SEISMIC DAMAGE DETECTION OF A CONCRETE BUILDING MODEL USING MEASUREMENTS OF AMBIENT VIBRATION TESTS

J. Valdés, J. De la Colina & C.A. González
Facultad de Ingeniería, Universidad Autónoma del Estado de México, México.

SUMMARY:
This paper presents a laboratory study of a representative model of a two-level reinforced concrete building which was progressively damaged until it reached a severe structural damage. The model was subjected to different progressive dynamic load stages that were representative of increasing earthquake ground motion intensities. This was achieved by using a testing pendulum, which is a device similar to a shaking table that excited the model attached to its platform with a harmonic motion along one horizontal direction at selected frequencies. It was possible to induce several "seismic" damage levels to the model. After each reached damage level, ambient vibration tests were performed and dynamic properties of the model were obtained. It was possible to characterize the damage level of the concrete building model in terms of the variation of its transfer functions amplitudes valued at the first modal frequency obtained from ambient vibration tests.

Keywords: detection, seismic damage, buildings, tests, ambient vibration

1. INTRODUCTION

All civil structures are exposed to damage and deterioration during their life. In particular, buildings located in seismic zones experiment earthquakes that may affect their structural integrity in different levels. For these buildings it is important to develop techniques and methods that allow estimating in a reliable way the possible damage caused by high intensity earthquakes. After a seismic event it is important to evaluate immediately its structural damage in order to make a fast decision about the possible building evacuation. A reliable first inspection is essential to avoid discomfort or risk to building occupants. The early detection of structural damage in different civil structures (buildings, bridges, dams, conduction and transmission lines, etc) is an issue of special interest, since it can prevent in last instance the collapse of these structures, avoiding human and economic losses. Currently, there are different non destructive methods developed for the evaluation of structural damage. They can be classified in two groups: the conventional methods and the dynamic methods. Among the conventional methods are: the visual inspection, the acoustic emission, the radiograph, the ultrasonic and so on. For instance, references of the use of these methods may be found in (Prine, 1998; Voigt et al., 2003; Wang, 2004; Rhazi, 2006). The main disadvantage of the conventional methods is that their application is not practical since they require know a priori the damage vicinity and free access to inspection zone, which does not happen in all cases (Salawu and Williams, 1995). Particularly in buildings, this is an important aspect because the structure of most buildings is covered by different non structural elements such as plafonds, false ceilings, division walls, etc., that preclude in a high grade the application of conventional inspection methods. Currently, the most common inspection method used in buildings after the occurrence of a high intensity earthquake is the visual inspection. In addition to the inconveniences cited before, the visual inspection needs to be made by qualified personnel whose judgment about the damage could be subjective and depends, in general, on the experience of the inspector. Most evaluation of this type for concrete buildings consists on quantifying and measuring the crack widths of structural elements and to relate these measurements with a certain damage level. Based on this visual inspection, decisions related to building evacuation or conducting detailed studies are made. The large number of building structures that need to be evaluated after an intense earthquake and the small number of qualified personnel that can perform these visual inspections shows the necessity of changing conventional inspection for automatic and more reliable methods.

In contrast, the dynamic methods are based on the vibration measurements of the structure to evaluate the damage. These methods are supported on the hypothesis that any structural damage represents a degradation of the structure stiffness which will modify their building dynamic properties (natural frequencies, modal damping ratios, mode shapes (including derivatives), etc.). Dynamic methods seem to be one of the most practical procedures for damage detection. They have the advantage of not requiring a priori information about damage location, nor complete free access to inspection zones. Studies using these types of methods have been carried out with results that show the advantages of using them. Doebling et al. (1996) present an extensive description of different dynamic methods and a literature review related to them. The future for dynamic methods is promissory, but there are many questions to be solved before they can be reliably applied in an extensive way.

This paper presents a laboratory study of a representative model of a two-level reinforced concrete building which was progressively damaged until it reached a severe structural damage. Unlike other similar experimental studies in which the structural damage was made in an “artificial” way, in this study the model was subjected to different progressive dynamic load stages that were representative of increasing earthquake ground motion intensities. This was achieved by using a testing pendulum, which is a device similar to a shaking table that excited the model attached to its platform with a harmonic motion along one horizontal direction at selected frequencies. Using this device, it was possible to induce several “seismic” damage levels to the model. After each reached damage level, ambient vibration tests were performed and dynamic properties of the model were obtained. The objective of the study was to characterize the damage level of the concrete building model tested on laboratory in terms of the variation of some characteristic related to its dynamic response calculated through ambient vibration tests. It was possible to characterize the damage level of the concrete building model tested on laboratory in terms of the variation of its transfer functions amplitudes valued at the first modal frequency of the model.

2. TESTING PENDULUM

The testing pendulum used in the experiments consists of a steel platform, which is hanged from the laboratory roof by four steel tensors. On the platform an eccentric mass exciter with vertical rotation axis is attached, which transmits to the pendulum platform a harmonic force in the longitudinal direction (Fig. 1). This force can be applied to different constant frequencies and amplitudes. The mechanism causes that during a test the pendulum platform presents a harmonic longitudinal motion. The reinforced concrete model was attached to the platform in such way that during a test the translation of the platform was transmitted to the model as if it was the ground motion occurred during an earthquake (see Figs. 2 and 3). The natural period of the whole system (pendulum plus model) was large enough compared with the modal vibration periods of the studied model alone, so it was possible to consider that both systems were virtually uncoupled. Only longitudinal motion of the pendulum platform was allowed during tests. Platform torsion was avoided with steel guides (see Fig. 3). Additional information about testing pendulum may be consulted in De la Colina and Valdés (2010).

Figure 1. Forced vibration generator (shaker) attached to the testing pendulum platform

Figure 2. Testing pendulum with the reinforced concrete model used for the identification of structural damage

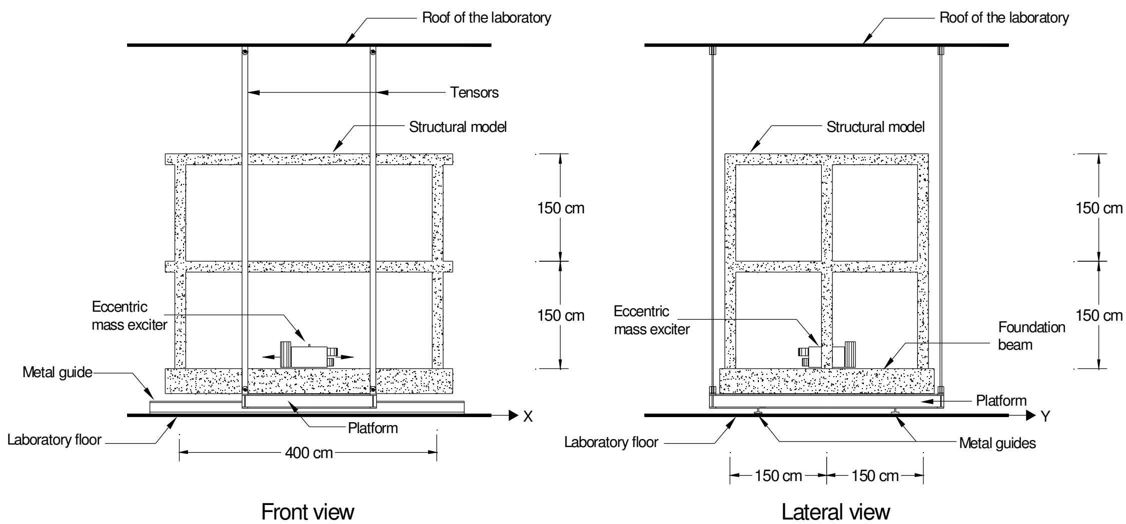


Figure 3. Front and lateral view of the testing pendulum with the tested model

3. EXPERIMENTAL MODEL

The reinforced concrete model used to study damage detection was a two-story building formed by orthogonal frames. The model plan dimensions were 4.00 m in the X direction and 3.00 m in the Y direction. In the X direction the model had a single bay while in the Y direction it had two bays. The height of two model stories was 1.50 m. The direction of the exciter force and the translation of the testing pendulum platform corresponded to the X direction. The model did not have slabs but steel braces were added to enforce rigid diaphragm behavior. The model foundation consisted of reinforced concrete beams with dimensions of 20 cm (width) x 35 cm (height), which were attached to the testing pendulum platform by steel anchors that guaranteed that model did not have any shift or rotation relative to the platform during tests. The model columns were anchored directly to the beam foundation. Fig. 4 shows the plan dimensions of the model (foundation and floors). Fig. 5 shows the dimensions, reinforcement detailing and material properties of different structural elements.

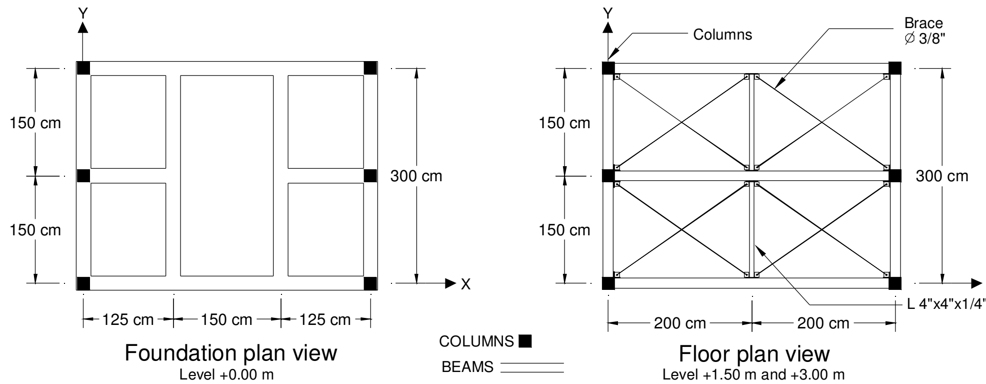


Figure 4. Plan dimensions of the model (foundation and floor beams)

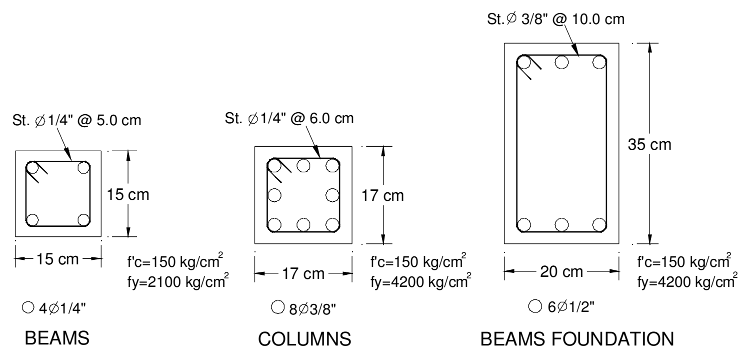


Figure 5. Reinforcement detailing for beams, columns and foundation beams, with their corresponding material properties

The dynamic response of the model was recorded by six accelerometers located as indicated next. One was located at the centre of the testing pendulum platform; three were in the first model level and two at the second model level. Fig. 6 shows the accelerometers location and the direction in which the signals were recorded. The model also was instrumented with five displacement transducers that recorded the translation of the model in the X direction corresponding to the acceleration channels 1 to 5. The accelerometers and the displacement measurers were synchronized.

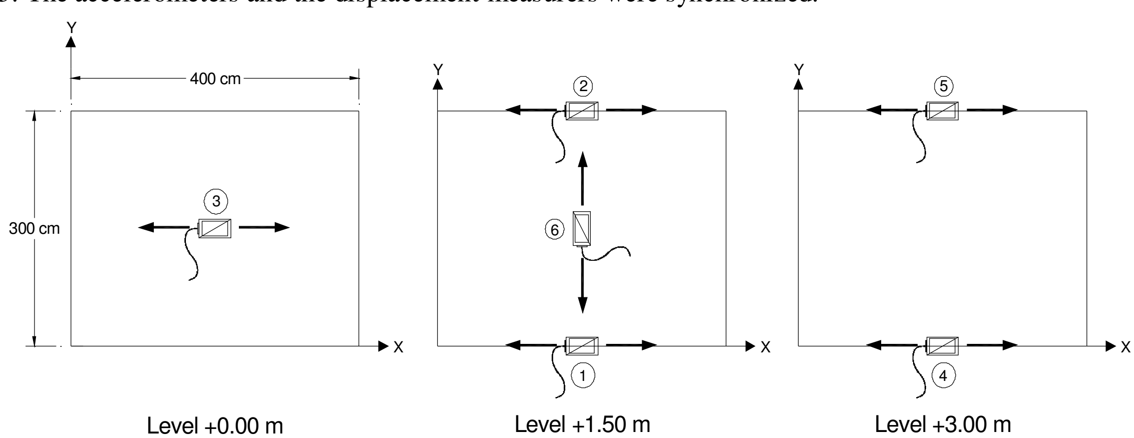


Figure 6. Location of accelerometers that recorded model vibration (record channels)

4. DAMAGE STAGES

Seventeen different damage stages were induced to the model by forced vibration tests. Each one corresponded to a specific test related to a particular operating frequency and rotational mass (applied force) of the exciter (shaker). Because the amplitude of the force induced by the shaker to the pendulum platform depends on operating frequency and rotational mass, this amplitude varied from one test to another. The rotational mass was increased progressively from one test to another in an approximate constant quantity. The shaker operating frequencies were f = 3.0 Hz for tests 1 to 6, f = 2.3 Hz for tests 7 to 9, f = 2.1 Hz for tests 10 to 14 and f = 2.0 Hz for tests 15 to 17. The frequency variation was necessary to attain approximate constant increments of the exciter induced forces. According to the variation of the operating frequency and rotational mass, and normalizing platform accelerations in terms of a shaker frequency f = 3.0 Hz, the maximum acceleration registered in testing pendulum platform (exciting intensity) increased approximately in a constant quantity from one test to another.

After each forced vibration test that produced a specific damage level in the model, an ambient vibration test was conducted. The ambient vibration tests consisted of recording during two minutes the vibration of the pendulum model system caused just by traffic and human activities in the surroundings of the laboratory. Because the model was located inside the laboratory, the wind did not excite it during these tests.

The accelerations obtained during all these forced and ambient vibration tests were baseline corrected and filtered in accordance with the recommendation of Chiu (1997). With this procedure, also displacement and velocity records were calculated.

To characterize the damage level for each forced vibration test, the maximum interstory drift corresponding to the upper model story was calculated (γ_{2nd}). This was achieved by using the calculated displacement obtained from accelerations recorded during the forced vibration test. These calculations were made within the steady state response. The interstory drift was calculated as the quotient of the relative displacement for the 2_{nd} story divided by the story height. Fig, 7 shows typical acceleration and displacement records obtained for test number 9 (N = 9).

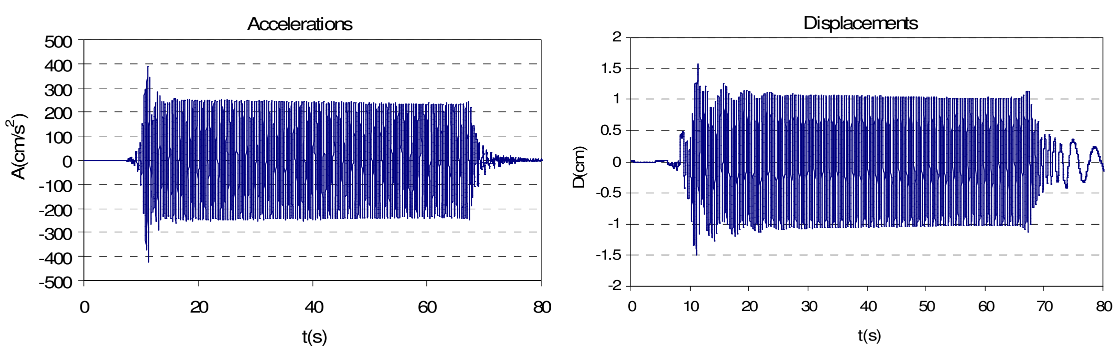


Figure 7. Acceleration and displacement records corresponding to channel 5 and test N = 9

Fig. 8 shows the values of the maximum interstory drift corresponding to the 2nd model story, calculated for each forced vibration test. It is clearly observed that the model remains in elastic behavior without apparent major damage during first six tests (N =1 to 6), that corresponds to values of γ_{2nd} < 0.0026. The first cracks were detected visually after the test N = 4 (γ_{2nd} = 0.0018). In accordance to the secant intersection criteria, the yielding point of the model was at γ_{2nd} = 0.005. Using an analytical model, it was corroborated that the yielding point was located nearly γ_{2nd} = 0.005. It could be established that yielding stage started from test N = 7. Considering that the largest interstory drift was close to γ_{2nd} = 0.03, then the largest ductility demand of the model was μ = 6.0 (approx.). The model was designed with the strong column and weak beam criteria, so the yielding stage corresponded to the case when all the model beams started their flexural yielding. Columns remained without major damage during all tests. Fig. 9 shows some of the beam cracks that appeared at different damage stages.

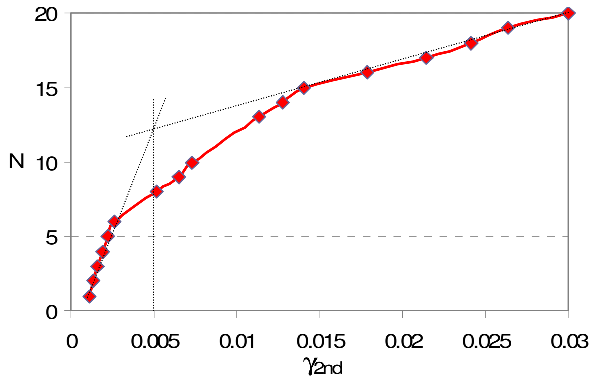
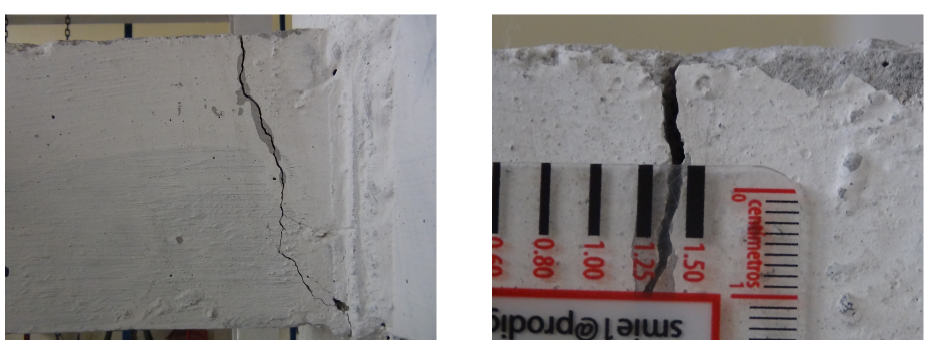


Figure 8. Plot showing the relation between the test number (*N*) and the maximum interstory drift of the second story (γ_{2nd}) reached during the steady state response of the corresponding test

a) Theoretical yielding point ($\gamma_{2nd} = 0.0051$, $N = 7$)



b) Yielding stage ($\gamma_{2nd} = 0.021$, $N = 14$)

Figure 9. Beams cracks at different damage stages

5. IDENTIFICATION OF DYNAMIC PROPERTIES

Using the acceleration data recorded during ambient vibration tests, the dynamic properties of the model were identified at each damage stage. Particularly, the first longitudinal translation modal frequency (f_1) and its corresponding modal shape were analyzed. Initially, the identification was made through the Fourier's amplitude spectrum. The data obtained by this nonparametric technique were verified using two parametric methods, a finite element model with nominal properties and a state-space identification model (MatLab, 2008). Considering that the records were obtained at 100 samples per second (d_t = 0.01 s), then 4096 points were enough to calculate spectra avoiding aliasing problem. Fig. 10 shows several Fourier's amplitude spectra corresponding to different damage stages that show the identification of f_1.

Fig. 11 shows the element finite model used as auxiliary to identify dynamic properties of the model.

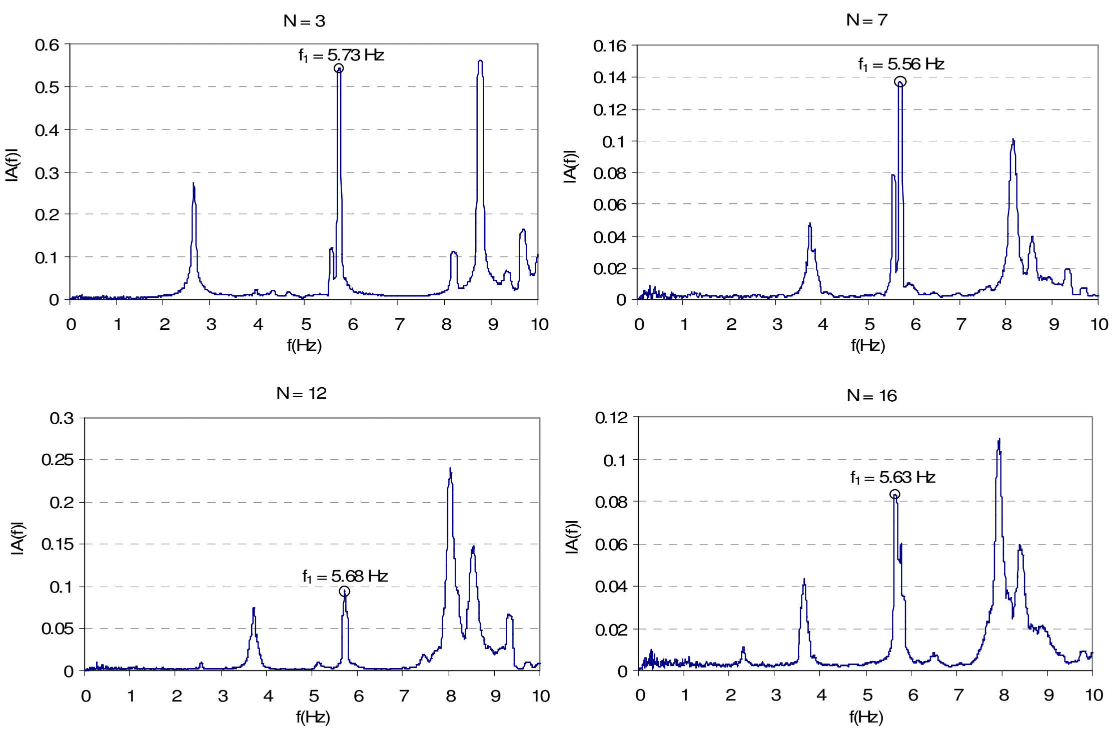


Figure 10. Fourier's amplitude spectra for different damage stages calculated with ambient vibration records

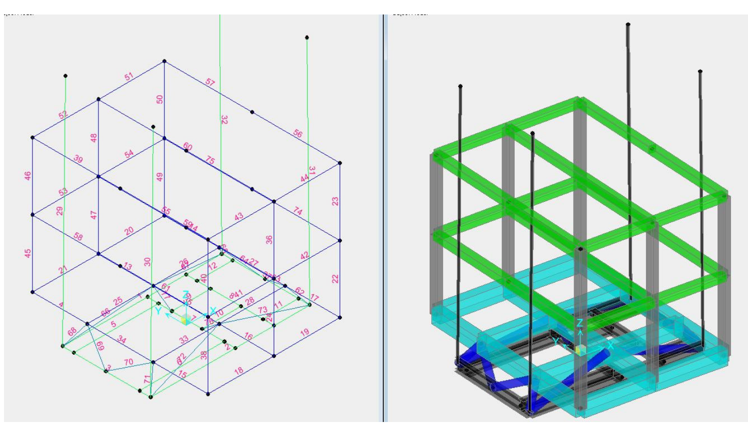


Figure 11. Finite element model used in identification of model dynamic properties

Fig. 12 shows the variation of f_1 as a function of the damage stage of the model. The variation is presented in terms of the difference in percentage of the f_1 value identified for each damage stage in comparison to the f_1 value identified for $N = 1$. It is observed how the variation reaches its maximum when $N = 7$ that is the stage when the model yielding point is reached, this difference is about 3%.

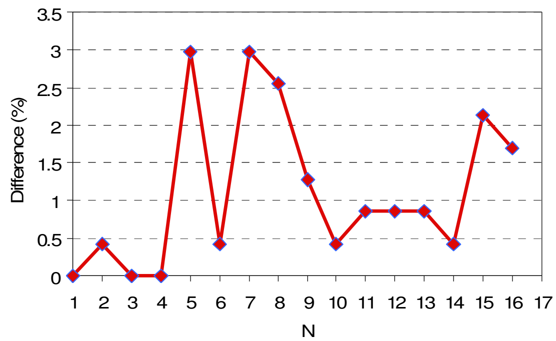


Figure 12. Variation of f_1 as a function of N in comparison to f_1 value identified for $N = 1$

In general, it is observed how the identified values of f_1 corresponding to different damage change very little. The maximum change that is about 3% occurs for tests $N = 5$ and $N = 7$ which correspond to the beginning of the yielding stage. For large ductility demands the difference is close to 2%. It is clear that this parameter does not give a good idea of the damage stage in the model. The *MAC* values (Allemang and Brown, 1982) were calculated from the identified modal shapes corresponding to f_1 for all damage stages. The *MAC* values were obtained to analyze the correlation between the modal shapes associated with a particular damage stage and the modal shape corresponding to $N = 1$. Neither *MAC* values give a good idea of the damage stages in the model; their values were too close to 1 for almost all tests. This could be obvious since the MAC criterion was formulated to discriminate modal shapes that correspond to different modes, but this criterion has been applied extensively to identify damage by comparing two modal shapes that correspond to the same mode but in two different damage stages. Doebling (1996) presents some application cases of both criteria (frequency and modal shapes). In general, it is recognized the difficulty to identify damage using these criteria; especially for damage in low and medium level.

6. TRANSFER FUNCTIONS

Transfer functions (*TF*) were calculated using the Fourier's amplitude spectra obtained from acceleration records of ambient vibration tests. Transfer functions were calculated as the quotient of the Fourier's amplitude spectra corresponding to a specific recording channel (1, 2, 4, 5 or 6) divided by the Fourier's amplitude spectra corresponding to channel number 3 (pendulum platform, see Fig. 6). With this definition, the *TF* represents the amplification of the model vibration in relation to the vibration of the model base (pendulum platform). In this way, *TF* has the advantage of eliminate from the model response possible disturbances induced by the excitation. Transfer functions are more reliable to identify dynamic properties than Fourier's amplitude spectra obtained directly from accelerations recorded in specific structure points. This is especially important in ambient vibration test, since this type of tests just produced low amplitude vibrations in the structure. For ambient vibration tests is probable that excitation disturbances significantly affect the recorded structure vibration. Because of these reasons, in this study *TF* were used to eliminate possible disturbances caused by the excitation.

In general, transfer functions show different amplitudes corresponding to different frequencies; in this study just amplitudes corresponding to first modal frequency of the model were analyzed.

Fig. 13 shows the variation of *TF* values at $f = f_1$ as a function of the damage stage (γ_{2nd}). Where f_1

corresponds to the first frequency of model identified for corresponding damage stage and recording channel. The *TF*(5/3) corresponds to the quotient of the Fourier's amplitude spectrum for channel number 5 (upper floor model) divided by corresponding spectrum of channel 3 (pendulum platform), both spectra valued at $f = f_1$. *TF*(2/3) is defined in analogy to *TF*(5/3). Channel 2 corresponds to first floor model.

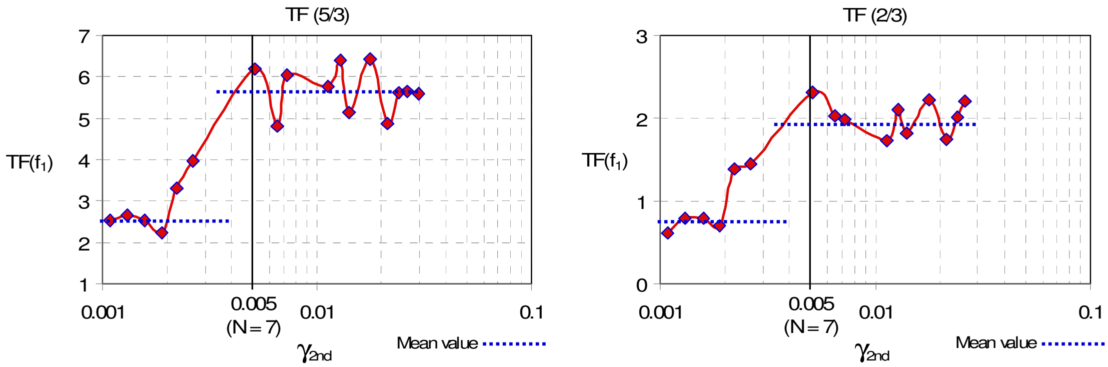


Figure 13. *TF* for $f = f_1$ as a function of damage stage (γ_{2nd})

Results show that the *TF* values change considerably for values of $\gamma_{2nd} > 0.005$ in comparison to those obtained for $\gamma_{2nd} < 0.005$. Considering that $\gamma_{2nd} = 0.005$ represents the yielding point of the model, results seem indicate that the post yielding stage of the model could be detected using the *TF* valued at first modal frequency as decision variable. This behavior is stable in both transfer functions *TF*(5/3) and *TF*(2/3). Considering mean values, the difference between transfer functions amplitude averages taken before and after yielding are 2.29 times for *TF*(5/3) and 2.73 times for *TF*(2/3). These differences are large enough to distinguish between both stages easily.

7. CONCLUSIONS

Based on experimental tests conducted in this study and analytical interpretation of the results, the main conclusions are next.

Given the observed differences of values obtained before and after yielding stages, the amplitude of the transfer function (*TF*) valued at first modal frequency (f_1) seems to be a useful parameter to identify damage caused by yielding.

The transfer function (*TF*) indicates the presence of damage, but not the level of damage reached during the tests (ductility demand). In any way *TF* is a variable decision that could be used in post earthquake inspections of emergency to know if the building is damaged.

It was corroborated the difficulty of identify damage using frequency and modal properties of the structure. In this study, the variation of these parameters was very small even for severe damage stages which reached ductility demands close to $\mu = 6$.

The *TF* is a parameter that can be estimated easily in a reliable way. This allows an automatic implementation of inspection procedures for emergency cases based on this parameter. To improve in practical and reliable sense an inspection procedure based on *TF* as a variable decision, it is necessary to know the *TF* amplitude level in healthy stage. It is important to conduct vibration tests in new buildings and also in existing buildings to establish the reference value for posterior and possible damage identification.

REFERENCES

Allemang, R.J., Brown, D.L. (1982). A correlation coefficient for modal vector analysis. *Proceedings of the 1st international modal analysis conference*. Orlando, Florida, USA.

Chiu, H. CH. (1997). Stable base line correction of digital strong – motion data. *Bull. of the Seismological Society of America*, **87:4**, 932–944.

De la Colina, J., Valdés, J. (2010). Péndulo de prueba para el estudio dinámico de modelos estructurales. *Revista de Ingeniería Sísmica*, **No. 82**, 35 – 56.

Doebling, S., Farrar, C., Prime, M., Shevitz, D. (1996). Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: a literature review. Los Alamos National Laboratory.

MatLab package software (2008), The Mathworks, Inc.

Prine, D. (1998). Steel bridge retrofit evaluation. *Proceedings of SPIE - The International Society for Optical Engineering*, 442-450.

Rhazi, J. (2006). Evaluation of concrete structures by the acoustic tomography technique. *Structural Health Monitoring, An International Journal*. **5:4**, 333 – 342.

Salawu, O., Williams, C. (1995). Bridge assessment using forced-vibration testing. *Journal of Structural Engineering*, **121:2**, 161-173.

Voigt, T., Akkaya, Y., Shah, S. (2003). Determination of early age mortar and concrete strength by ultrasonic wave reflections. *Journal of Materials in Civil Engineering*, **15:3**, 247-254.

Voigt, T., Shah, P. (2003). Nondestructive monitoring of setting and hardening of Portland cement mortar with sonic methods. *Proceedings of the Sixth International Symposium on Non-Destructive Testing in Civil Engineering (NDT-CE 2003).* Berlin, Germany.

Wang, H. (2004). Theoretical evaluation of embedded plate-like and solid cylindrical concrete structures with guided waves, Ph.D. Thesis, Northwestern University.