System identification Technique

The modal parameters of the building during seismic events were obtained using a parametric Multiple Input - Multiple Output Identification algorithm (MIMO, Beck (1976); Mau & Li (1991)). Based on the dynamic equilibrium equations ((1), (2)), the algorithm looks for the optimal combination of modal parameters that best fits the measured response in the building. The goodness of fit error for the estimated modal parameters, namely the target function of the optimization process in the MIMO algorithm, is a weighted least-square-error function, (3), between the recorded accelerations and the corresponding response estimations for all instrumented points.

$$\ddot{y}_j(t) + 2\cdot\omega_j\cdot\xi_j\cdot\dot{y}_j(t) + \omega_j^2\cdot y_j(t) = \sum_{i=1}^{r} L_{j,i}\cdot ag_i(t) \tag{1}$$

$$a_p(t) = \sum_{j=1}^{N} \phi_{j,p}\cdot\ddot{y}_j(t) \tag{2}$$

$$E = \sqrt{\frac{\sum_p \alpha_p \sum_t \left(a_{0,p}(t) - a_p(t)\right)^2}{\sum_p \alpha_p \sum_t \left(a_{0,p}(t)\right)^2}} \tag{3}$$

Where ω_j is the modal angular frequency, ξ_j the modal damping ratio, $L_{j,i}$ the modal participation coefficient for base acceleration $ag_i(t)$, and $\phi_{j,p}$ the mode shape

[1] Mode shape figures were taken from modal analysis results using MACEC Matlab toolbox (http:// bwk.kuleuven.be/bwm/macec). Mode shape values were obtained from a spline interpolation between the identification results of the two instrumented floors.

component at position *p*. Additionally, $a_{0,p}(t)$ and $a_p(t)$ are the measured and estimated responses at position *p* respectively. For equation (3), α_p are the weight coefficients, defined by the user, that control the influence of each channel of a seismic record in the optimization process. Finally, the goodness of fit error function, (3), also includes a normalization component: $\sum_p \alpha_p \sum_t \left(a_{0,p}(t)\right)^2$.

5.2 Data analysis considerations

The following provisions were taken in the identification process of the 42 analyzed seismic records:

- All channels of the seismic records were included in the process. Channel 7 and 8 at the base, Figure 2, were the input of the MIMO algorithm, whereas Channels 1 to 6 were the corresponding output.
- Before the application of the MIMO algorithm, all input and output records were filtered using a low-pass filter with 10Hz as the cutoff frequency.
- Only the strong shaking stage of each record was considered in the identification process. For the purposes of this study, the strong shaking stage of a seismic record was defined from a Husid plot (normalized Arias Intensity over time, Husid (1969)), setting the lower and upper limits as 0.02 and 0.98 respectively.
- The strong shaking stage of each record was analyzed using a moving window of 3 seconds length and 50% overlap between consecutive windows. With this procedure equivalent linear modal parameter variations during each window can be determined.

5.3 System Identification results

Over the 42 analyzed seismic records, modal parameters were identified for a total of 1700 3-seconds windows, with an average goodness of fit error, (3), of 8.6%, Figure 6. Based on previous studies using the MIMO Identification Algorithm, Carreno & Boroschek (2010), identified modal parameters in a seismic record are assumed to be accurate for analysis when the goodness of fit error is less than 15%, this criteria is also applied in this paper. An example of the goodness of fit is presented in Figure 7.

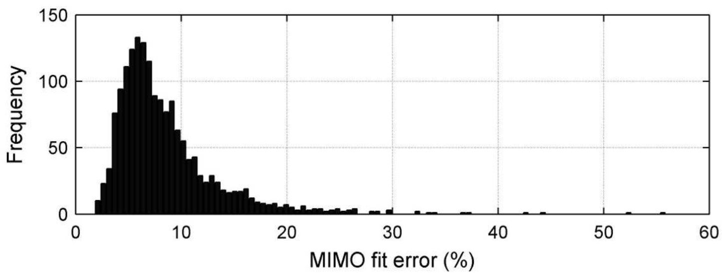
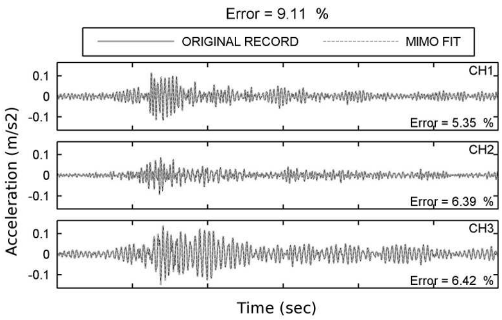
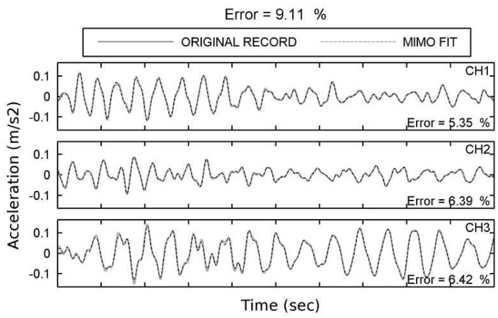


Figure 6. Histogram of MIMO fit error results.



(a) MIMO fit example. Strong shaking stage



(b) MIMO fit example. Zoom [12-22] seconds

Figure 7. MIMO fit example. Seismic event: 02/27/2010, 06:46 Hrs (GMT) (aftershock).

5.4 Modal periods analysis

5.4.1 Shaking level definition

The study of the structural nonlinear behavior of the building, during seismic events, is performed by estimating the correlation between identified modal periods and the severity of shaking. A number of definitions for the severity of shaking have been tested in previous studies, Carreno & Boroschek (2010), including Peak Ground Accelerations (PGA), Peak Accelerations (PA), Root Mean Square values (RMS), etc. From all tested definitions, a “modal RMS” criterion had the best correlation with the identified modal parameters. In this procedure, first a frequency band is defined as reference for each identified predominant frequency. Second, a band-pass filter, with cutoff frequencies defined by the mode’s frequency-band, is applied to the response records. Third, the RMS value of each filtered channel is determined. Finally, the level of shaking corresponds to the scalar projection of the RMS vector in the direction of the estimated mode shape, (4).

$$RMS_{\text{mode j}} = proj\left(\sqrt{\frac{1}{N}\sum_{t=1}^{N}\left(\left\{a_0(t)\right\}_{filt\left(\left[f_{j,1}-f_{j,2}\right]\right)}\right)^2}, \left\{\phi_j\right\}\right) \quad (4)$$

In equation (4), $\left\{a_0(t)\right\}_{filt\left(\left[f_{j,1}-f_{j,2}\right]\right)}$ are the response records of all channels over time, the subscript $filt\left(\left[f_{j,1}-f_{j,2}\right]\right)$ indicate the time-series are filtered with cutoff frequencies ($f_{j,1}$ and $f_{j,2}$) around the corresponding modal frequency. Additionally, $\left\{\phi_j\right\}$ is the mode’s estimated mode shape, and the *proj* function projects $\sqrt{\frac{1}{N}\sum_{t=1}^{N}\left(\left\{a_0(t)\right\}_{filt\left(\left[f_{j,1}-f_{j,2}\right]\right)}\right)^2}$ in the direction of $\left\{\phi_j\right\}$.

5.4.2 The 2010 Chile Earthquake

From all analyzed seismic records, only the Mw 8.8 event caused a permanent change in the modal periods of the building, Table 1, despite only minor structural and non-structural damage was detected afterwards. The MIMO Identification results show large average increases in the first 4 modal periods of the structure, reaching a maximum of 41% during the event, and 23% at the end of it, Figure 8. These results are both compatible with the SSI analysis over ambient vibration records, Table 1, and resemble the results of other lightly damaged buildings due to a high intensity earthquake; Clinton, Bradford, Heaton & Favela (2006).

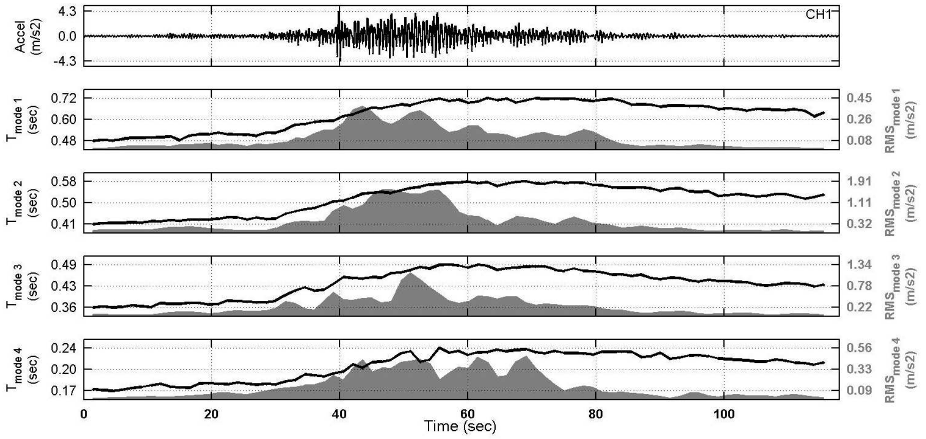


Figure 8. Evolution of modal periods during the Mw 8.8 earthquake.

Figure 8 shows an abrupt increase in all modal periods when the defined shaking level reaches its maximum values, in the time interval between 30 and 60 seconds. After such increase, modal periods stabilize and start to decrease up to the end of the seismic record. From this behavior of the modal periods, it is presumed that most of the permanent modal modifications took place in this [30 – 60] seconds time window.

5.4.3 Modal periods vs shaking level

Given the correlation distinguished between modal periods and shaking level of the structure during the Mw 8.8 Earthquake, Figure 8, further analysis of this behavior is performed. Figure 9 shows the identified modal periods over the defined shaking level, (4), for all seismic records before and after the large 2010 seismic event. Each graph also includes a tendency line for each of the two stages.

From Figure 9, modal periods of the first three modes of the building show a clear increasing relation with the severity of shaking. Furthermore, modal periods tend to stabilize as the shaking level increases, an expected behavior when no structural damage is caused by the seismic event. As for the magnitude of the change within the analyzed shaking levels, Figure 9, tendency lines show, on average, a maximum increase of 14% in the modal periods before the Mw 8.8 earthquake, meanwhile such increase reaches an 18% for the results after the event.

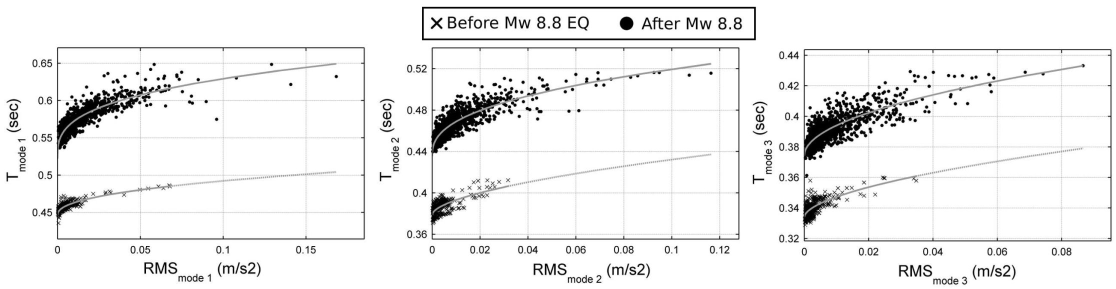


Figure 9. Modal periods vs. shaking level. Modes 1 to 3 before and after Mw 8.8 Earthquake.

6 CONCLUSIONS

In this study, the dynamic behavior of a 9 story shear wall building, located in Chile, is analyzed using 42 seismic records, obtained from September 2009 to May 2010. These records include the Mw 8.8 earthquake occurred in central Chile on February 27th 2010, and 30 of its aftershocks.

The structural nonlinear behavior of the building during the seismic events was assessed using the variation in its modal periods, which were identified using a parametric Multiple Input - Multiple Output (MIMO) identification algorithm.

From all analyzed seismic records, the Mw 8.8 earthquake not only caused the largest transient increase in the modal periods (41%), but it is also the only one generating a permanent change in their values (14%).

For the purposes of this study, a "modal level of shaking" was defined. The correlation analysis between this definition and the modal periods for non-damaging earthquakes was performed, finding a clear increasing relation between the two. For the analyzed range of shaking levels, modal periods increase up to 14% for seismic events before the large 2010 earthquake, and 18% for seismic events after it.

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