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IN-SITU DYNAMIC CHARACTERISTICS OF SEVEN REINFORCED CONCRETE BUILDINGS BEFORE AND AFTER SEISMIC RETROFIT

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ABSTRACT: This paper presents the in-situ dynamic properties (natural frequencies, modal shapes and damping ratios) of seven reinforced concrete buildings between 10 and 17 storeys of height, located in Cali, Colombia, before and after their seismic retrofit. It was found that the frequencies increased between 65 and 200% for buildings retrofitted using mainly shear walls, between 30 and 65% using a combination of shear walls and steel bracings, and between 15 and 20% for the sole building retrofitted using steel bracings only. The obtained frequencies and mode shapes were compared to those of analytical models. While there was a good agreement between mode shapes, the obtained differences for natural frequencies were between 5 and 60%. In all cases the experimental frequencies were higher than the analytical ones, implying a conservative design for displacements, but an underestimation of seismic forces. However, differences up to around 20% are acceptable and can be explained mainly by the higher mass of the modeled building compared with the test conditions. Finally, damping ratios were evaluated to confirm previous studies that suggest they will be adversely affected by the stiffening of the structure. Results showed a slight decrease of their values for the majority of buildings.

1. Introduction

Modal analysis is the study of the dynamic properties of a given structure excited by vibration. This technique has been widely used in mechanical engineering for several decades, with analysis techniques and testing equipment being progressively refined. Later, with the development of signal processing tools for output-only systems, modal analysis has also gained popularity for the evaluation of civil structures. Ambient vibration measurements are a particular type of modal analysis. As the name implies, the measurements capture the movement of the evaluated structure under ambient noise, like wind and traffic. The technique has been used successfully to determine the dynamic properties of civil structures for over 35 years (Ivanovic et al., 2000), demonstrating that it is reliable to establish natural frequencies and modal shapes, although the determination of damping is not as consistent (Brownjohn, 2003). The dynamic properties obtained can then be used, for example, to calibrate analytical models that will predict the response of a structure under service loads more reliably (Lord et al., 2004). Many studies of this type have been conducted for bridges, where predicting the dynamic behaviour is especially interesting because wind, earthquake and traffic loading can play a key role (Lu et al., 2006). Ambient vibration measurements also allow the real time structural health monitoring, where detected changes in the natural frequencies of the structure are correlated with possible damage (Montalvão et al., 2006). The measured properties have also been used to evaluated approximate code equations for natural periods, and to determine more accurate ones (Gilles and McClure, 2012). Finally, another interesting application that motivated the presented research is the use of ambient vibration measurements to determine the effect that seismic retrofitting has on a structure [Ruiz et al 2000]. Although the studies of these nature are scarce, some positive results have been obtained, showing an increased stiffness of the retrofitted structure.

The opportunity to study several structures before and after their seismic retrofit arose after the 7.2 Mw Pizarro earthquake hit the city of Cali, Colombia in 2004. Approximately 20 buildings suffered considerable, albeit mostly non-structural damage, and seismic retrofit was necessary. Seven of these buildings are included in the presented research. Ambient vibration measurements were taken before and after their retrofit, and changes in the natural frequencies, modal shapes and damping ratios were established.

2. Description of the studied buildings

Seven mid-rise (10 to 17 storeys) residential buildings were studied. The buildings are identified and their characteristics are summarized in Table 1. All are located in a relatively small area, where local soil conditions cause seismic wave amplification. Note that buildings 1A and 1B are two identical towers of the same residential complex. Before the earthquake, all buildings relied on spatial concrete frames as lateral load resisting systems (LLRS), typical for Colombian construction. Only one had a dual system with some slender shear walls. Another prevalent characteristic of the buildings was their plan irregularity.

The retrofit solutions relied on the addition of concrete shear walls or steel braces for all cases. The spatial frames were also retrofitted when necessary, adding concrete or steel beams and jacketing columns. The addition of beams was also used to reduce plan irregularity. Before the earthquake, all perimeter and interior walls were infilled solid clay bricks without any separation or reinforcing. While these walls certainly contributed to the behavior of the buildings during the Pizarro earthquake, they were most likely not considered during the original design. Since these walls were heavily damaged during the earthquake, they were almost entirely replaced by drywall after the retrofit. As a typical example, Fig. 1 shows the plan view of buildings 1A and 1B, with the original LLRS and its retrofit. The numbers on the plan view identify the test locations, which are described in more detail in the next section.

Table 1 – Characteristics of studied buildings.

Building	Number of storeys	Plan area (m^2)	Original LLRS	Main retrofit solution
1A, 1B	16	275	Spatial concrete frames and shear walls	Retrofit shear walls and steel braces
2	10	350	Spatial concrete frames	Shear walls
3	13	575	Spatial concrete frames	Shear walls and steel braces
4	13	325	Spatial concrete frames	Shear walls and steel braces
5	11	800	Spatial concrete frames	Shear walls and steel braces
6	17	650	Columns + waffle slabs	Steel braces and beams

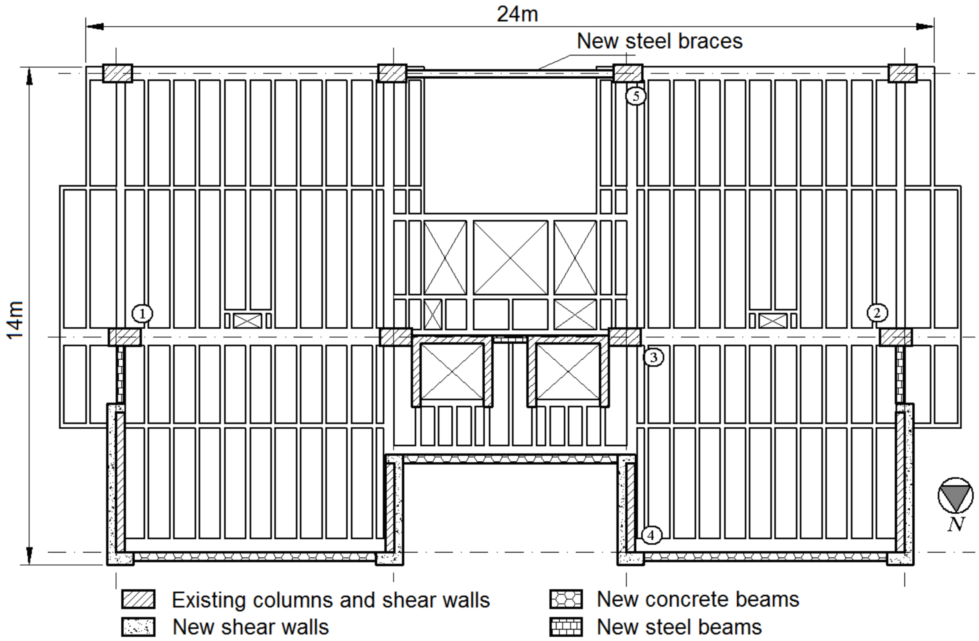

Fig. 1 – Buildings 1A and 1B: Existing LLRS, Retrofit Solution and Sensor Location

3. Experimental procedure and data analysis

The ambient vibration response of the buildings was registered using Wilcoxon Research Model 731A seismic accelerometers, each one connected to an Wilcoxon Research Model P31 amplificator. These accelerometers have an sensitivity of 10 V/g. Combined with the amplificators, the total sensitivity can be increase up to 1000 V/g. In addition of amplifying the signal, the P31 devices filter the signal with a nominal band width between 0.05 and 450 Hz.

For each record, five accelerometers were used simultaneously, two installed at the top floor and three at the lowest floor, as shown in Fig. 2. For the building shown in Fig. 1 for example, sensors at the top were placed at nodes 1 and 2, and at the bottom at nodes 3, 4 and 5 to evaluate the behaviour in the north-south direction. This configuration was chosen to identify the first translational and torsional modes, as well as the rocking at the base. Two 10 minute records with a sampling rate of 256Hz were taken for each principal direction of the building, before and after the seismic retrofit. At the time of the pre-retrofit measurements, most of the masonry infill walls had already been demolished.

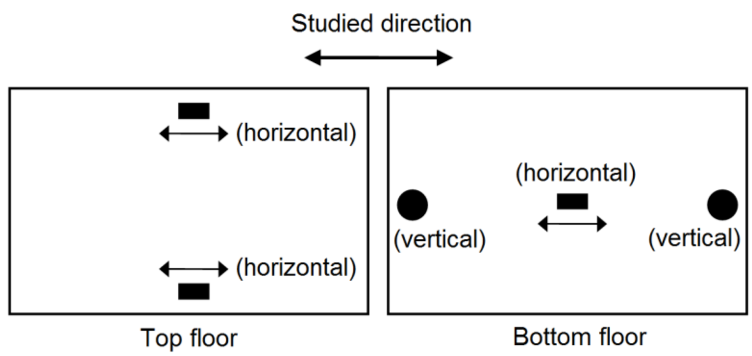

Fig. 2 – Sensor Placement

Measurements were analyzed using Matlab's digital signal processing toolbox (MathWorks, 2015). The records were first preprocessed by eliminating offsets, trimming them to exclude corrupt data points and resampling them at 10Hz. For each sensor of each record, power spectral density plots were generated.

A representative example is shown in Fig. 3, for one record before and after retrofit. The peaks of these plots are associated with frequencies of interest. Spectrograms were used to confirm that the so identified frequencies were constant over time. Finally, the analysis of transfer functions between all channels allowed to associate the identified frequencies with the first translational or rotational modes.

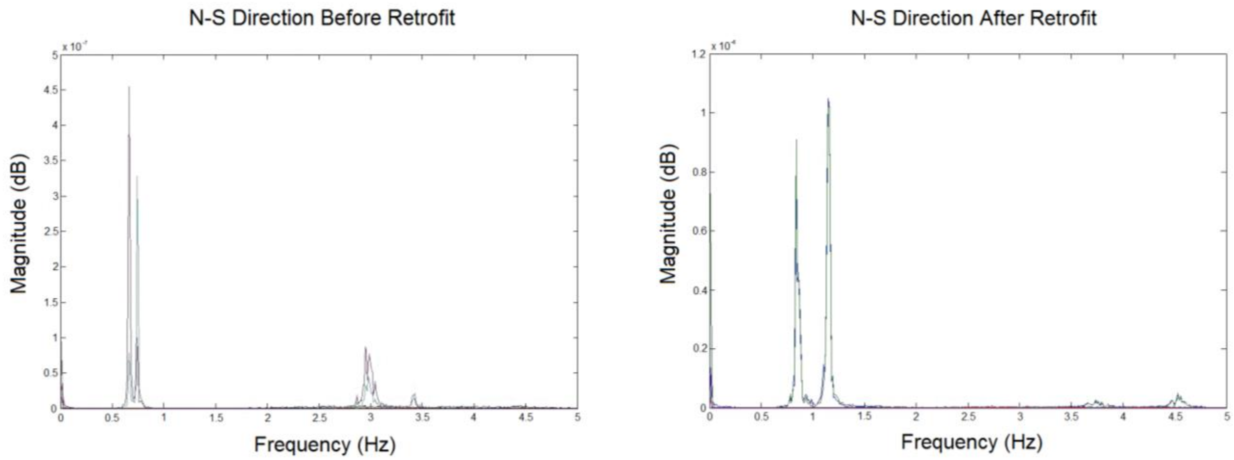

Fig. 3 – Sample Power Spectral Density Plot for One Test Setup Before and After Retrofit

The random decrement (RD) technique was used to identify the damping ratios associated with each mode (Asmusset *et al.*, 1998). By averaging time segments of the record selected with certain criteria and filtering the obtained data in frequency, so called RD functions are generated. They can then be interpreted as free decay functions, which are the superposition of a sinusoidal and an exponential function. The damping is then estimated by fitting an exponential curve to the maximums or minimums of the RD functions. Fig. 4 shows a sample RD function with the corresponding exponential curves. Only records with a good fit between the RD and exponential function (i.e. R^2 over 0.95) were retained.

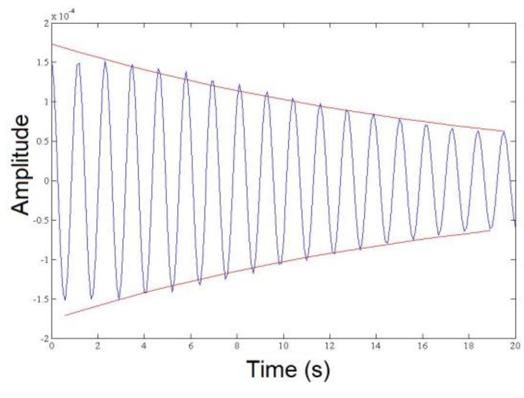

Fig. 4 – Sample RD Function with Fitted Exponential Curves

4. Experimental results

The natural frequencies and damping ratios obtained are summarized in Tables 2 and 3 respectively. Modes 1 and 2 are the first translational modes for each building's principal axis. Mode 3 is the first rotational mode. In the tables, values obtained before the retrofit are identified as Pre, and those corresponding to the retrofitted buildings as Post.

As expected, all natural frequencies increased with the retrofit. The average increase was 55%, although increase values varied widely between 15 and 200%. As a general observation, for each building the increase was similar for the two translational modes and slightly higher for the torsional mode. A correlation could also be established between the type of retrofit solution used and the increase of frequencies. Highest values were obtained for buildings were concrete shear walls predominated.

Building 2, the sole building retrofitted using only shear walls, had increases of over 100% for all modes. On the other hand, building 6, the only one retrofitted using steel braces only, had the lowest increases, with values under 20% for all modes.

Table 2 – Natural frequencies before and after retrofit.

Building	Mode 1 Pre (Hz)	Mode 1 Post (Hz)	Mode 2 Pre (Hz)	Mode 2 Post (Hz)	Mode 3 Pre (Hz)	Mode 3 Post (Hz)
1A	0.65	0.85	0.65	0.85	0.75	1.15
1B	0.60	0.80	0.60	0.85	0.70	1.15
2	0.75	1.85	0.75	1.60	0.65	1.95
3	0.65	1.00	0.85	1.05	0.75	1.20
4	0.85	1.00	0.85	1.05	1.05	1.30
5	-	1.05	-	-	0.65	1.20
6	0.65	0.75	0.65	0.75	0.80	0.95

Table 3 shows that measured damping ratios were between 0.8% and 2.5%. These values are comparable to values recommended in literature. For stress levels of under 50% yield stress, values should be between 0.5% and 1% are for concrete and steel structures without cracks and displacements in joints, and between 3% and 5% for highly cracked concrete structures (Chopra, 2011).

Damping values were expected to decrease with the retrofit and in general this was the case. However, the differences were mostly very small, and could be attributed to the uncertainty in the results. Only for two of the eleven studied ratios a significant decrease was noted, being 1.4% the highest decrease (from 2.7% to 1.3%).

Table 3 – Damping ratios before and after retrofit.

Building	Mode 1 Pre (%)	Mode 1 Post (%)	Mode 2 Pre (%)	Mode 2 Post (%)	Mode 3 Pre (%)	Mode 3 Post (%)
1A	1.7	1.2	-	1.2	2.2	1.2
1B	-	1.3	2.7	1.3	-	1.4
2	1.1	-	2.2	2.5	1.5	1.0
3	2.4	2.1	-	1.9	1.4	1.1
4	-	1.7	1.1	1.0	0.8	1.1
5	-	1.1	-	-	-	1.5
6	-	1.7	1.1	1.1	1.3	-

5. Comparison of analytical and experimental frequencies

For buildings 3 to 6, experimental frequencies were compared with those obtained from analytical models. These models were supplied by the structural engineers that developed the retrofit solutions. The experimental frequencies were always higher than the analytical ones. The percentages of the differences for each case are presented in Table 4. Values range from 8 to 58% difference, with an average of 27%.

Part of the difference can be explained by the difference in mass of the modeled buildings compared to the actual mass when the testing took place. To study the influence of the mass, an analytical model with the mass usually considered for design purposes was compared to the same model, using only the self weight of the structure and 20% of the superimposed load, which was considered representative for the testing conditions. Results showed around 20% higher frequencies with the reduced mass.

Table 4 – Difference between analytical and experimental frequencies in percentage.

Building	Mode 1 Pre (%)	Mode 1 Post (%)	Mode 2 Pre (%)	Mode 2 Post (%)	Mode 3 Pre (%)	Mode 3 Post (%)
3	8	16	14	13	16	18
4	38	17	18	18	15	24
5	-	40	-	-	23	38
6	52	27	49	24	58	32

6. Conclusions

This research allowed to quantify the effect of seismic retrofit on seven reinforced concrete buildings by comparing their dynamic properties (modal shapes, natural frequencies and damping ratios).

Natural frequencies increased for all cases, which shows a higher stiffness of the retrofitted building, considering that the mass was approximately constant for all measurements. A clear correlation was found between the type of retrofit solution used and the percentage of increase in natural frequencies. They increased between 65 and 200% for buildings retrofitted using mainly shear walls, between 30 and 65% using a combination of shear walls and steel bracings, and between 15 and 20% for the sole building retrofitted using steel bracings only.

An unavoidable effect of the increased frequencies is an increase of spectral acceleration values. Using the city's microzonation spectra, it was found that spectral accelerations became between 0 and 26% higher. In this particular case, increases were limited because the spectral acceleration plot has a plateau close to the frequencies of interest. On the other hand, as part of the interventions heavy masonry partitions were replaced by much lighter ones, reducing the total weight of the partitions by around 90%. The reduction of mass will help to offset the increase in spectral acceleration.

Experimental natural frequencies were also compared to those obtained from analytical models. For all cases the experimental frequencies were higher, with differences between around 5% and 60%. Higher experimental frequencies imply that the modeled structure is more flexible than in reality. This will be conservative for drifts, but will underestimate the seismic load. A high difference also shows that the analytical model fails to capture the real behaviour of the building. However, differences of about 20% were expected, and can be explained mainly by the difference in mass between the modeled building and the building at the time of the tests. Another usual explanation for differences in tested and analytical frequencies is the stiffness contribution of non-structural elements captured with ambient vibration tests but not considered in the models. This factor is not relevant in our case, because very little non-structural elements were present at the time of the tests. Finally, natural frequencies have shown to decrease with the amplitude of shaking the building is subjected to (Trifunac *et al.,* 2001a; Trifunac *et al.,* 2001b). Partly this can be explained by the soil-structure interaction, but also by the cracking of structural and non-structural elements. Again, the lack of non-structural elements while testing reduces the influence of this factor. In addition, the building had undergone a significant earthquake, so that the level of cracking of the structural elements is considerably higher compared to a new building. However, it cannot be excluded that the natural frequencies will change significantly in a future earthquake (Motosaka *et al.,* 2004.

It was also possible to establish damping ratios for 75% of the studied modes, with values between 0.8 and 2.5%. The average damping ratio was 1.5%. For most of the cases, values decreased slightly with the retrofit. However, only for two cases the decrease was large enough so it couldn't be explained solely by the inherent uncertainty of the results. No correlation could be established between the change in damping ratios and the retrofit solution used.

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