Spectrum-to-spectrum method for seismic assessment of acceleration-sensitive non-structural components

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ABSTRACT

In response to the need for an accurate method for seismic assessment of nonstructural building components (NSCs), this paper introduces an original approach to generate Floor Design Spectra (FDS) directly from Uniform Hazard Spectra (UHS) specified in building codes. Generated FDS play the same role as UHS for structural components and area simple, fast, and reliable tool for seismic assessment and analysis of NSCs particularly in existing post-critical buildings. To develop and validate the proposed method, a database of 27 existing Reinforced Concrete (RC) buildings tested by Ambient Vibration Measurements (AVM) has been collected. The procedure has been coded in MATLAB to generate elastic a Floor Response Spectrum (FRS) at every floor of the building in both orthogonal horizontal (X and Y) directions, and considering NSCs with several damping ratios (2, 5, 10, and 20% of critical viscous damping). The method has been validated through the detailed linear numerical modeling of Building #23 of the database. Firstly, the generated FRS for Roof level and 5% NSC damping have been statistically analyzed and compared with 5% damped UHS and, as a result, a method is proposed to generate FDS for roof level and ξ_{NSC}=5% directly from the UHS. Secondly, the effects of the NSCs damping ratio and location along the building height on the FDS have been statistically studied and two sets of modification factors were introduced that account for NSC damping and location effects. These modification factors were incorporated in the proposed method to extend its application to produce FDS directly from UHS at any selected floor level and for any NSC damping ratio of interest. The method enables the generation of an exclusive FDS for each existing building taking its dynamic characteristics into account (as extracted from AVM records) and the acceleration design spectrum for the site.

Keywords: Operational and Functional Components (OFCs); Operation Modal Analysis (OMA); Earthquake Engineering.

INTRODUCTION

Increasing demand for high performance structures requires a careful attention to seismic assessment of Non-Structural Components (NSCs) in buildings. Experiences from past earthquakes have shown that many buildings have failed to meet their performance objectives solely due to failure or malfunction of their NSCs while the structural systems have performed well. In general, the failure or malfunction of NSCs can give rise to undesired consequences that can be associated with: a) life-safety hazards (i.e. fatalities or injuries caused by falling or overturning NSCs, blockage of safe egress, etc. [1-3]); b) property loss due to direct and indirect damage costs (e.g. major part of the approximate economic loss of 25 billion dollars in the 2010 Maule, Chile earthquake [4] and 2 billion dollars in the 2001 Nisqually (Seattle) earthquake [5] was related to NSCs); and c) loss of building functionality (e.g. impairment or complete shut-down of 130 hospitals in the 2010 Maule, Chile earthquake [4] and of 32 commercial data processing centers in the 1989 Loma Prieta earthquake [6]).

According to the nature of the seismic response sensitivity and failure mechanism of NSCs, they can be categorized as either drift-sensitive or acceleration-sensitive components [7]. Damage to drift-sensitive components is triggered by seismically induced displacements and inter-story drift. Acceleration-sensitive components, which are the main focus of this study, undergo damage because of the inertia forces induced by the floor acceleration which is, in general, larger than that of the ground level. Several studies have focused on enhancing the understanding of acceleration demand on NSCs by estimating Peak Floor Acceleration (PFA) or Peak Component Acceleration (PCA) and by developing practical approaches for seismic design of this type of components [8-11]. Additionally, most of the current building codes also contain provisions to estimate NSC acceleration demand. *Table 1* summarizes the seismic force requirements for NSCs in Canada (National Building Code of Canada- NBCC 2015 [12]), United States (ASCE SEI-7-16 [13]), and Europe (Eurocode 8, EN. 1988. 1. 2004. [14]). However, these provisions are mostly incapable of considering several key factors such as the effects of building higher frequency modes and torsional modes, the effects of tuning/detuning of the primary and secondary systems, and the effect of NSCs internal damping. These shortcomings cause the code provisions to underestimate acceleration demand on NSCs as shown in several studies such as [9, 10, 15, 16].Therefore, there still appears to be a need for a simplified and practical method which can properly quantify seismic acceleration demand on NSCs. In an attempt to fulfill this need, an original approach is presented here to develop Floor Design Spectra (FDS) directly from Uniform Hazard Spectra (UHS). The developed FDS can be used for seismic assessment of NSCs in a similar way as Design Response Spectra (DRS) are for structural elements.

Table 1 - Building code seismic force requirements for acceleration-sensitive NSCs

Code	Recommendations	Seismic force demand	Design PGA	Building importance factor	Component importance factor	Component dynamic amplification factor	Component response reduction factor	Component elevation modification factor	Component weight
NBCC 2015 (Division B-Part 4)	$\boldsymbol{V_P = 0.3F_aS_a(0.2)I_ES_PW_P}$ $0.7 \le S_P = \dfrac{C_PA_rA_x}{R_P} \le 4.0$ $A_x = 1 + 2\dfrac{h_x}{h_n}$	V_P	$0.3F_aS_a(0.2)I_E$	I_E	C_P	A_r	R_P	A_x	W_P
ASCE-SEI-07-16 (Chapter 13)	$\boldsymbol{F_P = \dfrac{0.4a_PS_{DS}}{\left({R_P}/{I_P}\right)} \times \left(1 + 2\dfrac{Z}{H}\right) \times W_P}$ $1.6S_{DS}I_PW_P \le F_P \le 0.3S_{DS}I_PW_P$	F_P	$0.4S_{DS}$	-	I_P	a_P	R_P	$\left(1 + 2\dfrac{Z}{H}\right)$	W_P
Eurocode 8 (Part 4.3.5)	$\boldsymbol{F_a = {(S_aW_a\gamma_a)}/{q_a}}$ $S_a = \alpha.S.\left[\dfrac{3\left(1+\frac{Z}{H}\right)}{1+\left(1-\frac{T_a}{T_1}\right)^2} - 0.5\right] \ge \alpha S$	F_a	$\alpha.S$	-	γ_a	$1 + \left(1 - \dfrac{T_a}{T_1}\right)^2$	q_a	$3\left(1 + \dfrac{Z}{H}\right)$	W_a

METHODOLOGY OF THE PROPOSED APPROACH

In this research, a total of 27 existing RC buildings (12 low-rises, 10 medium-rise, and 5 high-rises, which had been already tested by AVM) have been studied in detail (see Table 2 for description of the building database). After extracting the building dynamic properties from AVM records and estimating the building floor mass and in-plane rotary inertia according to the information in structural and architectural drawings, an equivalent linear model of each building was generated using the 3D-SAM approach [17]. As the AVM results yield the dynamic properties of buildings under low-amplitude excitations and knowing that these properties will vary with the intensity of excitation [18, 19], a set of modification factors have been proposed to extend the applicability of the method to higher-amplitude excitations. These modification factors were derived after a careful review of studies on permanently instrumented RC buildings [20]. Using the 3D-SAM procedure and subjecting the buildings to a set of 20 synthetic ground accelerograms compatible with the UHS of NBCC 2015 for Montréal, the floor response histories of the buildings in two orthogonal horizontal directions have been generated. The acceleration floor response histories were then considered as the base excitation for NSCs and FRS curves have been generated for components with critical viscous damping ratios of 2, 5, 10, and 20 % and fundamental periods of [0-4] seconds with interval of 0.02 s. The automatic generation of the FRS has been implemented in MATLAB [21] adopting direct integration with Newmark's linear acceleration method [22] to solve the equation of motion of NSCs. Approximately 132,000 FRS curves have been generated for the selected RC buildings. The description of the building database, the record selection process and the characteristics of the ground motions, discussion on the proposed modification factors, a description of the FRS generator MATLAB code, and the validation of the proposed method through detailed numerical analysis of Building #23 of the database have been presented in details by the authors in [20, 23]. The experimentally derived peak acceleration floor response spectra (PA-FRS) have been used for statistical analysis to study the effect of the main parameters affecting NSCs' response comprising: a)- Tuning of fundamental period of NSCs with building modal periods, b)- Elevation of NSCs in the building, and c)- NSC damping ratios.

Table 2 – Building characteristics and AVM results

Building category	Building #	LLRS type	Construction year	H_A / H_B (m)	N_A / N_B	Mode 1 Translational mode		Mode 2 Translational mode		Mode 3 Torsional mode		NBCC period (s)
						AVM Period (s)	AVM ξ (%)	AVM Period (s)	AVM ξ (%)	AVM Period (s)	AVM ξ (%)	
Low-rise buildings	1	RCSW	1969	6.5 / 1.5	1 / 1	0.15	1.2	0.13	1.8	0.12	0.2	0.20
	2	RCSW	1969	6.5 / 1.5	1 / 1	0.27	4.1	0.24	1.9	NA	NA	0.20
	3	RCMF	1957	8.6 / 6.4	2 / 1	0.15	2.9	0.12	1.4	0.10	2.4	0.38
	4	RCMF	1957	7.7 / 3.3	2 / 1	0.18	1.5	0.18	1.3	0.10	2.0	0.35
	5	RCMF	1963	7.5 / 2.7	2 / 1	0.20	1.2	0.16	1.56	0.11	0.4	0.34
	6	RCMF	1963	7.5 / 2.7	2 / 1	0.18	2.5	0.13	1.2	NA	NA	0.34
	7	RCMF	1963	7.5 / 2.7	2 / 1	0.18	3.2	0.14	2.1	0.11	0.8	0.34
	8	RCMF	1993	8.4 / 3.3	2 / 1	0.19	2.0	0.18	1.8	0.13	2.1	0.37
	9	RCMF	1961	8.4 / 4.7	2 / 1	0.23	1.7	0.21	1.7	0.16	3.3	0.37
	10	RCMF	1964	17.1 / NA	2 / 1	0.38	3.6	0.38	3.9	0.15	1.4	0.63
	11	RCMF	1975	10.8 / 2.7	3 / 1	0.15	2.0	0.13	2.3	0.11	1.6	0.45
	12	RCMF	1964	13.0 / 4.1	3 / 1	0.38	4.1	0.38	4.0	0.23	2.9	0.51
Medium-rise buildings	13	RCMF	1967	13. 0/ 2.2	4 / 1	0.22	1.4	0.19	1.1	0.11	0.7	0.51
	14	RCMF	1964	12.0 / 3.1	4 / 1	0.18	2.7	0.15	2.7	0.12	0.1	0.48
	15	RCMF	1975	18.6 / 2.4	4 / 1	0.30	2.0	0.22	2.3	0.18	1.6	0.67
	16	RCMF	1975	15.9 / 5.1	4 / 2	0.30	2.0	0.22	2.9	0.18	2.6	0.60
	17	RCMF	1969	18.1 / 0.0	5 / 0	0.29	0.8	0.29	0.4	0.16	0.2	0.66
	18	RCSW	1998	19.6 / 3.6	5 / 1	0.40	2.3	0.36	1.7	0.28	2.8	0.47
	19	RCMF	1961	20.2 / 3.1	7 / 1	0.36	1.7	0.32	1.3	0.30	1.1	0.71
	20	RCMF	1961	20.2 / 3.1	7 / 1	0.37	1.4	0.31	0.8	0.29	1.0	0.71
	21	RCMF	1962	20.2 / 3.1	7 / 1	0.37	1.6	0.31	1.4	0.28	1.1	0.71
	22	RCSW	1971	28.0 / 6.7	7 / 2	0.59	3.6	0.46	4.4	0.36	1.7	0.61
High-rise buildings	23	RCMF	1957	36.0 / 3.5	10 / 1	0.53	1.7	0.40	1.2	0.37	1.1	1.10
	24	RCMF	1965	45.6 / 7.4	13 / 2	1.30	3.7	1.03	3.3	0.96	3.7	1.32
	25	RCSW	1969	55.4 / 8.4	13 / 2	0.70	1.78	0.68	1.7	0.41	2.0	1.01
	26	RCSW	1978	51.2 / 6.3	16 / 2	0.96	1.9	0.87	1.8	0.42	1.3	0.96
	27	RCMF	1965	58.7 / 7.9	18 / NA	1.25	2.5	1.03	2.9	0.94	2.2	1.59

RCSW = Reinforced Concrete Shear Wall system, RCMF = Reinforced Concrete Moment-resisting Frame system, H_A = Height above ground level (m), H_B = Height below ground level (m), N_A = Number of floors above ground level, N_B = Number of floors below ground level, ξ = Modal viscous damping ratio (percentage of critical value).

At the first phase, FDS for building roofs (given ξ_{NSC} = 5%) have been generated directly from the 5% damped UHS of NBCC 2015 corresponding to the building location: two separate sets of equations are proposed for low-rise and medium-rise buildings to generate FDS in three distinct spectral regions; namely short-period, fundamental-period, and long-period regions. Although the proposed methodology remains valid for high-rise buildings, no recommendations have been made for this category since the number of high-rises in the database was not deemed sufficient to identify clear trends. This building category could be the object of a future study by adding more AVM-tested high-rises to the database. It should also be noted that this study is mainly focused on post-disaster buildings that are mostly low/medium-rise buildings so the exclusion of high-rise buildings at this step does not impair the scope of the project.

At the second phase, the effect of NSCs' location/elevation in the building (i.e. Z/H) is quantified through statistical analysis of the generated PA-FRS for different floor levels of the various buildings. Similarly, the effect of NSCs damping ratios is measured by studying the results corresponding to various NSCs damping ratios in detailed analyses. As a result, two sets of modification factors are introduced in the previously proposed method and a set of complete equations is recommended to develop FDS directly from UHS for any selection of floor level ($0.0 \leq Z/H \leq 1.0$) and NSCs' damping ratio ($1\% \leq \xi_{NSC} \leq 30\%$) for RC low and medium rise buildings. The proposed approach is fast and reliable to generate an exclusive FDS for each building with no need for either structural or non-structural numerical analysis while accounting for the effects of the dynamic properties of both systems. The procedure improves the code recommendations and conventional approaches in several aspects by considering the effects of: a) dynamic interaction between structural system and NSCs, b) higher and torsional modes of the supporting structure, and c) internal damping of NSCs. A more detailed description of the methodology can be found in [20].

RESULTS AND DISCUSSION

This section presents a set of equations recommended to develop FDS directly from UHS for any selection of floor level ($0.0 \leq Z/H \leq 1.0$) and NSCs' damping ratio ($1\% \leq \xi_{NSC} \leq 30\%$) in both low and medium rise buildings. Figure 1 schematically shows how the spectral acceleration is idealized in each spectral region for both low and medium rise buildings.

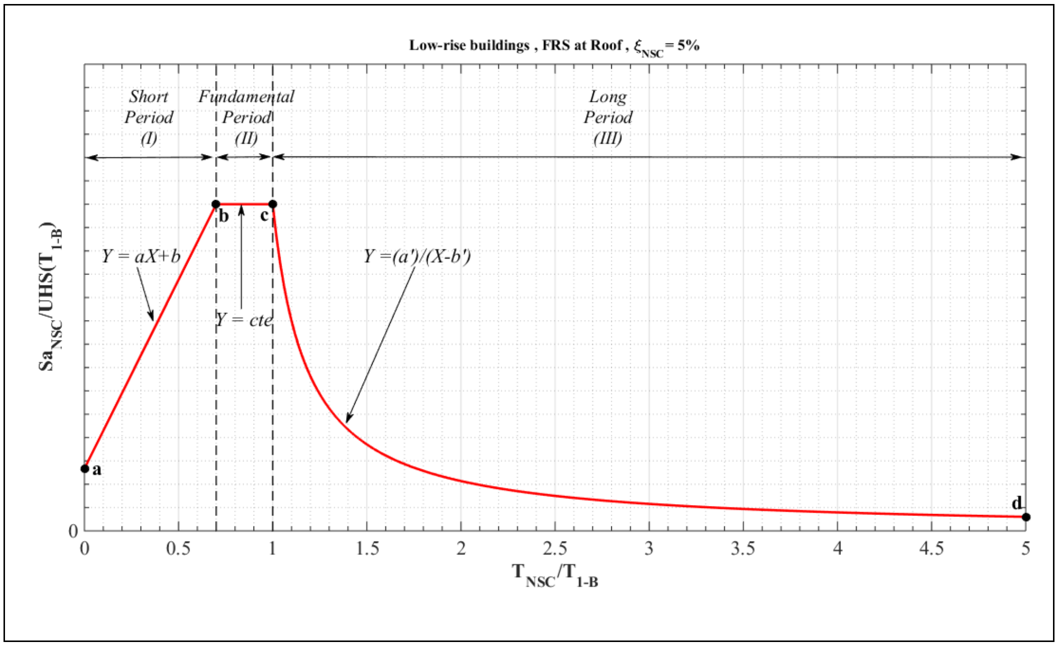

Figure 1 – Schematic of the proposed FDS and idealization of spectral acceleration for NSCs

Proposed FDS for low-rise buildings

As illustrated in Figure 1, the recommended FDS has a linear variation in the short-period region (point "a" to point "b"), a constant value in fundamental-period region (points "b" to "c"), and decays according to a rational function in the long-period region (points "c" to "d"). The following equations describe how the FDS values are calculated in each spectral region for RC low-rise buildings. It should be mentioned that in all the recommended equations, the first bracket is to calculate the FDS values at roof level given 5% NSC damping, the second bracket is the modification factor which accounts for relative height effect ($0.0 \leq Z/H \leq 1.0$), and the third bracket is the modification factor that accounts for NSCs' damping effect ($1\% \leq \xi_{NSC} \leq 30\%$).

In the short-period region, the FDS values are increased linearly from point "a" at $T_{NSC}/T_{1-B} = 0.0$ to point "b" at $T_{NSC}/T_{1-B} = 0.7$. Values of points "a" and "b" are calculated according to *Equation 1*:

$$\frac{Sa_{NSC}}{UHS(T_{1-B})} = \begin{cases} [2.0] \times \left[0.33 + 0.67\left(\frac{Z}{H}\right)\right] \times \left[\frac{0.69 \times \xi_{NSC} + 3.33}{\xi_{NSC} + 1.78}\right] & @ \quad \text{"a"}, \quad \frac{T_{NSC}}{T_{1-B}} = 0.0 \\ [10.5] \times \left[0.33 + 0.67\left(\frac{Z}{H}\right)\right] \times \left[\frac{0.14 \times \xi_{NSC} + 7.36}{\xi_{NSC} + 3.06}\right] & @ \quad \text{"b"}, \quad \frac{T_{NSC}}{T_{1-B}} = 0.0 \end{cases} \tag{1}$$

In the fundamental-period region, the FDS has a constant value determined at point "b" using Equation 1, between points "b" at $T_{NSC}/T_{1-B} = 0.7$ and "c" at $T_{NSC}/T_{1-B} = 1.0$. In the long-period region, the value of FDS is calculated according to Equation 2:

$$\frac{Sa_{NSC}}{UHS(T_{1-B})} = min\left\{\begin{matrix} [10.5] \times \left[0.33 + 0.67\left(\frac{Z}{H}\right)\right] \times \left[\frac{0.14 \times \xi_{NSC} + 7.36}{\xi_{NSC} + 3.06}\right] \\ \left[\frac{1.89}{\left(\frac{T_{NSC}}{T_{1-B}}\right) - 0.82}\right] \times \left[0.8 + 0.2\left(\frac{Z}{H}\right)\right] \times \left[\frac{0.3 \times \xi_{NSC} + 8.3}{\xi_{NSC} + 4.8}\right] \end{matrix}\right\} \quad : \quad 1.0 \leq \frac{T_{NSC}}{T_{1-B}} \leq 5.0 \tag{2}$$

The FDS is taken as the minimum of the two proposed equations because the rational function corresponding to the long-period region (lower part of Equation 2) does, in some cases, overestimate the FDS values in the vicinity of $T_{NSC}/T_{1-B} = 1.0$. If the FDS is required to be extended for a longer range, $5.0 \leq T_{NSC}/T_{1-B} \leq 10.0$, a conservative and simple approach is proposed where the $Sa_{NSC}/UHS(T_{1-B})$ is decreased linearly from its value at $T_{NSC}/T_{1-B} = 5.0$ to half of that at $T_{NSC}/T_{1-B} =10.0$.

Proposed FDS for medium-rise buildings

For RC medium-rise buildings, the FDS is generated using the same methodology as described for low-rise building but using a different set of equations are described below.

In the short-period region, the FDS values are increased linearly from point "a" at $T_{NSC}/T_{1-B} = 0.0$ to point "b" at $T_{NSC}/T_{1-B} = 0.7$. Values of point "a" and "b" are calculated according to Equation 3:

$$\frac{Sa_{NSC}}{UHS(T_{1-B})} = \begin{cases} [3.0] \times \left[0.2 + 0.8\left(\frac{Z}{H}\right)\right] \times \left[\frac{0.69 \times \xi_{NSC} + 3.33}{\xi_{NSC} + 1.78}\right] & @ \quad \text{"a"}, \quad \frac{T_{NSC}}{T_{1-B}} = 0.0 \\ [12.0] \times \left[0.2 + 0.8\left(\frac{Z}{H}\right)\right] \times \left[\frac{0.14 \times \xi_{NSC} + 7.36}{\xi_{NSC} + 3.06}\right] & @ \quad \text{"b"}, \quad \frac{T_{NSC}}{T_{1-B}} = 0.0 \end{cases} \tag{3}$$

In the fundamental-period region, the FDS has the constant value determined at point "b" using Equation 3, between points "b" at $T_{NSC}/T_{1-B} = 0.7$ and "c" at $T_{NSC}/T_{1-B} = 1.0$. In the long-period region, the value of FDS is calculated according to Equation 4:

$$\frac{Sa_{NSC}}{UHS(T_{1-B})} = min\left\{\begin{matrix} [12.0] \times \left[0.2 + 0.8\left(\frac{Z}{H}\right)\right] \times \left[\frac{0.14 \times \xi_{NSC} + 7.36}{\xi_{NSC} + 3.06}\right] \\ \left[\frac{1.68}{\left(\frac{T_{NSC}}{T_{1-B}}\right) - 0.86}\right] \times \left[0.64 + 0.36\left(\frac{Z}{H}\right)\right] \times \left[\frac{0.3 \times \xi_{NSC} + 8.3}{\xi_{NSC} + 4.8}\right] \end{matrix}\right\} \quad : \quad 1.0 \leq \frac{T_{NSC}}{T_{1-B}} \leq 5.0 \tag{4}$$

As explained previously for lower-rise buildings, the FDS is taken as the minimum of the two equations. Likewise, If the FDS is required to be extended for $5.0 \leq T_{NSC}/T_{1-B} \leq 10.0$, the same approach as indicated for lower-rise buildings can be used. The process of generating FDS for both low and medium-rise buildings according to the above equations was coded in aMATLAB program [21]. The extended code requires four inputs: the fundamental period of the building (T_{1-B}), its corresponding uniform hazard design spectral acceleration ($UHS(T_{1-B})$), the number of floors and their corresponding heights, and the height category of the building (either low-rise or medium-rise).

The application of the proposed method is presented next through generation of FDS for Building#4 as a low-rise example with three stories above ground, and Building#18 as a medium-rise example with five stories above ground. Figure 2 and Figure 3 show the derived results for Building#4 and Building#18, respectively. The proposed FDS for all floors of the buildings considering four different NSC damping ratios (2, 5, 10, and 20% of critical viscous damping) are generated using the MATLAB code [21] and depicted as solid lines in both figures. The generated FDS (solid lines) are then compared with the corresponding PA-FRS derived from dynamic analysis and shown as dashed lines. The comparison shows that the proposed methodology is a reliable tool to estimate the seismic acceleration demand on NSCs with any damping ratio and located at any floor level.

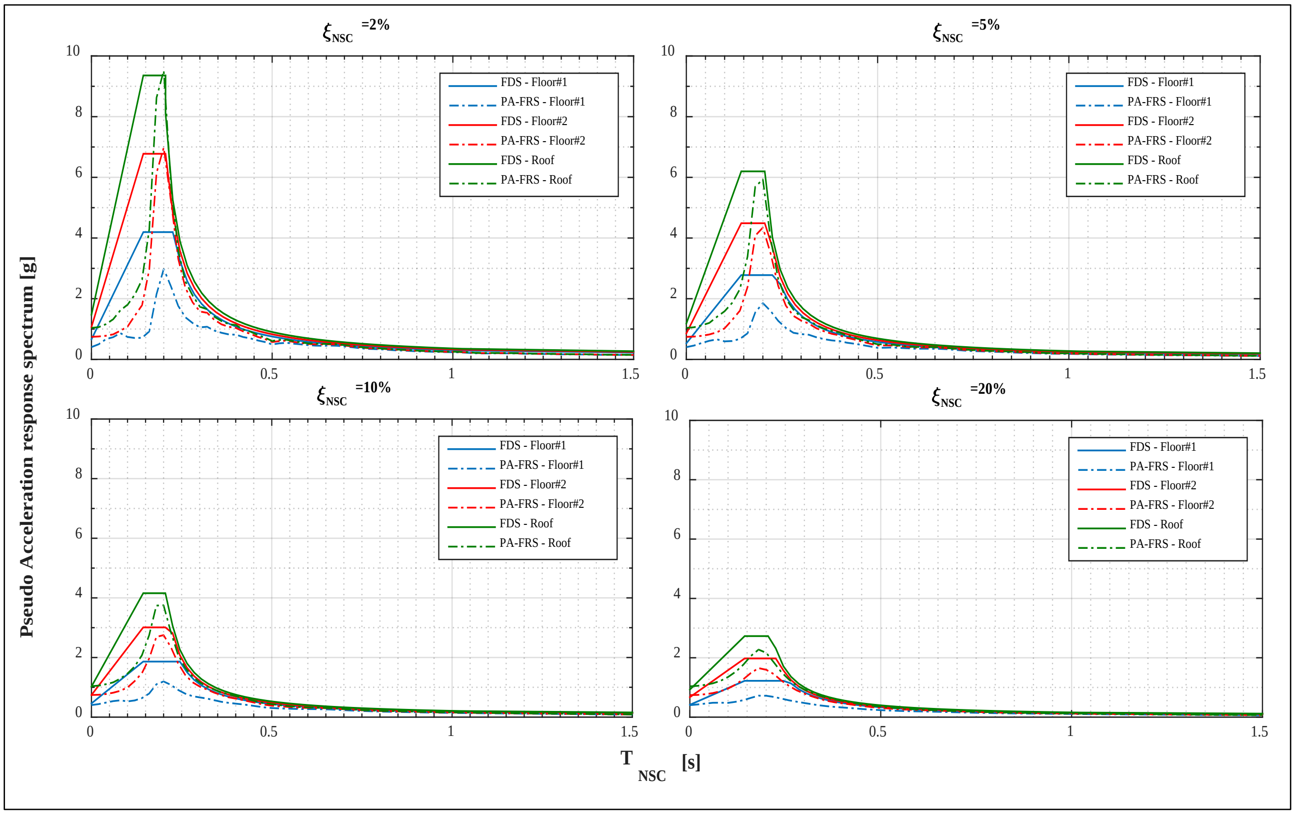

Figure 2 – Comparison of the proposed FDS and the PA-FRS generated for all floors of Building#4 considering NSCs damping ratios of 2, 5, 10, and 20 %

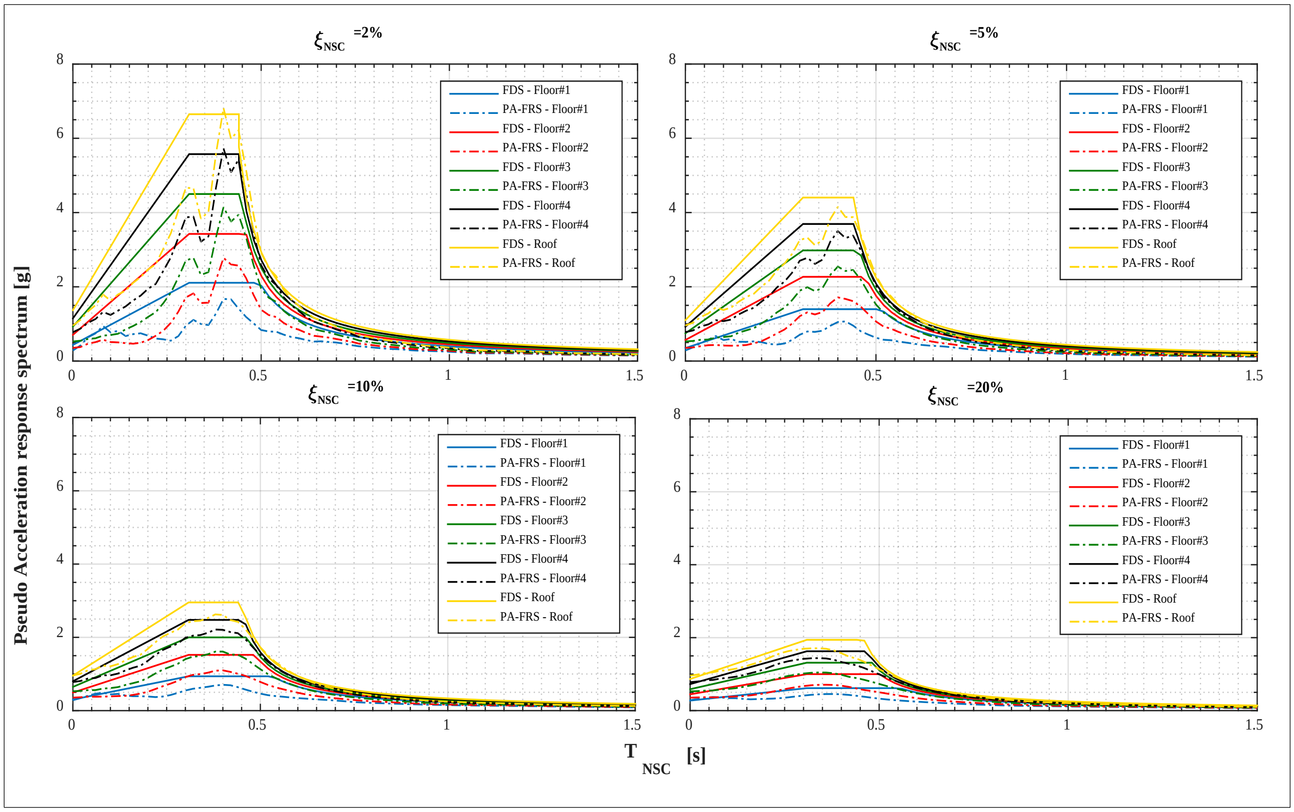

Figure 3 – Comparison of the proposed FDS and the PA-FRS generated for all floors of Building#18 considering NSCs damping ratios of 2, 5, 10, and 20 %

CONCLUSIONS

This study proposes a methodology to produce FDS for any selection of floor level and NSCs damping ratio. To achieve this result, a Pseudo Acceleration Floor Response Spectrum (PA-FRS) has been derived for every floor of the buildings in the database (12 low-rise, 10 medium-rise, and 5 high-rise) considering four different NSC damping ratios (2, 5, 10, and 20 % viscous damping). Approximately 132,000 PA-FRS have been generated for statistical analysis. Initially, the PA-FRS for roof level and 5% damping of NSCs have been compared with the 5% damped UHS of Montreal and a method has been developed to generate FDS for roof level and ξ_{NSC}=5% directly from the 5% damped UHS. Then, the effects of NSCs damping ratio (ξ_{NSC}) and their location along the building height (Z/H) on the derived PA-FRS have been quantified through statistical analysis and a height and a damping modification factors have been introduced. These factors are to modify the generated reference FDS at roof level (Z/H=1.0) and 5% NSCs damping (ξ_{NSC}=5%). These modification factors are incorporated into the reference FDS and two sets of updated equations are recommended for RC low and medium rise buildings.

The recommended equations have been coded in a MATLAB program [21] and then applied over the entire database: two examples of results have been presented as examples, for one low-rise (Building#4) and one medium-rise (Building#18). The FDS were generated for every floor of the 27 selected buildings given four different NSC damping ratios and compared with the corresponding PA-FRS derived from dynamic analysis. The comparison showed consistency between the results which attests the reliability of the proposed approach. Compared to the conventional analytical FRS approach and current building code recommendations, the proposed method offers several advantages and improvements, namely including capturing the effects of: 1- dynamic interaction between the supporting system and NSCs, 2- higher frequency and torsional modes of the supporting system, 3- NSCs internal damping ratios, and the generation of an exclusive FDS for each individual building, taking into account its dynamic characteristics (i.e. its fundamental period and its UHS design spectral accelerations). The generated FDS is a practical, accurate, and fast tool for seismic assessment and design of acceleration-sensitive NSCs particularly in post-critical existing buildings.

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