EFFECTS OF SPAN LENGTH AND BUILDING HEIGHT ON THE SEISMIC VERTICAL RESPONSE OF NSCS IN RC BUILDINGS

S. Mazloom[1], R. Assi[2] & C. Joseph[3]

[1] Research Associate, Department of Construction Engineering, École de technologie supérieure (ÉTS), Montreal, Quebec Canada. E-mail: shahabaldin.mazloom.1@ens.etsmtl.ca

[2] Associate Professor, Department of Construction Engineering, École de technologie supérieure (ÉTS), Montreal, Quebec, Canada. E-mail: rola.assi@etsmtl.ca

[3] M.Eng. Graduate, Department of Construction Engineering, École de technologie supérieure (ÉTS), Montreal, Quebec, Canada. E-mail: calvens.joseph.1@ens.etsmtl.ca

Abstract: *This study investigates the effects of building height and span length on the vertical seismic response of the floors in reinforced concrete moment-resisting frame buildings. Symmetrical 3- and 6-storey three-span regular code-compliant buildings were subjected to sixty-five vertical time history records from historic near-field strong earthquakes. Spans of 5.0 m, 7.0 m and 9.0 m were considered for each building height to compute the normalized vertical peak floor acceleration (PFA_V) and the vertical floor spectral acceleration (FSA_V). Values were computed at all floor elevations along the height and at different locations within the plan, including the centre of the slab bays and the middle of the interior beams of the buildings under study. Linearly increasing PFA_V from the base to the first floor was observed, followed by constant amplification up to the rooftop for all considered span lengths of both buildings. Likewise, an almost constant amplification of FSA_V along the height of the buildings was also noted. Moreover, the amplification of PFA_V and FSA_V is higher in the case of the 3-storey buildings, in comparison to the 6-storey buildings with the same plan dimensions and geometry. In addition, it was noted that the amount of acceleration amplification increased as the span length decreased, which is more evident in the 3-storey building. In this regard, the obtained median normalized PFA_V value at the centre of the interior slab in the 3-storey building with 5.0 m spans was 2.84 times the value obtained with 9.0 m spans, while only a 34% corresponding increase was measured in the 6-storey building. To conclude, this research highlights the importance of considering the vertical component of earthquakes in the design of restraints for NSCs in low-rise buildings with short spans.*

Keywords: Non-structural Component (NSC), vertical peak floor acceleration (PFA_V), vertical floor spectral acceleration (FSA_V), reinforced concrete (RC), moment resisting frame (MRF).

1. Introduction

The seismic performance of non-structural components (NSCs) is nowadays recognized as a hot topic in earthquake engineering and thus has attracted the attention of a significant number of researchers in the last decade. According to statistical studies in the United States, NSCs account for 82%, 87% and 92% of the total construction costs of office, hotel and hospital buildings, respectively (Miranda & Taghavi, 2003). While several studies such as Medina (2013), Petrone et al. (2015), Anajafimarzijarani (2018) and Kazantzi et al. (2020) were carried out on the horizontal seismic response of NSCs, studies focussing on their vertical seismic response have been limited (Wang et al., 2021). Widespread failures of structural elements and floor systems and significant damage to NSCs due to the vertical component of ground motion were reported in the 1994 M_w 6.7 Northridge earthquake (J. A. Norton et al., 1996; Papazoglou & Elnashai, 1996; Elgamal & He, 2004). Typically, the lateral seismic force demands on NSCs are calculated by taking into account three main factors:

the ground motions exerted on the building's base, the dynamic amplification caused by the resonance between the supporting structure and NSCs, and the height factor associated with the filtering and amplification of input ground motion as it transfers through the building's height (CSA-S832, 2014). The CSA-S832 (2014) recommends the use of a vertical force equal to 2/3 of the lateral force, which implies a constant empirical vertical-to-horizontal acceleration ratio, while the NBC 2020 (NBC 2020, 2022) recommends considering a vertical seismic design force equal to the lateral one, and this is only for limited cases such as horizontally cantilevered floors, balconies, beams. This implies that the vertical floor acceleration linearly increases along the building height, with a maximum amplification of 3 at the rooftop. On the other hand, ASCE/SEI 7-22 (ASCE/SEI 7-22, 2022) recommends a constant vertical seismic design force of $0.2S_{DS}W_p$ for the NSCs mounted above ground level, which implies no amplification of vertical accelerations along the building height. In this context, S_{DS} represents the site-specific design response spectral acceleration for short periods, and W_p stands for the weight of the NSC.

The seismic response of the floors, in the form of peak floor acceleration (PFA) and floor spectral acceleration (FSA), provides a reasonable estimate of the seismic design force for NSCs (Kehoe & Hachem, 2003). PFA and FSA are also used as input to fragility curves to determine the probability of failure of a structure or component for a given seismic motion (Hwang & Huo, 1994). Buildings were previously assumed to be rigid enough in the vertical direction, and the out-of-plane flexibility of the floors was overlooked and ignored (Pekcan et al., 2003). When the fundamental vertical frequencies of floors coincide with the frequency of the ground motion, the resonance can lead to significant amplification of the vertical forces and deformations imposed on NSCs (Kim & Elnashai, 2008; Guzman Pujols & Ryan, 2018). In addition, the vertical floor acceleration varies depending on location, from the areas close to the columns to the centre of the slab (Pekcan et al., 2003; Furukawa et al., 2013; Mazloom & Assi, 2022), a fact that is currently not considered in design codes.

Recently, a few recent studies were conducted to evaluate the effect of the vertical component of ground motions on the building floor system and vertical acceleration demands on NSCs. The effects of building height and out-of-plane flexibility of floor systems on the vertical acceleration demands on NSCs were investigated by Wieser et al. (2012) on a 3-storey hospital and 3-, 9-, and 20-storey office buildings with steel moment-resisting frame systems. Results showed an amplification in FSA_V, four times of vertical ground spectral acceleration GSA_V, away from the column supports and at the centre of the slabs. An analytical study by Moschen et al. (2015) on typical 1- to 21-storey regular steel moment-resisting frame structures subjected to near-fault and strong recorded ground motions demonstrated the significant amplification of the vertical peak floor acceleration (PFA_V) at the rooftops in the order of about four times the vertical peak ground acceleration (PGA_V) for rigid NSCs mounted in locations away from the columns and at the middle of the beams. Similarly, the experimental test by Ryan et al. (2016) conducted on a 5-storey steel moment-resisting frame building showed an amplification of PFA_V ranging from approximately 3.0 to 6.0 at the middle of the slabs in the building rooftop. Moreover, the research by Gremer et al. (2019) assessing the PFA_V of single-degree-of-freedom (SDOF) oscillators representing NSCs flexibly attached to 1-, 2-, 4-, 8-, 12-, and 20-storey steel frames showed a median PFA_V up to 5.0 times larger than the PGA_V, at the centre of the beams.

Lately, the vertical acceleration response of floors was investigated by Mazloom and Assi (2022) in regular RC moment-resisting frame buildings with three spans of 7.0 m in each direction, subjected to strong near-fault earthquakes. An almost constant amplification of PFA_V, with a downward trend at the centre of the interior, sides, and corner slabs, was generally observed through the buildings' heights, and almost no significant amplification was seen on the beam nodes for the exterior frame. In this regard, the median normalized PFA_V at the rooftop interior slab ranged from 4.45 for the 3-storey building to 1.24 for the 12-storey building. Moreover, an equation was proposed to derive the normalized PFA_V profile for the mentioned regular building models.

Another study by Mazloom and Assi (2023) highlighted the high amplification of the FSA_V above ground, especially at the centre of the slabs and in low-rise buildings. The FSA_Vs were amplified from the rigid nodes close to the columns to the centre of the slabs. A significant spectral amplification was observed from the buildings' base to the first floors, which remained near-constant along the upper floors, especially for shorter buildings, measuring up to 9 floors. In this context, two different equations were proposed for deriving the smoothed FSA_V for the studied buildings, according to the input vertical time history acceleration records: one for the out-of-plane flexible nodes at the centre of the interior slab in buildings below 12 storeys and the second one for the rigid nodes of all buildings (column nodes), as well as for all the floor nodes of buildings having 12 storeys and above. Therefore, according to these two recent studies, the significant amplification of the vertical floor acceleration has shown to be more prominent in RC low-rise moment-resisting frame buildings; nonetheless, a more detailed study is needed before generalizing the conclusions.

The purpose of this study is to investigate the effect of the variation of the span length and of the building height on the PFA_V and FSA_V in six low-rise 3- and 6-storey RC moment-resisting frame buildings assumed located in Montreal on Site Class C. The buildings were subjected to strong near-field earthquakes, which were used in the studies by Mazloom and Assi (2022 and 2023). The amplification of PFA_V and FSA_V through the buildings' height and at different slab nodes was assessed. Subsequently, the obtained median normalized profiles of PFA_V and FSA_V at the critical nodes of the floor were compared to those proposed by Mazloom and Assi (2022 and 2023), respectively.

2. Selected Vertical Acceleration Records of Earthquakes

The sixty-five vertical time history accelerations, recorded from 31 strong near-field earthquakes in the world, were collected from the PEER-NGA Database (PEER-NGA, 2018) according to the criteria detailed in Mazloom and Assi (2022). The pseudo-spectral acceleration of selected records corresponding to a damping ratio of 5%, and the computed median and 16th and 84th percentiles are presented in Figure 1. Calculated median values for ground response spectra showed a maximum vertical acceleration (1.012g) on the curve at the period of 0.0833 sec (12 Hz), which demonstrates the importance of vertical spectral acceleration in the shorter period range.

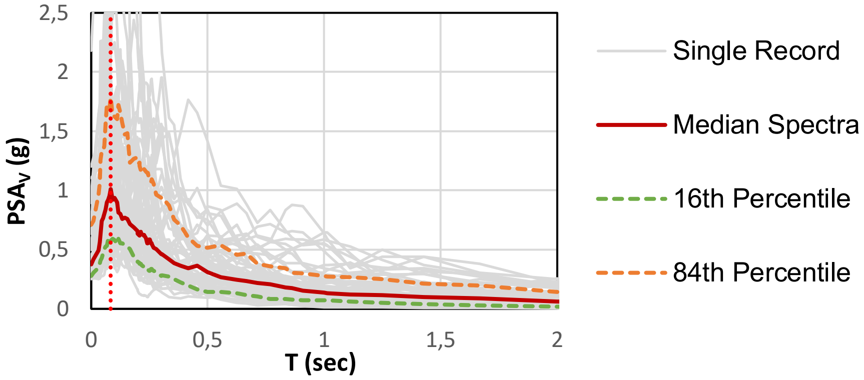

Figure 1. PSA_V of the vertical acceleration time history records corresponding to the 5% damping ratio.

3. Description of Archetype Buildings

3- and 6-storey regular moderately ductile RC moment-resisting frame buildings with 5.0 m, 7.0 m and 9.0 m spans, designed according to the NBC 2015 (NBC 2015, 2015) and CSA-A23.3-14 (CSA-A23.3, 2014) and assumed to be located in Montreal on very dense soil and soft rock (known as Site Class C in NBC 2015, with the average shear wave velocity, V_{s30}, between 360 and 760 m/s), were considered. The cross-sectional dimensions (in mm) of the structures' frames are presented in Table 1.

Table 1. Cross-sectional dimensions of the buildings' elements (in mm) with (a) 5.0 m, (b) 7.0 m, and (c) 9.0 m span lengths.

	Structure Reference	3-Storey (a)	3-Storey (b)	3-Storey (c)	6-Storey (a)	6-Storey (b)	6-Storey (c)
Column	**Internal**	300 × 300	400 × 400	500 × 500	450 × 450	600 × 600	700 × 700
	External	300 × 300	400 × 400	500 × 500	450 × 450	600 × 600	700 × 700
Beams (b × h)	**X-direction**	300 × 350	350 × 400	400 × 450	350 × 450	400 × 600	500 × 700
	X-direction	300 × 350	350 × 400	400 × 450	350 × 450	400 × 600	500 × 700

Each building has a symmetrical floor plan with three-span frames in each direction to minimize torsional effects. The main buildings with span lengths of 7.0 m were taken from the study of Mazloom and Assi (2022) and expanded for buildings with spans of 5.0 m and 9.0 m. For all buildings, the finished heights of the floors and of the RC slab floor system are equal to 3.0 m and 140 mm, respectively, as shown in the elevation and plan views in Figure 2. As well, the selected critical nodes on the buildings' floor plans are shown in Figure 2. The 3D finite element models for the selected buildings were created using the ETABS software (CSI, 2017). The floors' diaphragms were modelled with a mesh size of 500 × 500 mm, to account for their in-plane stiffness in the horizontal direction and out-of-plane flexibility in the vertical direction. Also, the classical Rayleigh damping with a ratio of 5% was considered for the finite element models.

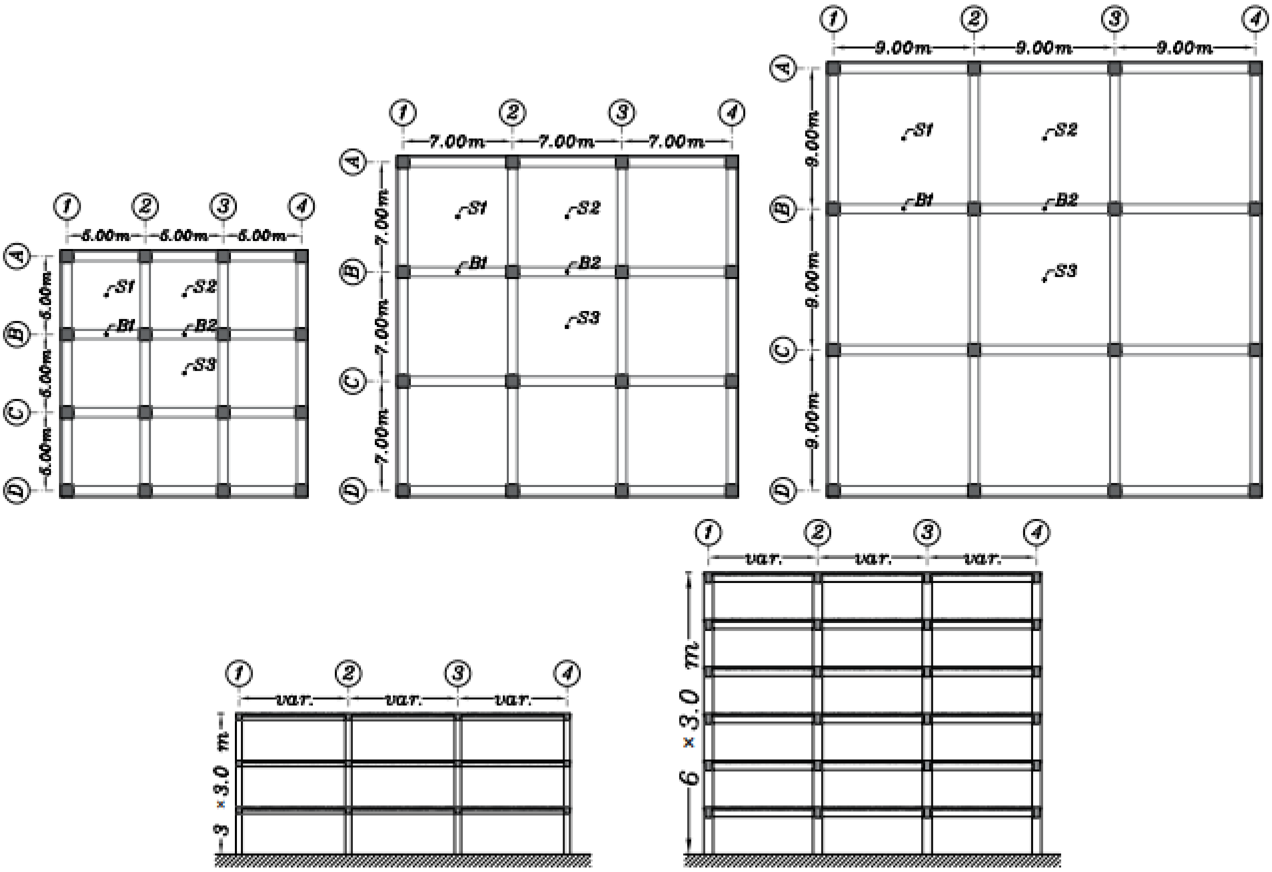

Figure 2. Plan and elevation views of the archetype RC moment-resisting frame buildings and considered critical nodes on the buildings' floor plan.

3.1. Vertical Modal Analysis of the Buildings and Floors

As shown in Figure 3, the obtained horizontal and vertical fundamental periods of the buildings indicate the effect of the building height on the horizontal fundamental period, while no effect of the span length variation was observed. On the other hand, the effect of the span length on the vertical fundamental period is evident, while no effect of the building height was found.

In order to have a better understanding of the vertical vibration characteristics of the floor system, 200 modes of vibration were considered in the modal analysis of the selected structures. A similar number of modes were considered in the vertical modal analysis of floors, which was performed separately for the corresponding floors of the buildings. The obtained modal participation factors are presented in Table 2. It can also be pointed out that with the increase in the length of the span and the height of the structure, the modal load participation ratio of the buildings decreased for the same number of modes considered.

Also, the comparison of the fundamental periods of the selected buildings, as outlined in Figure 3, and the corresponding first fundamental vertical modal period of the floors, presented in Table 3, reveals a striking similarity of the first vertical modal period, which indicates that the fundamental vertical period of the buildings is a function of the characteristics of the floor rather than the whole structure. Since the much higher vertical modes of the floors are not effective and are almost close to each other, only the first 12 modes out of 200 are presented in Table 3.

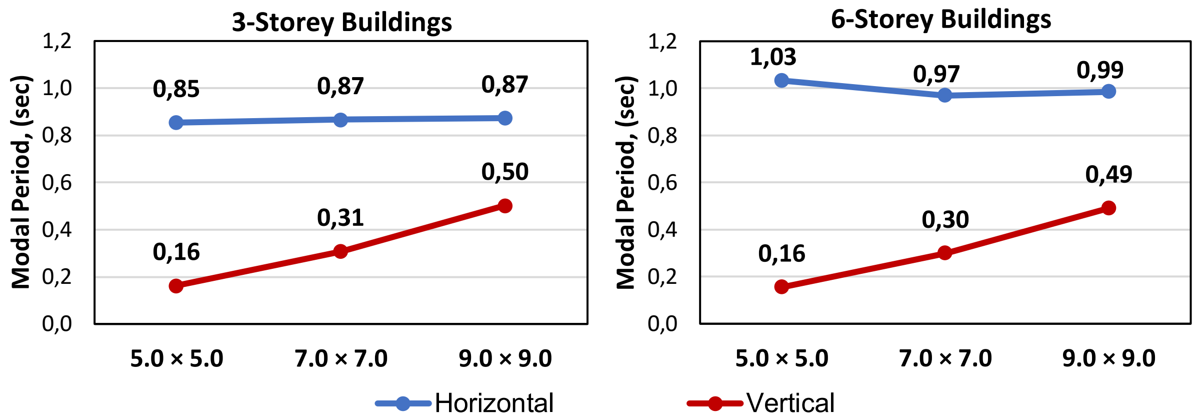

Figure 3. Fundamental horizontal and vertical modal periods of the selected (a) 3-storey (b) 6-storey buildings with 5.0 m, 7.0m, and 9.0 m spans.

Table 2. Vertical modal participation ratios of the selected buildings and their corresponding floors (in %) with (a) 5.0 m, (b) 7.0 m, and (c) 9.0 m span lengths.

Type	3-Storey			6-Storey		
	(a)	(b)	(c)	(a)	(b)	(c)
Building	92.48	68.27	65.27	89.88	68.44	36.27
Floor	91.05	91.05	91.05	91.05	91.05	91.05

Table 3. First 12 vertical modal periods of the floors (in sec) for the selected buildings with (a) 5.0 m, (b) 7.0 m, and (c) 9.0 m span lengths.

Mode	3-Storey			6-Storey		
	(a)	(b)	(c)	(a)	(b)	(c)
1	0.15	0.29	0.48	0.15	0.29	0.48
2	0.14	0.26	0.44	0.14	0.26	0.44
3	0.14	0.26	0.44	0.14	0.26	0.43
4	0.13	0.24	0.40	0.13	0.24	0.40
5	0.11	0.22	0.36	0.11	0.22	0.36
6	0.11	0.22	0.36	0.11	0.22	0.36
7	0.11	0.21	0.34	0.11	0.21	0.34
8	0.11	0.21	0.34	0.11	0.21	0.34
9	0.09	0.18	0.30	0.09	0.18	0.30
10	0.06	0.12	0.19	0.06	0.12	0.19
11	0.06	0.12	0.19	0.06	0.12	0.19
12	0.06	0.11	0.19	0.06	0.11	0.19

4. Vertical Acceleration Response of the Floors

The effects of building filtering on the amplification of the vertical seismic floor acceleration were investigated at a series of nodes at the centre of the slabs (S1, S2, and S3) and at the midpoint of the interior frame beam spans (B1 and B2), depicted in Figure 2, in all floor elevations of the selected buildings of this study.

4.1. Vertical Peak Floor Acceleration (PFA_V)

In this section, the variation of normalized PFA_V with respect to the PGA_V was assessed through the considered nodes along the height of the structures normalized to the total height of the building ($h_{norm} = h_x/h_{building}$). The individual results resulting from 65 input vertical time history accelerations, along with the median, 16th and 84th percentiles, are illustrated in Figures 4 and 5 for the selected 3- and 6-storey buildings, respectively.

The results reveal a notable increase in vertical acceleration at the slab nodes above ground, particularly at the central point of the interior slab, denoted as S3. This acceleration shows a linear increase from the base to the first floor and maintains a relatively constant value up to the rooftop. Also, the normalized PFA_V gradually increases from the centre of the corner slab, S1, to the side slab node, S2, and then increases significantly to the centre of the interior slab, S3. As an example, in the case of the 3-storey building with 5.0 m spans, the median normalized PFA_V of 6.83, 4.12 and 3.17 were obtained for the nodes S3, S2, and S1, respectively. This increase is more evident in the slab nodes; however, in the structures with shorter spans (5.0 m and 7.0 m), the acceleration amplification at the beam nodes is still insignificant compared to the slabs.

The median values calculated for the slab nodes of 3- and 6-storey buildings are presented in Figure 6, along with the PFA_V profile proposed by Mazloom and Assi (2022), which makes clear that the acceleration increases as the span length decreases. The median normalized PFA_V at the centre of the interior slab, S3, reached the values of 6.83, 3.96, and 2.72 at the rooftop of the 3-storey buildings with 5.0 m, 7.0 m, and 9.0 m span lengths, respectively. On the other hand, there is no significant amplification at the corner slab node, S1, of the 6-storey building with a 7.0 m span length and at the corner, S1, and side, S2, slab nodes of the building with 9.0 m span lengths. Thus, the results still show the importance of buildings with shorter span lengths where the median normalized PFA_V of 4.44, 3.00, and 2.08 were concluded for the nodes S3, S2, and S1, respectively. It should be noted that the profile proposed by Mazloom and Assi (2022) almost covers the obtained median values corresponding to the selected buildings of this study.

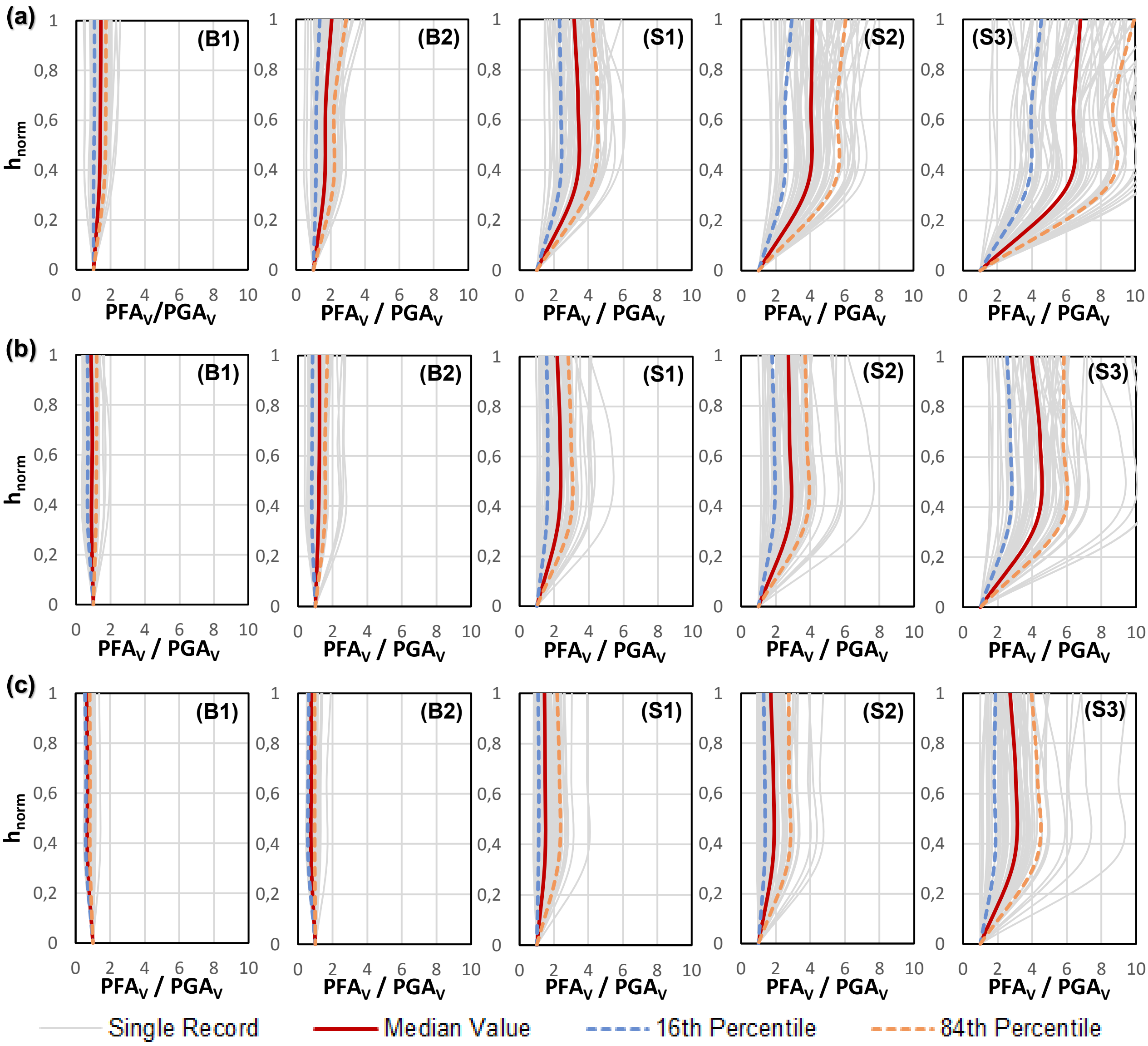

Figure 4. Profiles of the normalized PFA_V at the considered nodes of the 3-storey buildings with (a) 5.0 m, (b) 7.0 m, and (c) 9.0 m spans.

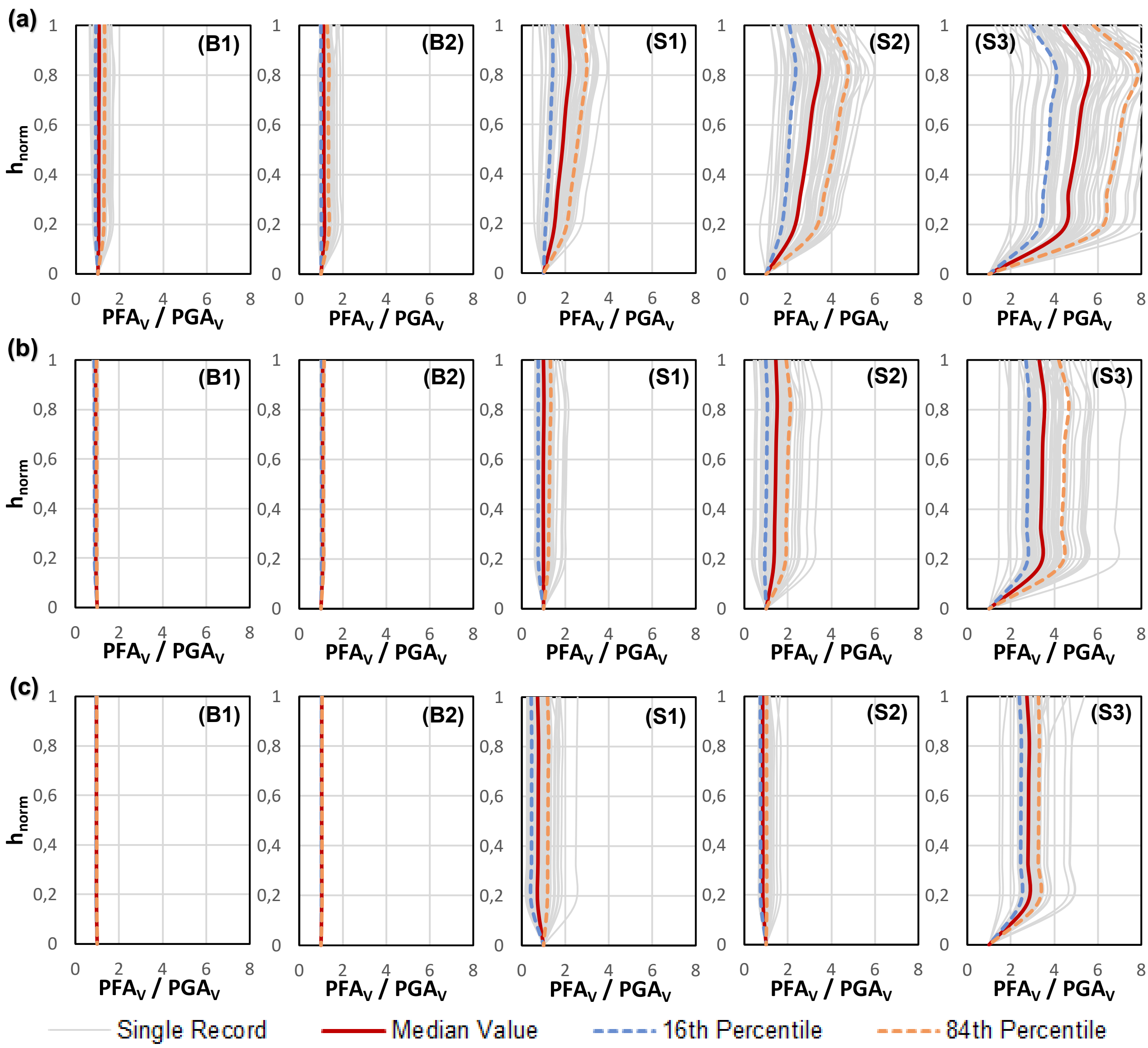

Figure 5. Profiles of the normalized PFA_V at the considered nodes of the 6-storey buildings with (a) 5.0, (b) 7.0, and (c) 9.0 m spans.

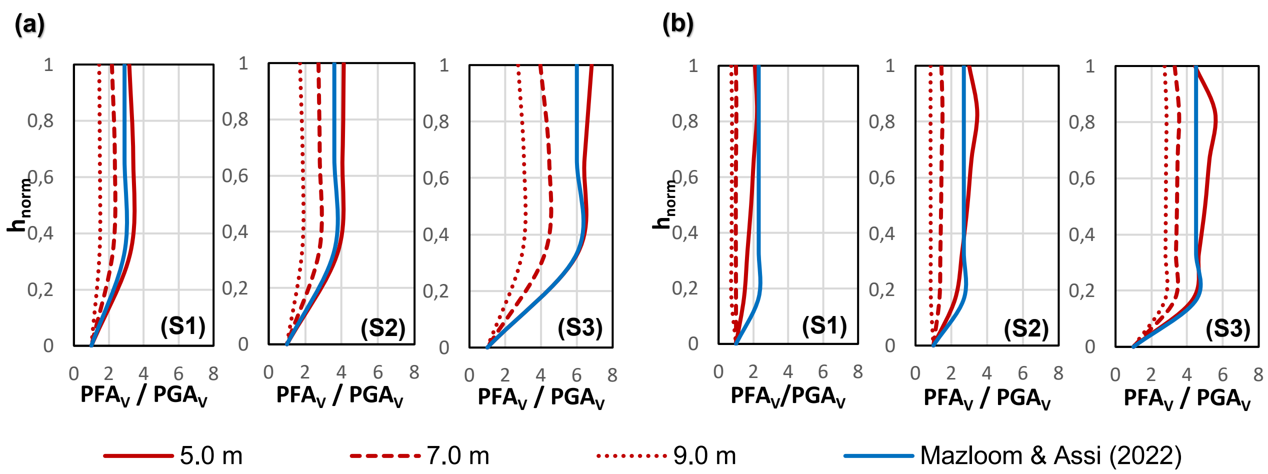

Figure 6. The median normalized PFA_V at the centre of the slabs of the buildings: (a) 3 storeys and (b) 6 storeys.

4.2. Vertical Floor Spectral Acceleration (FSA_V)

In this section, the response spectral acceleration of the floors subjected to input vertical acceleration time histories were assessed. For this purpose, the FSA_V with a damping ratio of 5%, corresponding to the ground motions selected as the input GSA_V, was computed. The FSA_V derived from 65 earthquake time history records, indicated by grey lines, along with the calculated median spectra, 16th and 84th percentiles (mean ± standard deviation) are shown in Figures 7 and 8 for the 3- and 6-storey buildings, respectively. It is important to highlight that the response spectra for the floors were assessed at the centre of the interior slab, known as the most critical node on the floor plan of buildings.

The obtained results show the almost constant amplification of spectral profiles through the height of each building, in which the maximum acceleration on the shape of FSA_V decreases with the increase of the spans' length and shifts towards a higher period. In this regard, the maximum spectral accelerations of 14.5 g, 11.5 g, and 6.3 g were obtained on the median FSA_V curve of 3-storey buildings with span lengths of 5.0 m, 7.0 m, and 9.0 m, respectively. Correspondingly, the peaks in the 6-storey buildings with 5.0 m, 7.0 m, and 9.0 m spans reached to 9.5 g, 6.3 g, and 3.0 g, respectively. These values were observed at the periods 0.13, 0.22, and 0.36 sec on the median spectral profile of the 3- and 6-storey buildings with 5.0 m, 7.0 m, and 9.0 m span lengths, respectively, that seem to correlate with the higher vertical modes of the floors. However, two peaks (a wider range) are seen on the spectral curve of the 6-storey building with 9.0 m spans; the first of which was equal to 2.4 g at the period 0.0833 sec, which is similar to the observed peak on the median spectral curve of GSA_V (Figure 1) that occurred at this period. According to the results, these maximum vertical accelerations occurred at the 4th vertical mode of floors for the 3- and 6-storey structures with 5.0 m spans and at the 5th mode for the other buildings with 7.0 m and 9.0 m spans. It is worth noting that, except for the 6-storey structure with 9.0 m spans, only one peak (summit) is observed on the obtained FSA_V curve of all the buildings. This finding aligns with those of the experimental research conducted by Ryan et al. (2016) and the outcomes of the experiments undertaken by Guzman Pujols and Ryan (2018) on a five-story steel moment-resisting frame structure, which concluded that slab vibrations were predominantly governed by a single-mode response.

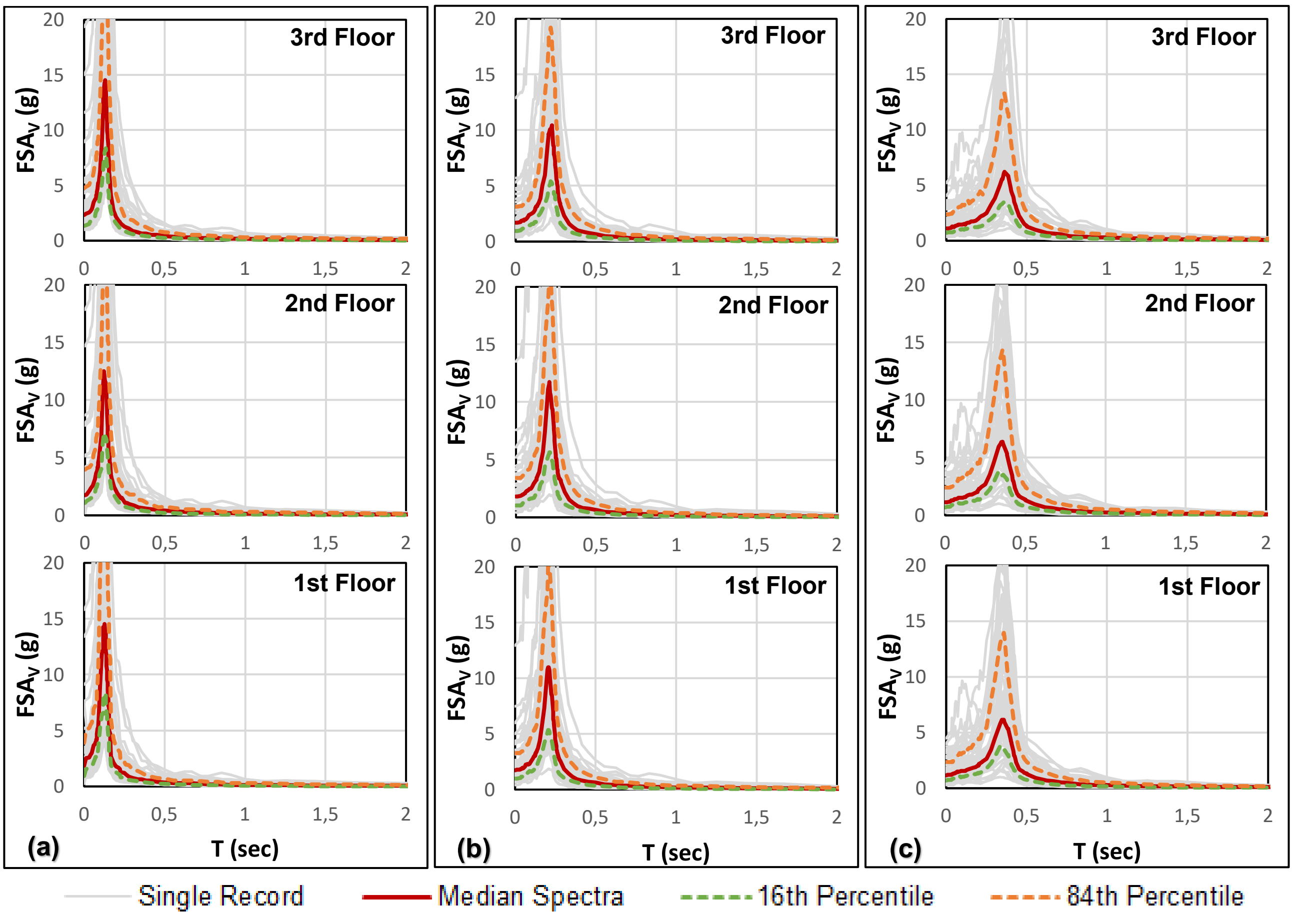

Figure 7. Computed FSA_V at the centre of the interior slab of the 3-storey buildings with (a) 5.0 m, (b) 7.0 m, and (c) 9.0 m spans.

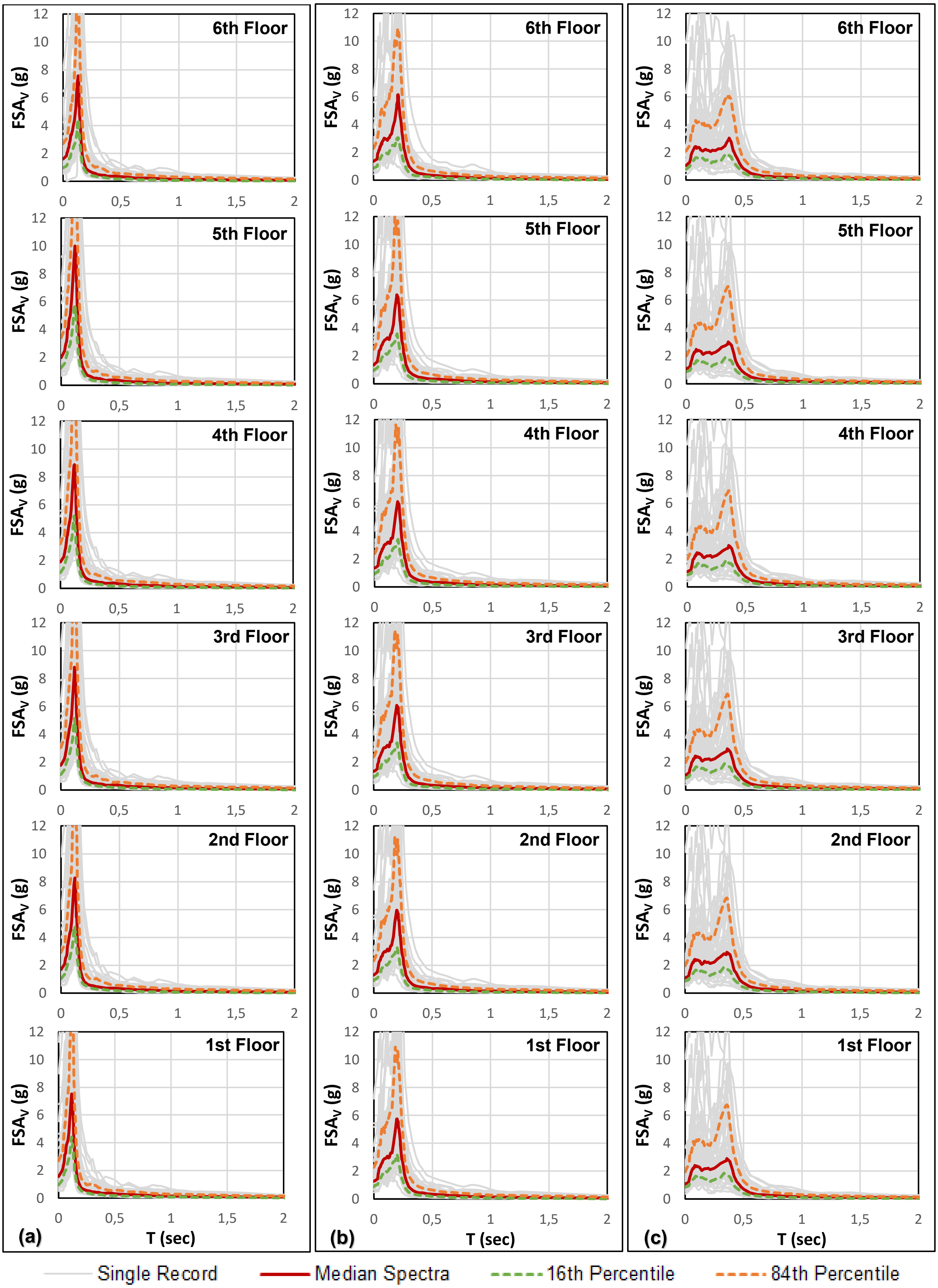

Figure 8. Computed FSA_V at the centre of the interior slabs of the 6-storey buildings with (a) 5.0 m, (b) 7.0 m, and (c) 9.0 m spans.

The median FSA_V obtained from the selected buildings of this study and those obtained from the equation proposed by Mazloom and Assi (2023) for the out-of-plane flexible nodes (which are typically considered as the nodes at the centre of the slabs) are presented in Figure 9. Overall, the proposed equation yields overestimated spectra for buildings with spans of more than 7.0 m. Given that structures with exceptionally large spans are generally not advised and are seldom constructed, the profiles derived from the equations introduced by Mazloom and Assi (2023) prove to be highly practical for estimating the vertical floor spectra for spans up to 7.0 m. Therefore, the recommended equation provides an acceptable and reasonable profile of FSA_V for the low- to mid-rise RC moment-resisting frame buildings.

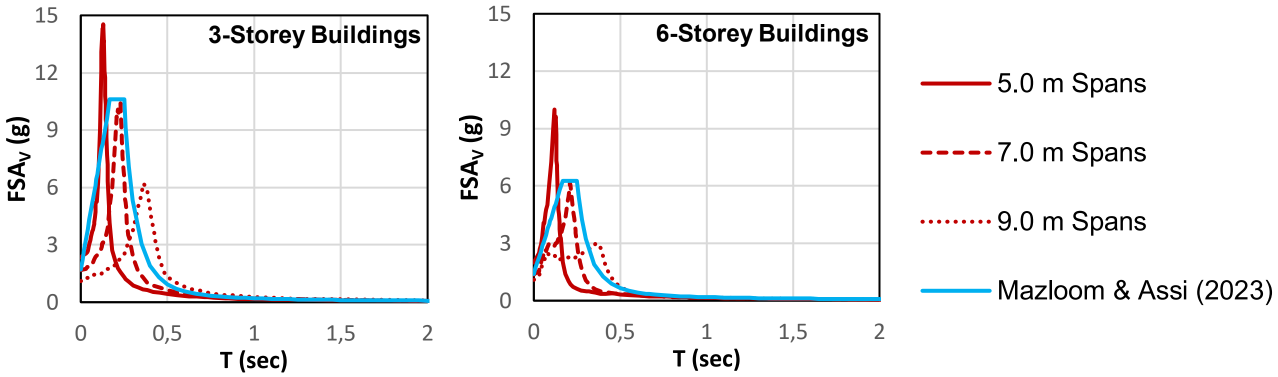

Figure 9. Comparison of the computed median FSA_V at the centre of the interior slabs of the 3- and 6-storey buildings with the proposed profile by Mazloom and Assi (2023).

5. Conclusion

The vertical acceleration response of the floors, in the form of PFA_V and FSA_V, was assessed in this study using 3- and 6-storey elastic RC moment-resisting frame buildings, symmetrical in plan with 5.0 m, 7.0 m, and 9.0 m spans. The buildings assumed to be located in Montreal on Site Class C were subjected to 65 sets of vertical time history accelerations recorded on Site Class C that were selected from 31 strong near-field earthquakes.

The PFA_V, normalized with respect to the PGA_V, was statistically assessed along the buildings' height for the nodes at the centre of the slabs and at the middle of the beam spans of the interior frames. An almost constant amplification was observed through the height of all selected buildings. The amount of amplification gradually increases from the rigid nodes closest to the columns to the nodes at the centre of the slab bays. The largest median normalized PFA_V values of 6.83 and 4.44 were obtained at the centre of the interior slab in the 3- and 6-storey building plans with 5.0 m spans, respectively, which refers to the largest amplification in these buildings. This outcome indicates the high importance of considering the vertical component of ground motion in low-rise buildings with shorter spans, especially at the interior slab node, known as the most critical node. Furthermore, the median normalized PFA_V profiles obtained in this study are in close agreement with those obtained from the equation proposed by Mazloom and Assi (2022).

On the other hand, assessing the FSA_V for the critical node (at the centre of the interior slab) reveals a significant spectral amplification at the centre of the interior slab, linearly increasing from the base of the structures to their first floors. The amplification then remains almost constant throughout the buildings' height, particularly in the shorter buildings with shorter spans. Therefore, the importance of considering the vertical component of ground motions in low-rise buildings with shorter spans that are subjected to a strong vertical component of ground motion was affirmed. Moreover, the computed median FSA_V of the selected buildings confirmed the accuracy of the smoothed spectral curve obtained from the equation proposed in the study by Mazloom and Assi (2023). Accordingly, it can be seen that the maximum values on the FSA_V curve occurred at the higher modes of the floors (4^{th} and 5^{th}).

The findings of this study underscore a foremost and primary concern in this field of research, namely, the significance of out-of-plane slab flexibility in amplifying the acceleration of an earthquake's vertical component. Furthermore, a comparison of the horizontal and vertical fundamental periods of the structures indicated that the vertical period of the structure is primarily influenced by the dimensional characteristics of the individual floors (span length) rather than the entire structure, and it is then subject to variation according to the span length.

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