DYNAMIC RESPONSE AND DESIGN EFFECT OF VERTICAL SEISMIC COMPONENTS IN TALL BUILDINGS

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Abstract

For design, the vertical seismic component is generally ignored, or it is considered as an additional static load. The dynamic characteristics of the overall structure in the vertical direction is not considered for the seismic design except for cantilever components, long length beams or large dimension slabs. For the typical medium and low-rise structure these assumptions and procedures have proved correct. Nevertheless, several tall buildings, more than 30 stories, are now common in several highly seismic areas. Some of them have shown an increased damage in cantilever elements and vertical elements, for example in the 2010 Mw 8.8 Chile Earthquake.

To evaluate the effect in the design of critical structural elements, twelve designed and constructed tall buildings, were modeled considering the dynamic vertical structural properties. We have included the horizontal and vertical modes, modifying the damping value for the horizontal and vertically predominant modes. The design demands were evaluated with and without consideration of the vertical seismic components and different damping values for the predominant vertical modes. The effect of the vertical records component and damping was evaluated in the volume of reinforcement required, given the existing geometrical conditions of the building elements. The analysis indicates that structures of more than 120 meters (approximately 40 stories) show an increased demand and increased reinforcement requirements. As expected, the amount of additional reinforcement depends heavily on the assumed damping for the vertical modes.

Keywords: vertical amplification; tall buildings; damping; vertical components

1. Introduction

In the design practice, the vertical seismic component is only considered for some structural elements, such as cantilever beams and large dimension slabs, and ignored in others. It is usual to consider it as an additional static load, computed as a fraction of the horizontal peak of acceleration or a portion of the dead weight. This is the case of Chilean standard, as well as New Zealand and Indian standards [1]. On the other hand, Eurocode 8, for instance, includes an elastic response spectrum in the vertical direction, which should be applied only in the cases mentioned above and if the effective acceleration is greater than 0.25g [2]. This is also the case of the American Standard ASCE7-16, which includes a design spectrum in the vertical direction for the first time, as opposed to previous version of 2005 [3].

In general, the dynamic properties of the overall structure are not considered in the vertical direction (period, modal shape and damping), assuming that buildings are stiff enough so there is no vertical dynamic amplification [3]. Although these assumptions have proved correct for low and medium-rise buildings, some high-rise buildings (over 120 meters) have indicated a clear response and possible damage due to vertical seismic loads. Nowadays, the increase in height of structures being built suggests that vertical amplification should be evaluated and considered, since buildings will become more flexible in that direction.

This article presents the effect of the inclusion of the vertical component of the earthquake in the design process of some high-rise buildings on the Chilean experience and seismic environment.

The hypothesis of the importance of the vertical component excitation will be evaluated by numerical considerations on twelve Chilean buildings. They are modeled including their dynamic characteristics in the vertical direction.

First, the vertical amplification at the core structural walls on the top floor is analyzed by obtaining theoretically the transfer function in the frequency domain and also by estimating an empirical transfer functions due to the excitation of 28 earthquake records.

Since 10 of the 12 buildings have simple structural wall core sections the effect of the vertical component excitation and dynamic modification is evaluated on of reinforcement ratios on critical elements of the wall.

Earthquake loads will be combined with and without the vertical component of each record. Therefore, the reinforcement quantity will be computed with and without the seismic load in the corresponding vertical direction. In order to consider the dependency of forces on modal damping, the reinforcement will be first computed with the usual 5% and then using 3% as modal vertical damping.

2. Analysis

Twelve constructed tall buildings in Chile were modeled considering the dynamic vertical structural properties.

For simplicity, the Buildings are numbered from 1 to 12. In terms of use of the structures, Buildings 1, 2, 3 and 5 are for offices, while the others are for residential use. Table 1 shows a list of the Buildings with number of stories, total weight and total height of each one.

Fig. 1 presents a summary of the analyzed buildings in terms of number of stories and predominant periods in each relevant direction. The dynamic properties are obtained from the computational models. The number of stories range from 26 to 68 and the periods in the vertical direction from 0.16s to 0.55s. This period range is already an indication of the flexibility of these structures as a whole in the vertical direction.

These periods are not to be confused with the typically slab vibration periods that in Chile ranges from 4 to 12 Hz.

The ratio of number of stories and height to predominant horizontal, vertical and rotational periods are shown in Fig. 2. In Chile typical ratio for translational period in midrise (10-25 stories) structures is 0.035 to 0.05 the number of stories [4][5]. For a simple number the vertical period is close to N/150 for the buildings studied.

Also, the ratio between horizontal and vertical predominant periods is shown in Fig. 3 and clearly horizontal predominant periods are at least 5 times greater than verticals and being up to 15 in the case of the tallest buildings and average value of 10.

Table 1 – Characteristics of Buildings

Building	Number of Stories Overground	Number of Stories Underground	Total Weight [ton]	Total Height [m]	Use
1	30	5	61000	115	Office
2	54	7	170000	212	Office
3	63	5	215300	405	Office
4	34	2	18600	93	Residential
5	20	6	30000	166	Office
6	30	4	34000	94	Residential
7	31	3	16300	82	Residential
8	31	3	17400	89	Residential
9	35	1	37700	132	Residential
10	31	1	33300	120	Residential
11	29	2	24000	74	Residential
12	30	2	21300	76	Residential

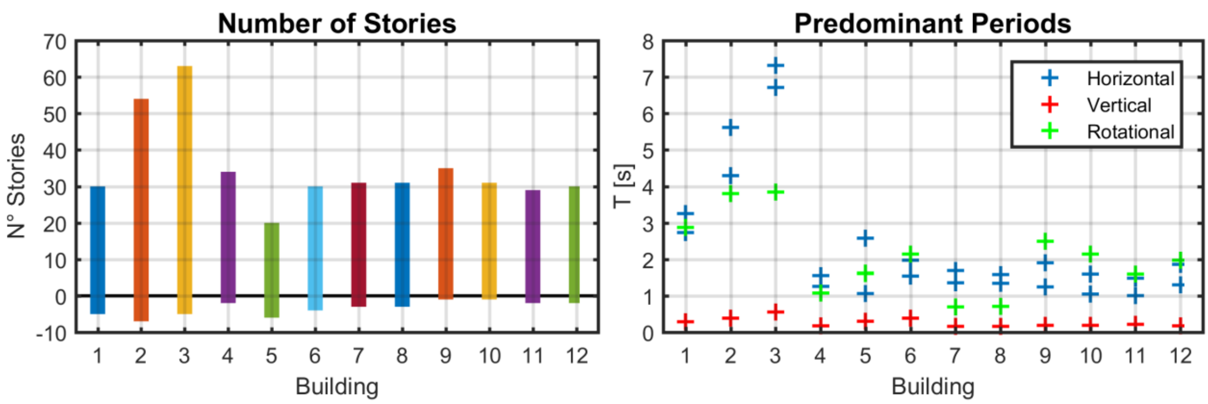


Fig. 1 – Summary of the properties of the studied buildings: number of stories and predominant periods in every direction

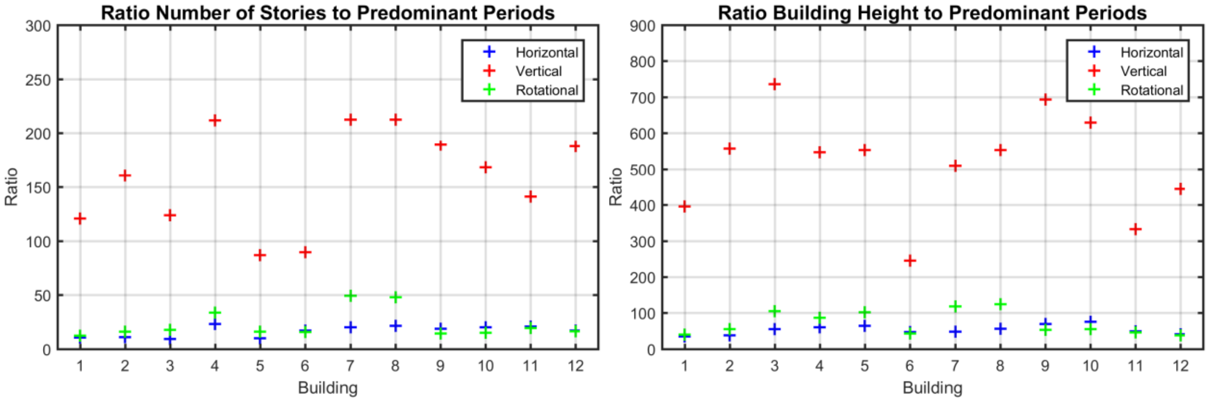


Fig. 2 – Ratio of number of stories and building height to predominant periods

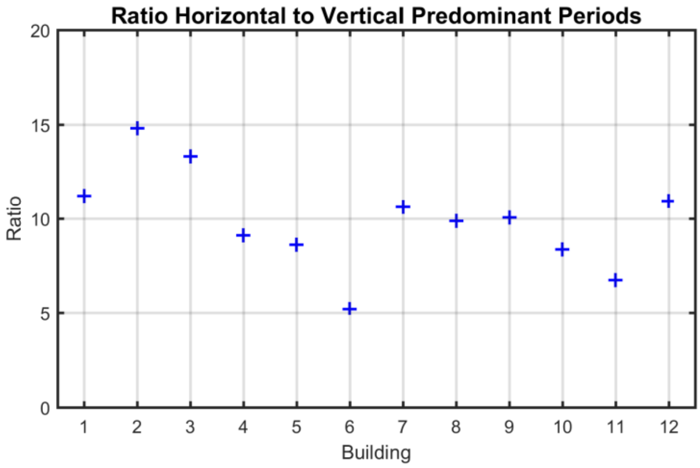
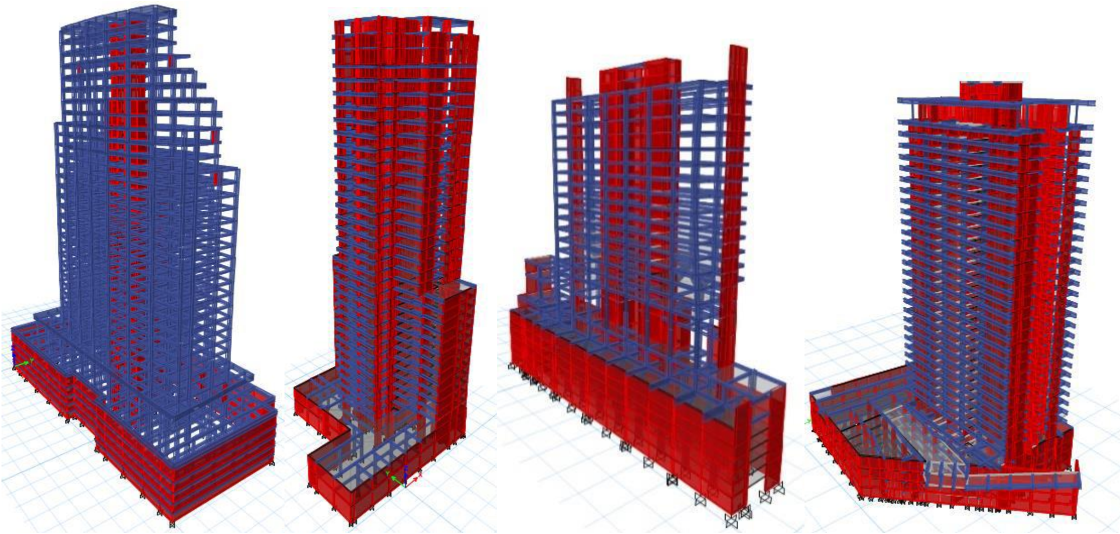


Fig. 3 – Ratio of horizontal to vertical predominant periods

The first six buildings in this study (numbered from 1 to 6) are located in the Chilean Seismic Zone 2 (intermediate intensity in Chilean standards, associated with an effective acceleration Ao of 0.3), while the others (numbered from 7 to 12) are in Chilean Seismic Zone 3 (high seismicity with Ao = 0.4). Fig. 4 shows a 3D view of some of the models in Zone 2, and Fig. 5 illustrates some of the models corresponding to Zone 3. Buildings 2 and 3 model are not present as requested by the owners. The model of Buildings 8, 10 and 12 are also not shown because they are the second tower of the projects containing Buildings 7, 9 and 11, respectively, and therefore are similar.

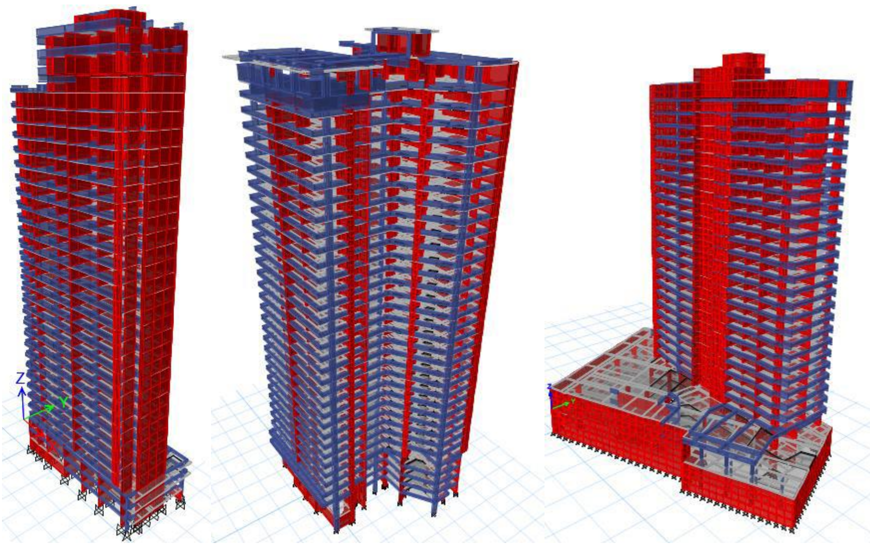
All Buildings are located on Soil Type B, which has the characteristics shown in Table 2.

Earthquake records are selected, in which the peak ground acceleration is at least 20% of the gravity acceleration that were obtained in Chile in the same Zone and Soil Type. Table 3 lists the records employed for Zone 2 buildings, while Table 4 shows the ones corresponding to Zone 3 structures.



Building 1 Building 4 Building 5 Building 6

Fig. 4 – 3D view of some of the models in Zone 2



Building 7 Building 9 Building 11

Fig. 5 – 3D view of some of the models in Zone 3

Table 2 – Characteristics of Soil Type B

Description	**Vs_{30} (m/s)**	**q_u (MPa)**	**N_1 (blows/ft)**
Soft rock or very dense soil	≥500	≥0.40	≥50

These records are included as a time-history excitation function for the finite element models. The models are ran considering a number of modes that reach first one o the following 90% modal mass in the vertical direction, minimum period of 0.03 or less or 1000 vibration modes. In some cases, this ensures 90% of the participating mass in every direction, including the vertical component. In others, the vertical direction does not present 90% of the participating mass, but a very stiff period is achieved. Table 5 shows a list of the number of modes needed to achieve 90% of the participating mass or the period reached, in the vertical direction.

Table 3 – Available Earthquake records in Zone 2

Rec N°	Event Date	Mw	Station Name	Max. acc. EW [g]	Max. acc. NS [g]	Max acc. UD [g]
1	27/2/2010	8.8	Curicó	0.20	0.47	0.41
2	10/9/2008	5.7	Pica	0.63	0.56	0.45
3	13/6/2005	7.8	Pica	0.57	0.72	0.80
4	14/11/2007	7.7	Pica	0.18	0.20	0.10
5	1/4/2014	8.1	Pica	0.28	0.34	0.23
6	27/2/2010	8.8	Talca	0.48	0.42	0.24
7	3/3/1985	7.9	San Fernando	0.34	0.29	0.12
8	3/3/1985	7.9	Talca	0.17	0.17	0.07

Table 4 – Available Earthquake records in Zone 3

Rec N°	Event Date	Mw	Station Name	Max. acc. EW [g]	Max. acc. NS [g]	Max. acc. UD [g]
1	10/9/2008	5.7	Alto Hospicio	0.30	0.18	0.14
2	13/7/2014	5.6	Alto Hospicio	0.11	0.24	0.11
3	27/2/2010	8.8	Hualañe	0.39	0.45	0.39
4	15/10/1997	7.1	Illapel	0.29	0.37	0.19
5	27/2/2010	8.8	Papudo	0.29	0.42	0.16
6	1/4/2014	8.1	Poconchile	0.21	0.29	0.14
7	13/6/2005	7.8	Poconchile	0.39	0.33	0.22
8	16/9/2015	8.3	La Higuera-Comisaria	0.19	0.19	0.09
9	16/9/2015	8.3	Coquimbo-Hospital	0.25	0.26	0.18
10	16/9/2015	8.3	El Pedregal	0.29	0.35	0.19
11	26/9/2015	6.3	El Pedregal	0.15	0.22	0.15
12	3/3/1985	7.9	Iloca	0.28	0.23	0.09
13	3/3/1985	7.9	Llay Llay	0.47	0.35	0.23
14	3/3/1985	7.9	Melipilla	0.53	0.69	0.26
15	3/3/1985	7.9	Pichilemu	0.18	0.26	0.12
16	3/3/1985	7.9	Quintay	0.26	0.24	0.18
17	3/3/1985	7.9	San Felipe	0.43	0.31	0.20
18	3/3/1985	7.9	Zapallar	0.31	0.27	0.19
19	1/4/2014	8.1	Alto Hospicio	0.84	1.12	1.03
20	1/4/2014	8.1	Iquique Chipana	0.41	0.60	0.43

Table 5 – Number of Modes per Model

Building	Participating Mass Achieved [%]	Period Reached [s]
1	79	0.06
2	76	0.12
3	74	0.19
4	92	0.03
5	81	0.05
6	85	0.05
7	93	0.03
8	93	0.03
9	92	0.05
10	92	0.04
11	88	0.04
12	94	0.04

3. Results

3.1 Vertical amplification

Vertical amplification is calculated theoretically and from the acceleration response of several nodes on the base and the top of each building. The ratio between corresponding pairs of points is computed in the frequency domain. Fig. 6 and Fig. 7 show the ratio for each time-history record and the averaged proportion is also shown for the case of all horizontal and vertical modes with 5% critical damping ratio. Black lines are depicted to illustrate the frequencies at which the modal participating mass is at least 2% in the vertical direction, while an additional red line shows the first frequency where the vertical direction is predominant.

As expected, peaks in amplification develop at frequencies in which the effective modal mass is significantly vertical. The complexity of the transfer function depends on the building structural systems and the relative participation of higher vertical modes in the frequency band presented. The mix system (wall-frame) presents the apparent most complicated transfer function. The closeness of the modes is related with the presence of similar slab-frame system. The amplification values are also quite different for each building again due to structural characteristics. Typically, the amplification of the largest modal mass is higher than 5 and can reach a value of 12.

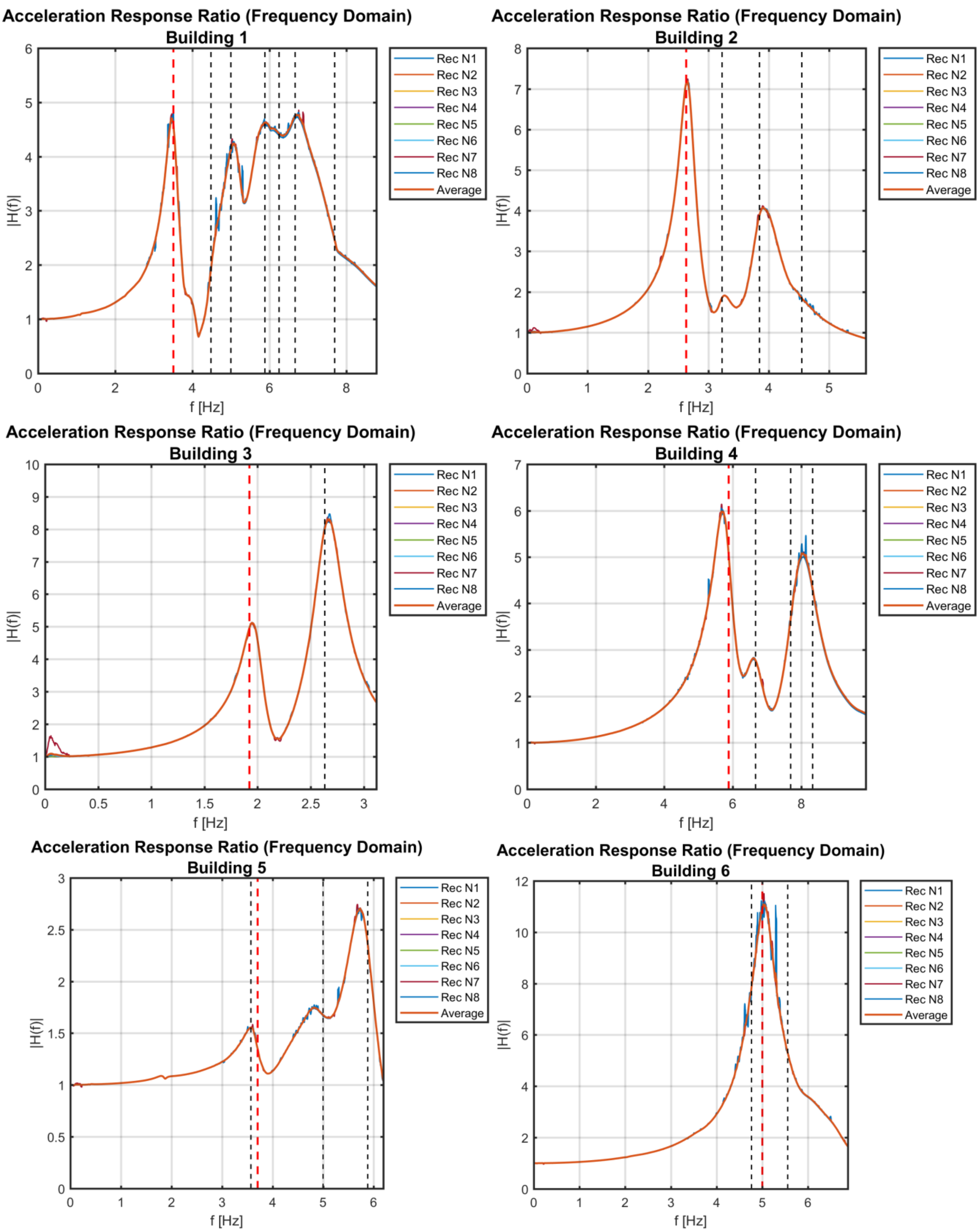


Fig. 6 – Acceleration response ratio for Buildings 1 to 6

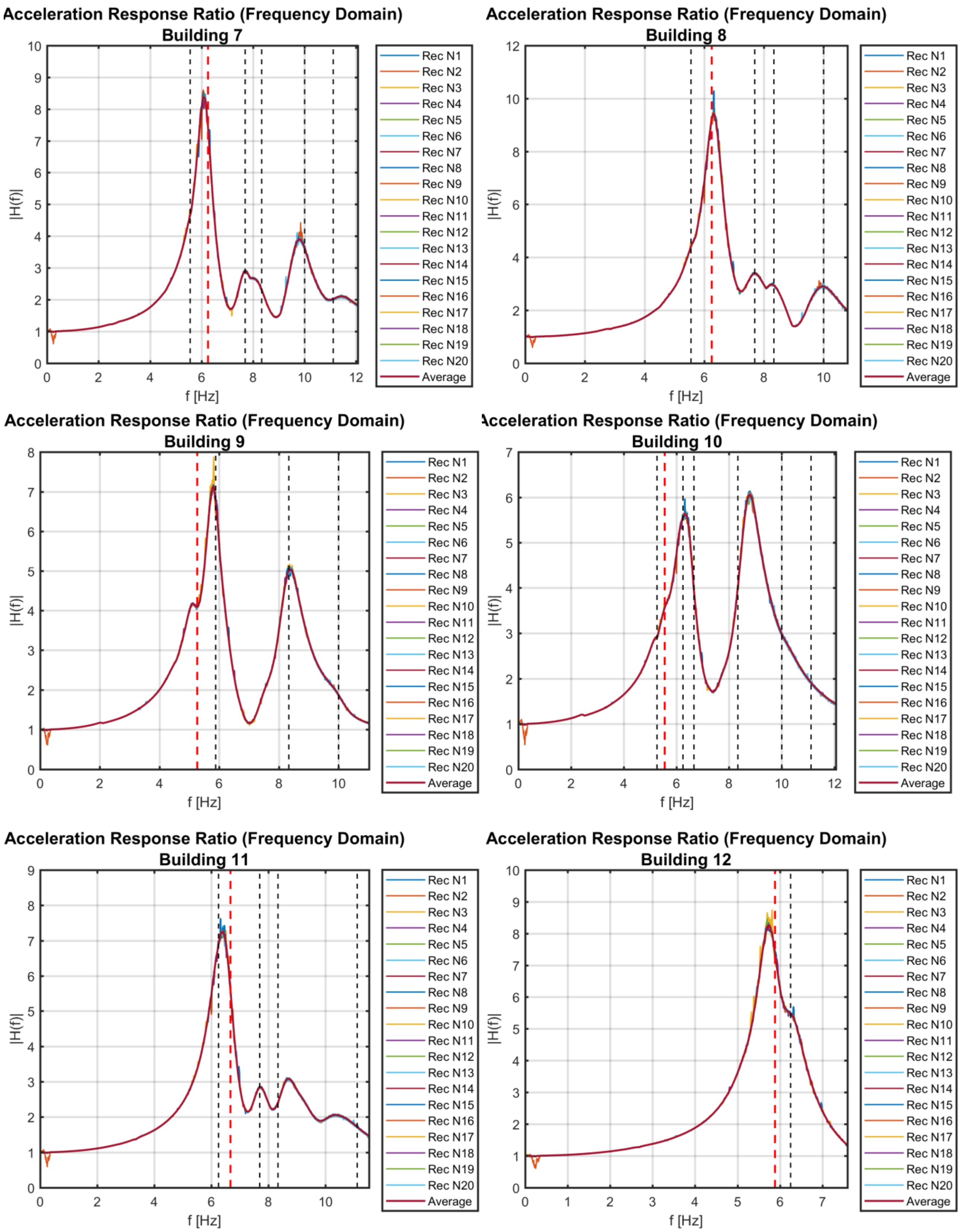
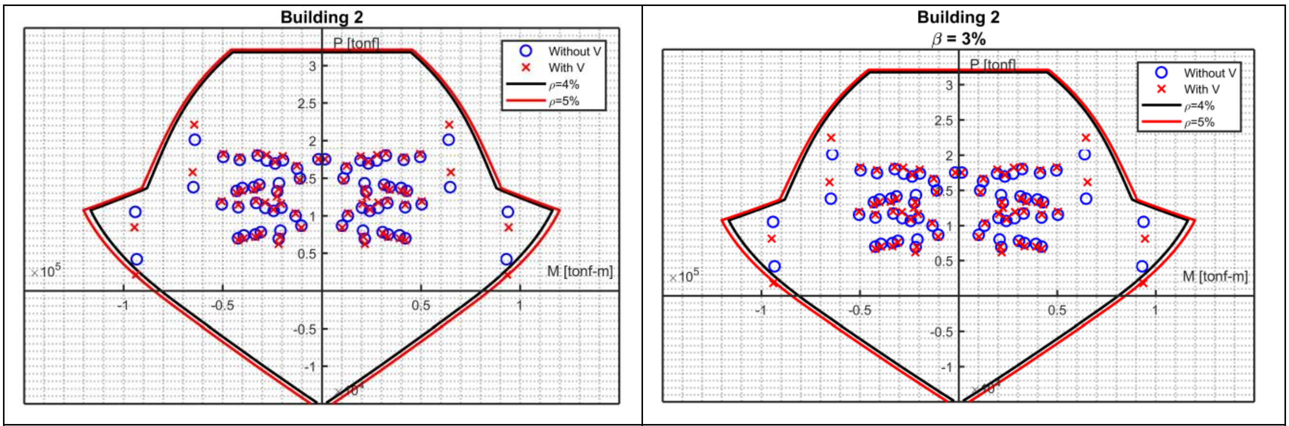


Fig. 7 – Acceleration response ratio for Buildings 7 to 12

3.2 Effect on reinforcement quantity

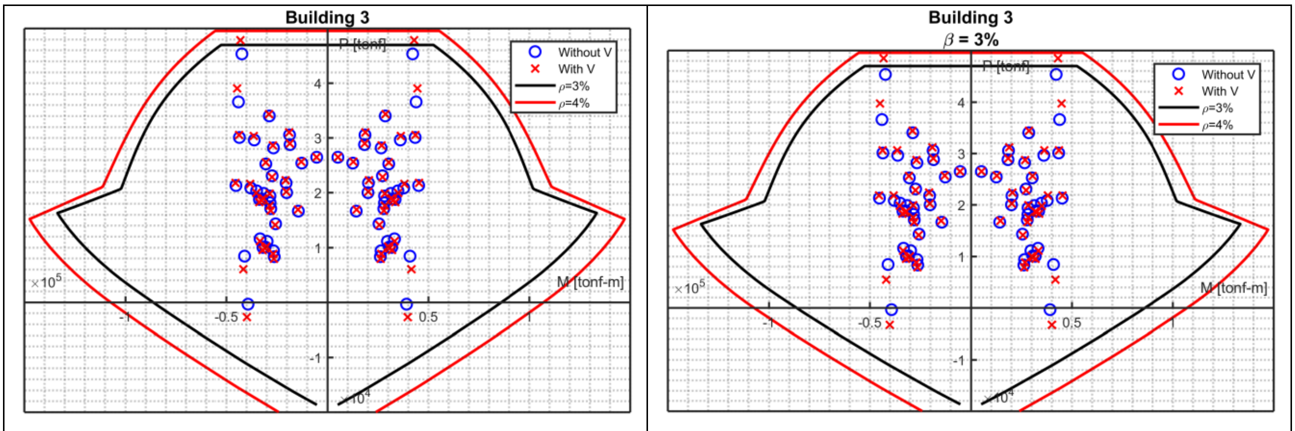
Ten of the 12 buildings have typical C-section shear walls at the core. The effect of the dynamic properties and inclusion of the vertical seismic component is evaluated in terms of reinforcement quantity required for design, preserving the original geometry. From the analysis of all the cases, in two buildings the rebar quantity should be increased. This is the case for 5% and 3% damping for vertical modes. These are precisely the tallest buildings analyzed, Building 2 and 3, with heights of 212 and 405 meters and 61 and 68 stories, respectively. A P-M interaction diagram is provided in Fig. 8 and Fig. 9 for these tall buildings.

Clearly an increase from 4% to 5% in reinforcement quantity is needed for Building 2 when including the vertical component in time-history analysis, while in Building 3 it rises from 3% to 4%, when using 5% critical damping ratio in the vertical direction. This is substantial because it involves maintaining the geometry and the number of rebars but changing its size from $\phi 32$ bars to $\phi 36$ bars in the critical section of the wall (corners) in both cases.



(a) (b)

Fig. 8 – P-M interaction diagram of shear wall in Building 2 considering in damping: (a) the usual 5%, and (b) 3%.



(a) (b)

Fig. 9 – P-M interaction diagram of shear wall in Building 3 considering in damping: (a) the usual 5%, and (b) 3%.

4. Conclusions

Evidence has shown that the increase in height of buildings has made them more flexible in the vertical direction. Therefore, the assumption of buildings being stiff enough so no vertical amplification exists may no longer be reasonable. This has been shown numerically by analysing the vertical component of acceleration and displacement amplifications from base to top of the building are a factor between 5 and 10 (accelerations).

By studying the vertical accelerations ratio in the frequency domain, it has been demonstrated that amplification exists precisely at the frequencies where there is a significant modal participating mass in the vertical direction and the excitation has enough energy.

The analysis of the effect on reinforcement quantity showed that taller buildings are more affected by the consideration of seismic vertical components and dynamic properties. This effect is even clearer when decreasing the modal damping in the vertical direction, which suggests that damping assumptions are critical for design. Hence modal damping in the vertical direction should be studied more carefully, specially by obtaining empirical data. A companion experimental study is currently being carried out. Further studies are also being undertaken to check the validity of the models used in the present analysis.

5. References

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