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GENERATING SEISMIC FLOOR DESIGN SPECTRA OF EXISTING BUILDINGS USING AVM TESTING

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Abstract

Attaining global good seismic performance of a building requires maintaining integrity and functionality of both its structural systems and Non-Structural Components (NSCs). Proper seismic design and vulnerability assessment of NSCs is, however, contingent on having an accurate method to estimate floor seismic demand on NSCs. In an effort to fulfill this need, an original approach is developed in this study to generate Floor Design Spectra (FDS) directly from Uniform Hazard Spectra (UHS) using Ambient Vibration Measurement (AVM) on existing buildings. The generated FDS can be used as a reliable tool for seismic analysis and assessment of acceleration-sensitive NSCs particularly in existing post-critical buildings which have to remain operational during and after earthquakes.

Figure 1 schematically describes the research methodology in a step-by-step manner. To develop and validate the proposed method, a database of 27 existing Reinforced Concrete (RC) buildings (12 low-rise, 10 medium-rise, and 5 high-rise) tested by AVM has been collected. The proposed procedure has been coded in MATLAB, which takes the required input parameters and subjects each building model to a set of 20 site-compatible seismic records. It then derives Pseudo Acceleration Floor Response Spectra (PA-FRS) for every floor of the building in two orthogonal horizontal directions considering four different NSC damping ratios (i.e. 2, 5, 10, and 20% of critical viscous damping). The proposed method has been validated through the detailed linear numerical modeling of one building of the database. In the first part, the generated FRS for roof level and 5% NSC damping are statistically analyzed and compared with 5% damped UHS, and a method is proposed to derive FDS directly from UHS for roof level and ξ_{NSC}=5% only. Then, the effects of NSCs damping ratio and NSCs location along the building height on the FDS have been studied and two sets of modification factors are introduced to account for these two parameters. The modification factors are then incorporated into the proposed method to extend its application to derive FDS at any selected floor level and any NSC damping ratio of interest. The method is employed over the entire building database from which the results of three buildings (one low-, one medium-, and one high- rise) are presented and discussed here. The generated FDS can serve as a fast and powerful means for seismic assessment and design of acceleration-sensitive NSCs.

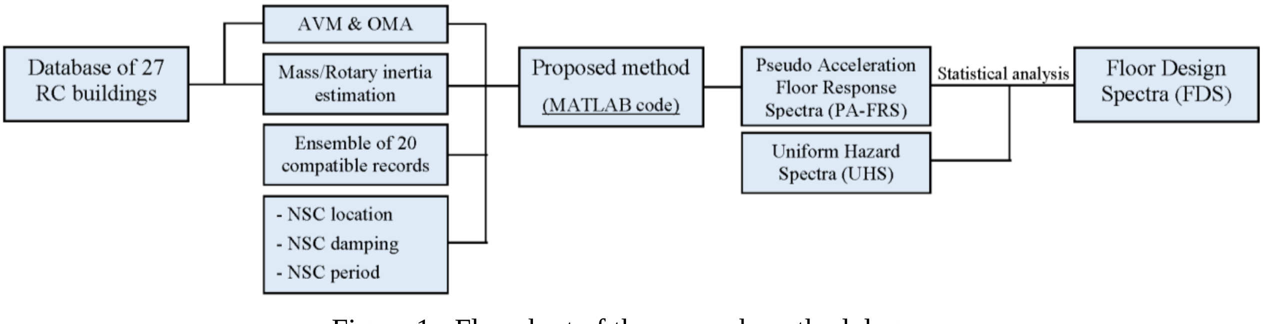


Figure 1 - Flowchart of the research methodology

Keywords: Acceleration-sensitive Non-structural Components (NSCs); Operational Modal Analysis; Spectrum-to-Spectrum.

1. Introduction

Observations in past earthquakes have emphasized the fact that achieving the overall good performance of buildings is contingent upon assuring the good performance of both the structural system and Non-Structural Components (NSCs). Structural components are designed to resist and transfer the building loads (gravity and lateral loads), however, NSCs, also called Operational and Functional Components (OFCs) in Canadian standards, are not meant to be a part of the main load-bearing system of the building. Nevertheless, NSCs may be subjected to large-seismically induced forces/displacements during earthquakes [1] and undergo damages resulting in undesired aftereffects which are mainly associated with: a) life-safety hazards (i.e. fatalities/injuries caused by falling/overturning NSCs, etc. [2-4]), b) property loss due to direct/indirect damage costs (e.g. major part of approximate economic loss of 25 billion dollars in 2010 Maule, Chile earthquake [5] and 2 billion dollars in 2001 Nisqually (Seattle) earthquake [6]), and c) loss of building functionality (e.g. impairment or complete shut-down of 130 hospitals in 2010 Maule, Chile earthquake [5] and of 32 commercial data processing centers in 1989 Loma Prieta earthquake [7]). Economic and functionality losses can exceed the ones caused by structural damage considering the facts that: 1- NSC damage is typically triggered at seismic intensities lower than those required to damage structural components, and 2- NSCs account for a major portion of total direct building cost (e.g. 80-90% of the total investment in office, hotel and hospital buildings in the United States according to Taghavi [8]). Hence, the cost associated with NSCs failure can be more than the replacement cost of the building itself especially when the loss of inventory and downtime costs are also added [9, 10]. Therefore, to achieve an acceptable global seismic performance of the building, one has to ensure that both structural and non-structural systems will perform satisfactorily during seismic events [11].

Considering the driving Engineering Demand Parameter (EDP) for seismic design/analysis of NSCs, these components can be addressed as either: 1) drift-sensitive components that are prone to be damaged by seismically induced displacement/drift, or 2) acceleration-sensitive components that are subject to damage by the inertia forces induced by the seismic floor accelerations [8]. Therefore, proper seismic design/assessment of NSCs necessitate the need for reliable approaches to accurately quantify these two main EDPs. As for drift-sensitive components and after the introduction of the displacement-based design approach, firstly in 1993 in New Zealand [12], many studies (e.g. [13-16]) have focused on quantifying story drift demand and as a result a range of reliable approaches have been developed to estimate this EDP.

As for acceleration-sensitive components, which are the main focus of this paper, several studies have addressed evaluating the acceleration demand on NSCs by estimating Peak Floor Acceleration (PFA) or Peak Component Acceleration (PCA) and also by developing practical approaches for seismic design of this type of components [17-23]. Seismic design of acceleration-sensitive NSCs is also addressed in most of the current building codes by recommending empirical equations to calculate NSC acceleration demand (i.e. equivalent static seismic force) for which the component and its anchoring system must be designed. Table 1 lists the seismic force requirements for NSCs in Canada (National Building Code of Canada- NBC 2015 [24]), United States (ASCE SEI-7-16 [25]), and Europe (Eurocode 8, EN. 1988. 1. 2004. [26]). As shown in Table 1, the equations all follow a similar approach, which is the multiplication of the design spectral acceleration or design Peak Ground Acceleration (PGA) by some modification factors to compute the seismic acceleration/force demand on the NSC. In general, these modification factors comprise: 1- Component importance factor, which accounts for the seismic risk associated with the failure of the NSC; 2- Component dynamic amplification factor, which represents the dynamic amplification of the component relative to the position of its attachment (i.e. tuning/detuning effects with the supporting structure); 3- Component response reduction factor, which expresses the energy dissipation capacity of the NSC and its attachments; and 4- Component elevation modification factor, which accounts for the variation of Peak Floor Acceleration (PFA) along the building height.

Table 1 - Code provisions for acceleration-sensitive NSCs

NBC 2015 (Division B-Part 4)	$\boldsymbol{V_P = 0.3F_aS_a(0.2)I_ES_PW_P}$; $0.7 \le S_P = \frac{C_PA_rA_x}{R_P} \le 4.0$, $A_x = 1 + 2\frac{h_x}{h_n}$
ASCE/SEI-07-10 (Chapter 13)	$\boldsymbol{F_P = \frac{0.4a_PS_{DS}}{\left(R_P/I_P\right)} \times \left(1 + 2\frac{Z}{H}\right) \times W_P}$; $1.6S_{DS}I_PW_P \le F_P \le 0.3S_{DS}I_PW_P$
Eurocode 8 (Part 4.3.5)	$\boldsymbol{F_a = (S_aW_a\gamma_a)/q_a}$; $S_a = \alpha.S.\left[\frac{3\left(1+\frac{Z}{H}\right)}{1+\left(1-\frac{T_a}{T_1}\right)^2} - 0.5\right] \ge \alpha S$

However, these provisions still remain incapable of properly 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 NSC internal damping. These shortcomings cause the code estimation of the acceleration demand on NSCs to be of limited accuracy and reliability as shown in several studies such as [18, 19, 27, 28]. Therefore, as an attempt to resolve these shortcomings and to provide a practical and yet reliable approach for seismic design/assessment of acceleration-sensitive NSCs, this paper introduces an original method to generate Floor Design Spectra (FDS) that can be used in a similar way as Design Response Spectra (DRS) are used for structural elements. The methodology of the proposed approach is described in the following sections.

2. Methodology

Figure 1 schematically explains the steps of the research methodology. The study was initiated by collecting a database of AVM records and structural details for 27 existing Reinforced Concrete (RC) frame buildings comprising 12 low-rises, 10 medium-rises, and 5 high-rises, all located in Montreal, Canada and designated as post-disaster structures. Extracted dynamic properties from AVM measurements together with floor mass and in-plane rotary inertia of the buildings estimated according to the collected structural and architectural drawings form the set of input parameters required to generate an equivalent 3D model of the building [29]. The buidling database information is summarized in Table 2. As the AVM results represent the dynamic properties of buildings at low-amplitude excitations (PGA < 10^{-5}g) and knowing that these properties will vary with the intensity of excitation (i.e. wandering of the natural frequencies and damping ratios [30, 31]), a set of modification factors have been proposed to extend the applicability of the method by correlating the AVM results to higher-amplitude excitations. These modification factors were derived after a careful review of studies on permanently instrumented RC buildings that is presented in details by the authors in [32]. Subjecting the equivalent building models to a set of 20 synthetic ground accelerograms compatible with the UHS of NBC 2015 for Montreal, the floor response histories of the buildings in two orthogonal horizontal directions have been generated at every building floor and at roof level. The derived 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 up to 4 seconds with interval of 0.02 s. Automatic generation of the FRS has been implemented in MATLAB [33] adopting direct integration with Newmark's linear acceleration method [34] to solve the equation of motion of NSCs. Approximately 132,000 FRS curves have been generated for the selected RC buildings. 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 by the authors in [32, 35, 36]. The experimentally derived PA-FRS have been used for statistical analysis first, 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 AVM Period (s)	Mode 1 Translational mode AVM ξ (%)	Mode 2 Translational mode AVM Period (s)	Mode 2 Translational mode AVM ξ (%)	Mode 3 Torsional mode AVM Period (s)	Mode 3 Torsional mode AVM ξ (%)	NBC period (s)
Low-rise buildings	1	RCSW	1969	6.5 / 1.5	1 / 1	0.15	1.15	0.13	1.81	0.12	0.16	0.20
	2	RCSW	1969	6.5 / 1.5	1 / 1	0.27	4.10	0.24	1.90	-	-	0.20
	3	RCMF	1957	8.6 / 6.4	2 / 1	0.15	2.90	0.12	1.40	0.10	2.40	0.38
	4	RCMF	1957	7.7 / 3.3	2 / 1	0.18	1.50	0.18	1.30	0.10	2.00	0.35
	5	RCMF	1963	7.5 / 2.7	2 / 1	0.20	1.18	0.16	1.55	0.11	0.42	0.34
	6	RCMF	1963	7.5 / 2.7	2 / 1	0.18	2.53	0.13	1.17	-	-	0.34
	7	RCMF	1963	7.5 / 2.7	2 / 1	0.18	3.17	0.14	2.14	0.11	0.75	0.34
	8	RCMF	1993	8.4 / 3.3	2 / 1	0.19	2.00	0.18	1.80	0.13	2.10	0.37
	9	RCMF	1961	8.4 / 4.7	2 / 1	0.23	1.70	0.21	1.70	0.16	3.30	0.37
	10	RCMF	1964	17.1 / NA	2 / 1	0.38	3.60	0.38	3.90	0.15	1.40	0.63
	11	RCMF	1975	10.8 / 2.7	3 / 1	0.15	2.00	0.13	2.30	0.11	1.60	0.45
	12	RCMF	1964	13.0 / 4.1	3 / 1	0.38	4.10	0.38	4.00	0.23	2.90	0.51
Medium-rise buildings	13	RCMF	1967	13. 0/ 2.2	4 / 1	0.22	1.44	0.19	1.08	0.11	0.67	0.51
	14	RCMF	1964	12.0 / 3.1	4 / 1	0.18	2.72	0.15	2.70	0.12	0.09	0.48
	15	RCMF	1975	18.6 / 2.4	4 / 1	0.30	2.00	0.22	2.30	0.18	1.60	0.67
	16	RCMF	1975	15.9 / 5.1	4 / 2	0.30	2.00	0.22	2.90	0.18	2.60	0.60
	17	RCMF	1969	18.1 / 0.0	5 / 0	0.29	0.81	0.29	0.39	0.16	0.20	0.66
	18	RCSW	1998	19.6 / 3.6	5 / 1	0.40	2.32	0.36	1.66	0.28	2.76	0.47
	19	RCMF	1961	20.2 / 3.1	7 / 1	0.36	1.74	0.32	1.34	0.30	1.09	0.71
	20	RCMF	1961	20.2 / 3.1	7 / 1	0.37	1.42	0.31	0.75	0.29	1.01	0.71
	21	RCMF	1962	20.2 / 3.1	7 / 1	0.37	1.63	0.31	1.41	0.28	1.07	0.71
	22	RCSW	1971	28.0 / 6.7	7 / 2	0.59	3.61	0.46	4.35	0.36	1.72	0.61
High-rise buildings	23	RCMF	1957	36.0 / 3.5	10 / 1	0.53	1.72	0.40	1.22	0.37	1.09	1.10
	24	RCMF	1965	45.6 / 7.4	13 / 2	1.30	3.70	1.03	3.3	0.96	3.70	1.32
	25	RCSW	1969	55.4 / 8.4	13 / 2	0.70	1.79	0.68	1.70	0.41	2.04	1.01
	26	RCSW	1978	51.2 / 6.3	16 / 2	0.96	1.89	0.87	1.78	0.42	1.30	0.96
	27	RCMF	1965	58.7 / 7.9	18 / NA	1.25	2.54	1.03	2.87	0.94	2.15	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).

Then at the first phase, a procedure was developed to generate FDS for the building roof (given ξ_{NSC}=5%) directly from the 5% damped UHS of NBC 2015 corresponding to the building location. Two separate sets of equations are introduced 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 for inference. This can be done as 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 [35].

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-FRA 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 and incorporated in the 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 ($2\% \leq \xi_{NSC} \leq 20\%$) for RC low- and medium-rise buildings. The 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 method improves the code recommendations and conventional approaches in several aspects by considering the effects of: a) dynamic interaction between structure and NSCs, b) higher and torsional modes of the supporting structure, and c) internal damping of NSCs [36].

3. Proposed Seismic Floor Design Spectra (FDS)

Figure 2 schematically shows how the spectral acceleration is idealized in each spectral region for both low- and medium-rise buildings. The following sections firstly describe the recommended equations to generate FDS and secondly, the application of the proposed equations is presented through generation of seismic FDS for Building#8 as a low-rise example and Building#15 as a medium-rise example. The general information of both buildings, typical plan view, 3D view, and the AVM results for the three lowest frequency modes are summarized in Tables 3 and 4, respectively. The mode shapes are illustrated schematically where the blue color shapes show the building at rest and the green color represents the deformed modal shape corresponding to the extracted natural frequency. 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 [33] and depicted as solid lines in Figs. 3 and 4. The generated FDS are then compared with the corresponding PA-FRS derived from the dynamic analysis shown as dashed lines. The comparison indicates 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.

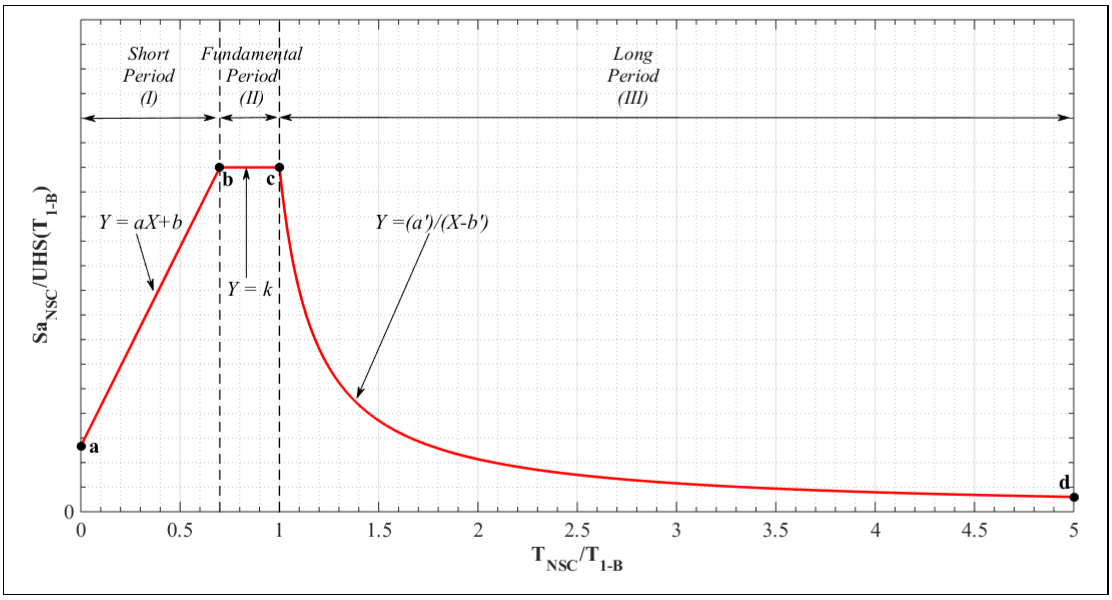


Figure 2– Schematic of the proposed FDS and idealization of spectral acceleration for NSCs

3.1 Low-rise buildings

As illustrated in Figure 2, 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. In all the recommended equations, the first square bracket is to calculate the FDS values at roof level given 5% NSC damping, the second bracket is the modification factor which accounts for the relative height effect (0.0≤Z/H≤1.0), and the third bracket is the modification factor that accounts for NSCs' damping effect ($2\% \leq \xi_{NSC} \leq 20\%$).

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

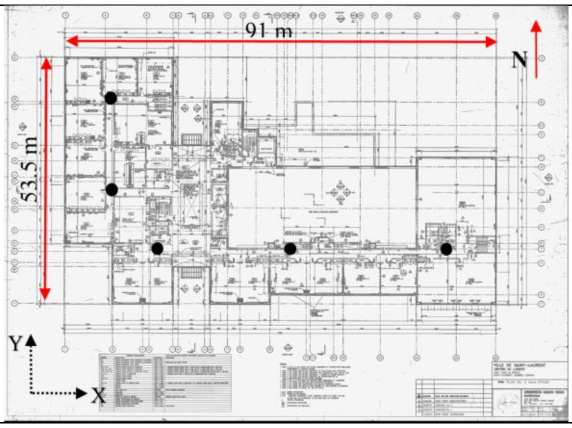
$$\frac{Sa_{NSC}}{UHS(T_{1-B})} = \begin{cases} [2.0]\times\left[0.33+0.67\left(\frac{Z}{H}\right)\right]\times\left[\frac{0.69\times\xi_{NSC}+3.33}{\xi_{NSC}+1.78}\right] & @\ \text{"a"},\ \frac{T_{NSC}}{T_{1-B}}=0.0 \\ [10.5]\times\left[0.33+0.67\left(\frac{Z}{H}\right)\right]\times\left[\frac{0.14\times\xi_{NSC}+7.36}{\xi_{NSC}+3.06}\right]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

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

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

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 (2) does, in some cases, overestimate the FDS values in the vicinity of $T_{NSC}/T_{1\text{-}B}$ = 1.0. If FDS is required to be extended for a longer range, 5.0 ≤ $T_{NSC}/T_{1\text{-}B}$ ≤10.0, a conservative and simple approach is proposed where the $Sa_{NSC}/UHS(T_{1\text{-}B})$ is decreased linearly from its value at $T_{NSC}/T_{1\text{-}B}$ = 5.0 to half of that at $T_{NSC}/T_{1\text{-}B}$ =10.0.

Table 3 - Structural information and AVM results of Building#8

<table>
<tr><th colspan="6">Building # 8</th></tr>
<tr><td>LLRS type</td><td>RCMF</td><td colspan="2">Construction year</td><td colspan="2">1993</td></tr>
<tr><td>H_A / H_B (m)</td><td>8.4 / 3.3</td><td colspan="4">Typical plan dimension (m)</td></tr>
<tr><td>N_A / N_B</td><td>2 /</td><td>L =</td><td>91</td><td>W =</td><td>53.5</td></tr>
<tr><td colspan="2">Typical plan view</td><td colspan="4">3D view</td></tr>
<tr><td colspan="2">
</td><td colspan="4">
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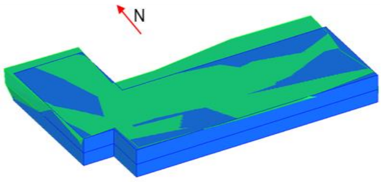
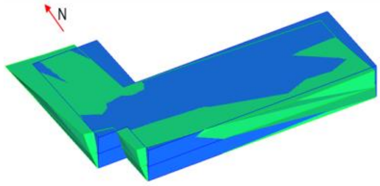
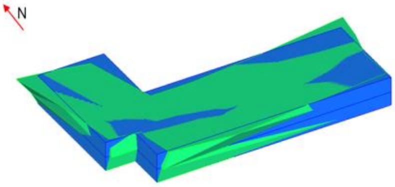
</table>

Modal properties extracted from AVM		
Mode 1-Translation in Y dir.	Mode 2-Translation in X dir.	Mode 3-Torsion
f = 5.25 Hz ξ = 2.0 %	f = 5.60 Hz ξ = 1.8 %	f = 7.50 Hz ξ = 2.1 %
		

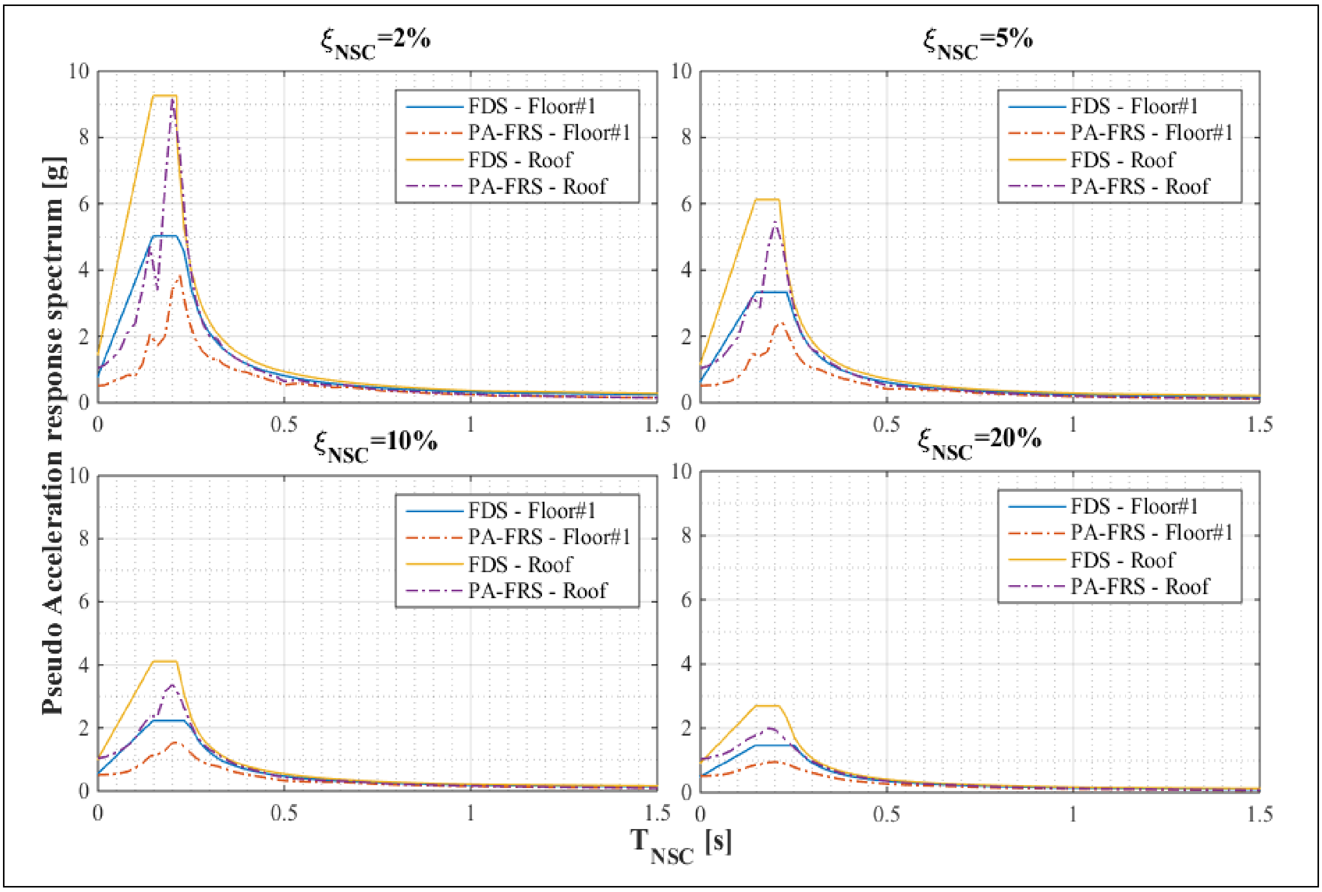


Figure 3 - Comparison of the proposed FDS and the real PA-FRS generated for both floors of Building#8 considering NSCs damping ratios of 2, 5, 10, and 20 %.

3.2 Medium-rise buildings

For RC medium-rise buildings, FDS is generated using the same methodology as described for low-rise buildings 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 $T_{NSC}/T_{1\text{-}B}$ = 0.0 to point “b” at $T_{NSC}/T_{1\text{-}B}$ = 0.7. Values of point “a” and “b” can be calculated according to Eq. (3):

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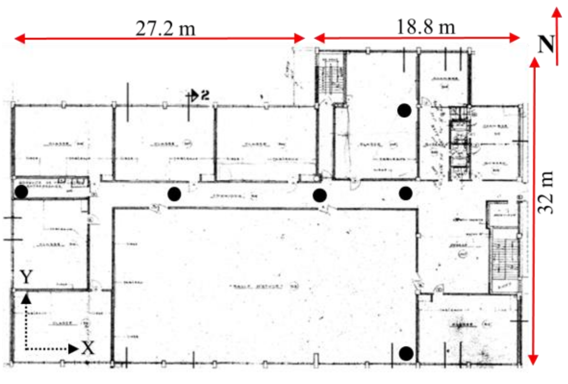
$$\frac{Sa_{NSC}}{UHS(T_{1-B})} = \begin{cases} [3.0] \times \left[0.2 + 0.8\left(\frac{Z}{H}\right)\right] \times \left[\frac{0.69 \times \xi_{NSC} + 3.33}{\xi_{NSC} + 1.78}\right] & @ \ \text{"a"}, \ \frac{T_{NSC}}{T_{1-B}} = 0.0 \\ [12.0] \times \left[0.2 + 0.8\left(\frac{Z}{H}\right)\right] \times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

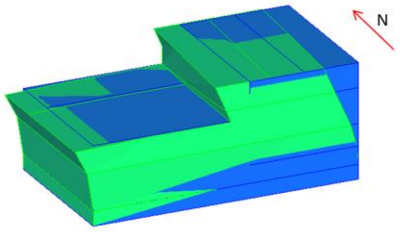
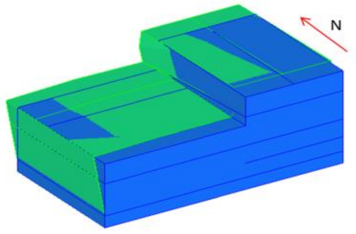
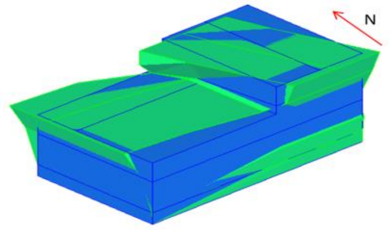
In the fundamental-period region, the FDS has the constant value determined at point “b” using (3, between points “b” at $T_{NSC}/T_{1\text{-}B}$ = 0.7 and “c” at $T_{NSC}/T_{1\text{-}B}$ = 1.0. In the long-period region, the value of FDS is calculated according to Eq. (4):

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

As explained previously for lower-rise buildings, the FDS is taken as the minimum of the two equations. Likewise, If FDS is required to be extended for 5.0 ≤ $T_{NSC}/T_{1\text{-}B}$ ≤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 the MATLAB program [33]. The extended code requires four inputs: the fundamental period of the building ($T_{1\text{-}B}$), its corresponding uniform hazard design spectral acceleration (UHS ($T_{1\text{-}B}$)), the number of floors and their corresponding heights, and the category of the building (either low-rise or medium-rise).

Table 4 - Structural information and AVM results of Building#15

Building # 15					
LLRS type	RCMF	Construction year		1975	
H_A / H_B (m)	18.6 / 2.4	Typical plan dimension (m)			
N_A / N_B	4 / 1	L =	46.0	W =	32.0
Typical plan view		**3D view**			
					

Modal properties extracted from AVM					
Mode 1-Translation in X dir.		Mode 2-Translation in Y dir.		Mode 3-Torsion	
f = 3.38 Hz	ξ = 2.00 %	f = 4.52 Hz	ξ = 2.3 %	f = 5.47 Hz	ξ = 1.6 %
					

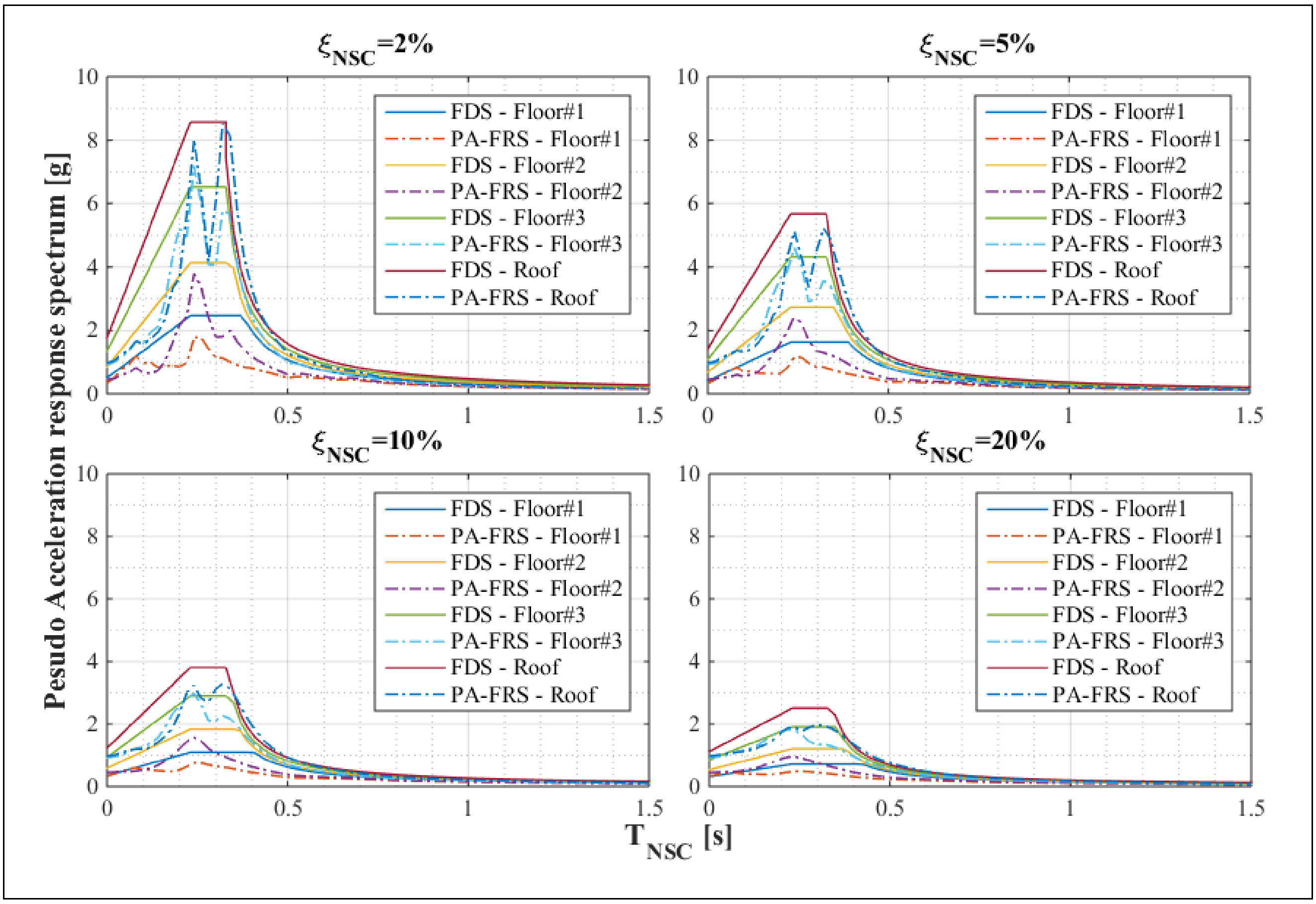


Figure 4 - Comparison of the proposed FDS and the real PA-FRS generated for both floors of Building#15 considering NSCs damping ratios of 2, 5, 10, and 20 %.

3.3 High-rise buildings

As previously mentioned, a generalized equation to derive seismic FDS is not proposed for high-rise buildings considering the small number of high-rise buildings available in the database. However, the rest of procedures have been deployed over the five high-rise buildings. Figure 5 depicts the experimentally-derived roof PA-FRS for the five high-rise buildings (gray lines) accompanied with their median (red dashed line) and median+σ (84th percentile) (blue dashed line) curves. The proposed methodology can be also employed to derive the FDS for this category upon having a sufficient number of cases in the building data base. Particular attention should be paid to the fact that for high-rises, the dominant response peaks are not happening in the fundamental-period region ($0.7 \leq T_{NSC}/T_{1\text{-}B} \leq 1.0$) (tuning range) due to the relative importance of the building higher modes of vibration. In other words, the response of NSCs mounted in high-rise buildings is mainly driven by the building higher modes of vibration rather than the sway fundamental mode. It can be seen in Figure 5 that the highest peak response is happening in vicinity of the 2nd and 3rd modes of vibration of the building rather than the first one.

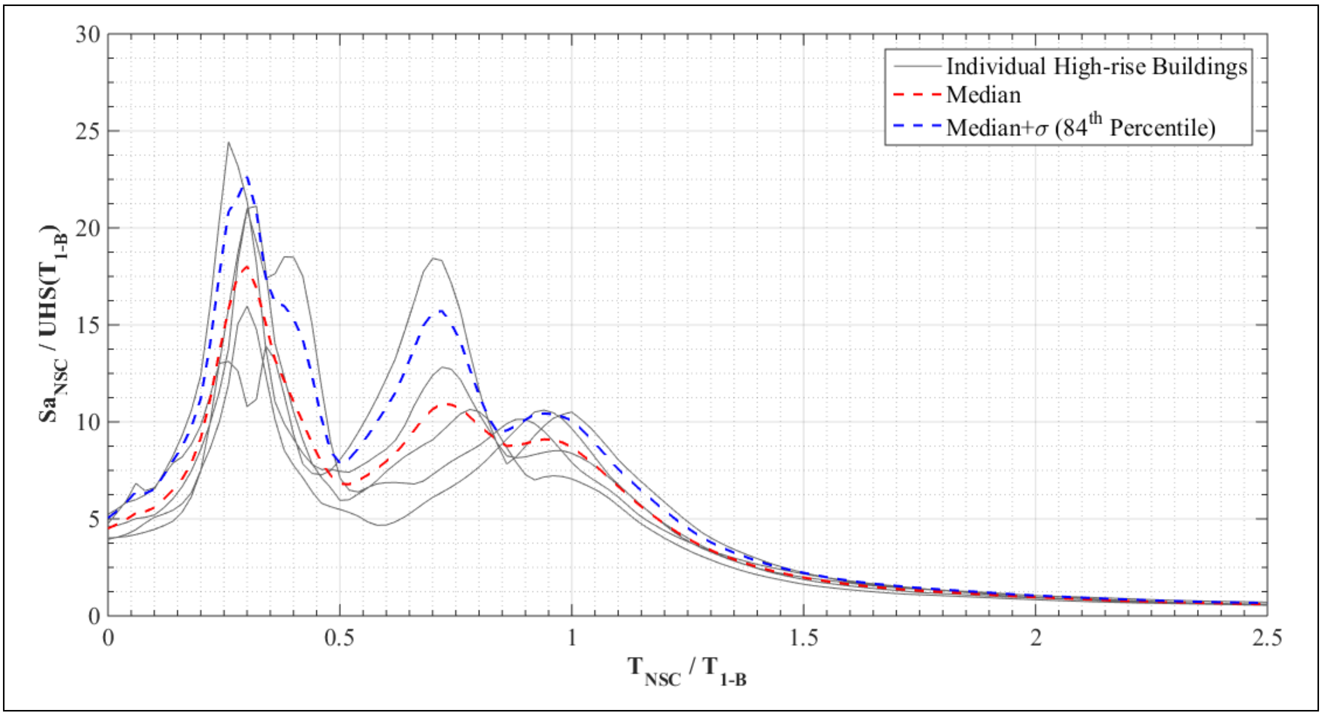


Figure 5 - Proposed FDS for roof level of high-rise buildings given ξ_{NSC}=5%.

4. Conclusions

This paper has presented a methodology to produce FDS for any selection of the floor level and NSCs damping ratio. The Pseudo Acceleration Floor Response Spectra (PA-FRS) have been derived for every floor of 27 RC buildings (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 formulas have been developed to generate FDS for roof level and ξ_{NSC}=5% directly from 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 multiply the generated reference FDS at roof level (Z/H=1.0) and 5% NSCs damping (ξ_{NSC}=5%). They are incorporated into the reference FDS and two sets of equations are recommended for RC low- and medium-rise buildings. Although for high-rise buildings a general equation was not proposed at this stage, the methodology still stands valid for this category as well, and equations could be derived if statistically significant results become available. It was shown that for high-rise buildings, the generated PA-FRS show slightly different trends than lower buildings as the peak responses happen in vicinity of higher building modes instead of at the fundamental sway mode of vibration. This important effect is disregarded if using current code recommendations to estimate acceleration demand on NSCs.

The automated FDS generation has been implemented in a MATLAB program [33] and deployed over the entire database from which one low-rise (Building#8) and one medium-rise (Building#15) cases have been presented to illustrate the method. The FDS were generated for every floor of the 22 selected buildings given four different NSC damping ratios and compared with the corresponding PA-FRS derived from the 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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