16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 1105 (Abstract ID)

Registration Code: S-W461171500

NEW MTHODOLOGY FOR SEISMIC ASSESSMENT OF NON-STRUCTURAL BUILDING COMPONENTS BASED ON AMBIENT VIBRATION MEASUREMENTS

A. Asgarian(1), G. McClure(2)

(1) *Ph.D. candidate, Department of Civil Engineering and Applied Mechanics, McGill University, Canada, amin.asgarian@mail.mcgill.ca*

(2) *Professor, Department of Civil Engineering and Applied Mechanics, McGill University, Canada, ghyslaine.mcclure@mcgill.ca*

Abstract

Experiences from past and recent earthquakes clearly demonstrate the importance of the good seismic performance of Non-Structural Components (NSCs) to maintain the post-earthquake functionality of post-disaster buildings. Seismic design of NSCs is also essential to protect life safety of occupants and to avoid costly property damages in normal importance buildings. Non-structural building components can be categorized in accordance with their function as: Architectural components, Building services, and Building contents. They can also be classified in terms of their seismic response sensitivity as: Inter-story-drift-sensitive, Floor-acceleration-sensitive, and both inter-story-drift and floor-acceleration-sensitive components [1]. Severe NSC damage observed in past moderate to strong earthquakes emphasizes that NSCs require a simple, practical and yet reasonably accurate approach to be designed against the seismically-induced forces and displacement effects.

Various analytical approaches have been developed for seismic evaluation of NSCs during the past few decades. These approaches can be fit into two general groups according to dynamic coupling/decoupling of the structural (primary system) and non-structural (secondary system) components in the analysis. They are: 1- Floor Response Spectra (FRS) approach and 2- Combined Primary-Secondary System (CPSS) approach. In addition to these analysis approaches, recent building codes and standards have included several recommendations and provisions for seismic risk assessment and mitigation of NSCs in existing buildings, and empirical equations for seismic design of NSCs and their restraints. However, these analytical approaches and empirical equations have shortcomings that make them either impractical or imprecise.

In this study, an original method is proposed to generate both Floor Response Spectrum (FRS) and inter-story drift curves based on building floor response histories generated using ambient vibration measurements (AVM) according to a method derived by Mirshafiei [2]. The proposed experimentally-derived FRS method improves the practicality and accuracy of seismic analysis of NSCs in several ways compared to the aforementioned analytical approaches and building codes. The method is validated through a case-study of pediatric hospital buildings in Montreal (Canada), by comparing the numerical results derived from a detailed calibrated finite element model of the building and the experimental results produced using the proposed method. The method is then employed for a database comprising 27 post-disaster buildings located in Montreal in which AVM were performed. FRS curves have been generated for every floor of all 27 buildings in two orthogonal horizontal directions considering different damping ratios for the NSCs. The input ground motions used in the study are comprised of a set of 20 seismic records compatible to the design Uniform Hazard Spectrum (UHS) of Montreal, as defined by the National Building Code of Canada (NBCC) [3]. The results are presented to show the effect of different parameters on the FRS curves.

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

1. Introduction

Recent earthquakes as well as earlier ones have highlighted the fact that the overall good performance of buildings is achievable by assuring the good performance of both its structural system and Non-Structural Components (NSCs) at the same time. The distinction between these two types of building components is that the structural components and systems are designed to resist and transfer the loads (either gravity or lateral loads) while the NSCs are not meant to be a part of the main load-bearing system of the building. That is why structural components are often called as “Primary system” or “Supporting structure” and NSCs as “Secondary system” in the literature. NSCs can be sub-categorized according to their functions as: Architectural components, Building services (mechanical, electrical, and telecommunication equipment), and Building contents (common and specialized) [4, 5]. They can also be classified into three different groups in accordance with the nature of their seismic sensitivity as: 1- Inter-story-drift-sensitive components, 2- Floor-acceleration-sensitive components, and 3- both Inter-story-drift- and floor-acceleration-sensitive components [1]. In general, the failure or malfunction of NSCs can give a rise to some adverse consequences that can be associated with:

1- Life safety: Collapse of NSCs can become a safety hazard and hamper the safe movement of occupants as they evacuate or of rescuers as they enter the building [6].

2- Building functionality: Seismic failure or malfunction of NSCs can severely limit the continuous functionality of critical facilities such as hospitals, emergency shelters, etc.

3- Property protection: As NSCs represent a large portion of the total cost of buildings (e.g. 65% to 85% of the total cost depending on their use and occupancy), their damage can result in large financial losses that can be direct or indirect losses [1, 4].

Experiences and observations from past earthquakes and current knowledge of the seismic performance of building structures indicate that NSCs are subjected to large seismically induced forces and displacements which have to be taken care of by a rational, precise, and yet practical seismic design and analysis procedures. This matter is of great importance as the integrity of NSCs plays a vital role in the overall performance of the buildings.

2. Background

2.1. Seismic design and analysis of NSCs

2.1.1. Analytical approaches

Predicting the seismic response of NSCs is a challenging problem which has been the interest of many scholars during past four decades. Although numerous efforts have been made to develop rational yet practical methods for seismic analysis of NSCs, a consensus on a generally accepted approach has not been reached yet. The complexity of the problem arises from several factors including:1- Diverse dynamic characteristics of NSCs due to the various configurations of the NSCs themselves and their anchoring systems, being single/multiple attachment point components, etc.; 2- Possible dynamic interaction between NSCs and the primary system; 3- Tuning effects (i.e. coincidence of fundamental period of NSCs with one of the fundamental periods of the building causing local NSC resonance); and 4- Low internal damping of NSCs compared to the primary system which causes non-classical damping.

The currently available approaches for seismic response analysis of NSCs can be fit into two general groups: 1- Floor Response Spectrum (FRS) approach, and 2- Combined Primary-Secondary system (CPSS) approach. The main difference between these two analysis methods is the assumption of dynamic coupling or decoupling of the primary and secondary systems. The FRS approach essentially assumes the primary and secondary systems as decoupled and analyses them independently (i.e. no dynamic interaction is considered between them) while the CPSS approach analyses the structure and the NSC as a coupled, combined unit thus accounting for any possible dynamic interactions. The FRS approach is considerably simpler, faster, and computationally more economical compared to the CPSS method since it avoids all the complexities caused by dynamic coupling. However, the FRS approach has the limitations of ignoring: 1- Dynamic interaction between primary and secondary systems, 2- Non-classical damping effects, 3- Cross-correlation of the response for multi-supported NSCs, and 4- Effects of torsional response of the primary system on NSC response. The CPSS approach will circumvent all of the aforementioned drawbacks by capturing the coupling effects and dynamic interactions but will typically result in a coupled system with a large number of DOFs and non-classical damping characteristics, which has to be reanalyzed entirely every time a change is made in the NSC parameters. The CPSS approach is additionally limited in terms of practicality as the design of the structural (primary) system is not synchronized with the design of NSCs, and these two tasks involve different teams of professionals, in most instances [5, 7, 8].

2.1.2. Building code and standard requirements

In addition to above-mentioned analytical approaches, recent building codes and standards have a section pertaining to the seismic design and analysis of NSCs, which includes recommendations and provisions for seismic vulnerability assessment and risk mitigation actions of NSCs in existing buildings, and empirical equations for seismic design of NSCs in new buildings. Examples of the American codes comprising seismic design requirements for NSCs are Uniform Building Code (UBC) [9], the National Earthquake Hazard Reduction Program (NEHRP) provisions [10], and ASCE/SEI 7-10 [11]. In Canada, a set of recommendations and guidelines are presented in the National Building Code of Canada (NBCC) for new buildings [3], and in CSA S832-14 [4] for both new and existing buildings. The current NBCC 2015 edition includes two types of seismic requirements for NSC design: 1-Seismic force requirement in which the lateral equivalent static force required for design of NSCs and their connections is calculated using an empirical equation based on the Uniform Hazard Spectrum (UHS) approach used for design of building structures, and 2-Seismic displacement requirements in terms of building inter-story drift limits. CSA-S832 [4] is the Canadian standard for "Seismic risk reduction of operational and functional components (OFCs) of buildings" that must be used in conjunction with the NBCC seismic requirements.

These codes and standards have some common limitations including: 1- Neglecting the effect of NSC damping when estimating the acceleration demand by most of the codes, 2- Disregarding the effect of higher building modes that can be very important in evaluating the response of NSCs particularly in high-rise buildings [12], 3- Ignoring the effect of the torsional motion of the primary system on the seismic response of its NSCs, which can be of great influence for those NSCs located in the periphery of irregular structures, 4- Assuming a linear variation of the floor acceleration over the building height which is not quite realistic, 5- Calculating the seismic force for design of NSCs based on the spectral acceleration at short period (at 0.2 s) considering that most components in buildings are stiff or rigid, however, a more accurate and economical approach is to consider the natural periods of NSCs, tuning, detuning, and resonance effects.

2.2. Experimental modal identification using Ambient Vibration Measurements (AVM)

Modal parameters of the primary system, i.e. natural frequencies, modal damping ratios and mode shapes, play a key role in predicting the seismic response of a building structure and, subsequently, its NSCs. Thanks to technological advances in sensing techniques, AVM has become a well-known, robust, and reliable technique to derive dynamic properties of existing buildings without causing any interruption in their normal operation. During the AVM tests conducted in this study, the velocities induced by ambient excitations in two orthogonal horizontal directions are recorded at several locations at each floor of the building depending on the test setup. Afterwards, recorded data are analyzed using two different operational modal analysis techniques- namely, Frequency Domain Decomposition-Peak Picking (FDD) and Enhanced Frequency Domain Decomposition-Peak Picking (EFDD)[13], and the dynamic properties of the building including the lowest natural frequencies, corresponding mode shapes, and effective modal damping ratios, are extracted. These experimental dynamic properties are then used as input parameters to derive the response time-history and subsequently the floor response spectra for selected floors of the buildings. Further details pertaining to AVM and experimental modal analysis of buildings can be found in [14, 15].

3. Methodology

3.1. Description of the proposed experimental FRS method

Despite the research efforts in seismic analysis of NSCs, modern building codes and standards still do not reflect our current level of understanding of their seismic behavior. Furthermore, the code provisions for seismic design and analysis of NSCs mostly use empirical methods with force modification coefficients which are, for the most part, based on past experience, engineering judgment and expert intuitions, rather than on objective experimental and analytical results. These issues may be attributed to the fact that the previously developed methods are too complicated and cumbersome to be employed in the design of ordinary NSCs housed in conventional buildings. The solution to this problem is to introduce an analysis method that is rational and reasonably accurate on the one hand, and simple enough to be employed on the other hand, while reflecting the real building characteristics. Such an approach will involve the use of floor design spectra to assess the seismic performance of NSCs in existing buildings and to design them against seismic excitations in new structures. NBCC 2015 includes the most recent seismic hazard data for building design in the form of a Uniform Hazard Spectrum (UHS). However, floor design spectra for NSC design (NSC-FRS) compatible with the UHS of NBCC are currently not available. In this study, an original approach is proposed to fill this gap by generating the NSC-FRS based on experimental data obtained from AVM in buildings.

The research project was initiated by collecting an inclusive database of buildings in which AVM had been already conducted. The initial intention was to properly cover different types of lateral load resisting systems (LLRS) (i.e. Reinforced Concrete (RC) buildings and steel structures of various types) but as most of the measured buildings in the database were RC shear and moment frame buildings, the focus was narrowed down to only RC buildings covering various height levels (low, medium, and high rise buildings). The parameters of the building database are described in details in section 3.2.

The AVM data recorded on the selected buildings have been reanalyzed and the dynamic properties of the buildings have been extracted utilizing the commercial software ARTeMIS Extractor™ [16]. The mass and in-plane rotary inertia of the building floors have been estimated according to the available structural and architectural drawings. The extracted modal properties and the estimated mass/inertia of the building floors establish the input parameters required for the 3D-SAM simplified dynamic analysis approach developed by Mirshafiei [2, 17]. Worth-mentioning that the linear model is assumed for the buildings as the dynamic properties extracted from AVM are representative of linear dynamic behavior of the structures. Solving the equation of motions and deriving the floor response histories are conducted using modal analysis techniques. The floor response histories of the building subjected to a set of twenty synthetic ground accelerograms, compatible with UHS of NBCC 2015 for Montréal, are derived in two perpendicular horizontal directions and are subsequently assumed as base excitations for NSCs to develop their FRS. The selection and scaling process of seismic inputs are explained in section 3.3. It should be noted that although linear model is assumed for the buildings at this stage, but the applicability of the method are extended to the non-linear range of responses using a set of modification factors which are explained in section 3.4.

A code has been written in MATLAB [18] to generate the elastic FRS and inter-story drift curves at every floor of the building in both orthogonal horizontal (X and Y) directions, considering NSCs with several damping ratios (0, 2, 5, 10, and 20 % critical) having a fundamental period range of [0-4] seconds with intervals of 0.02 s (damping ratios, period range, and intervals can be set to any valid value in the program). Direct integration with Newmark's linear method was adopted to solve the equation of motion of NSCs [19], where the beta and gamma parameters were set as 0.25 and 0.5, respectively to ensure the unconditional stability of the operator; other values can also be selected in the program. The analysis proceeds over the entire set of seismic records and then the mean, mean + standard deviation, and the mean - standard deviation results are calculated and represented. The envelope graph of FRS curves in X and Y directions is also produced. The proposed method has been validated through the case-study of CHU Sainte-Justine Hospital, a pediatric hospital located in Montréal and affiliated to the University of Montreal, for which a detailed linear elastic finite element model has been generated in SAP 2000 v.14.0.0 [20]. The comparison of FRS and inter-story drift curves produced by the proposed experimental method with the ones derived from the finite element model has shown very good agreement between the experimental and numerical results. The detailed description of the validation process has been presented in Asgarian [21].

3.2. Description of the database

Achieving the objectives of the research study necessitates having a database of buildings in which AVM are conducted. Hence, the first part of the project involved collecting an inclusive database of the tested buildings properly covering different types of lateral load resisting systems (LLRS) (i.e. reinforced concrete buildings and steel structures of various types), and various heights (i.e. low, medium, and high rise buildings) in which the AVM records had already been collected by the McGill team on the island of Montreal. Data were collected for 156 buildings in total from which a subset of 59 reinforced concrete (RC) shear and moment frame buildings met the initial criteria required for the procedure (i.e. adequate quality of AVM results, proper AVM test-setup arrangements, availability of architectural and structural drawings, to name a few). As most of the measured buildings were RC structures, the focus was narrowed down to that building category. More database refinements were made to select only the most complete cases. Finally, the buildings retained in the study comprise 27 RC structures including 12 low-rise, 10 medium-rise, and 5 high-rise. The building information and AVM results are presented in Table 1. The last column gives the value of the fundamental period of the building as determined by the NBCC period formula [3].

Table 1 – 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 (sec)
						AVM Period (sec)	AVM ξ (%)	AVM Period (sec)	AVM ξ (%)	AVM Period (sec)	AVM ξ (%)	
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	NA	NA	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	NA	NA	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 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 damping ratio (percentage).

3.3. Selection and scaling of ground motions

The buildings are subjected to a set of 20 seismic records compatible with the UHS of Montreal for soil site class "C" corresponding to a probability of exceedance of 2% in 50 years, as defined by NBCC 2015 [3]. The seismic inputs have been selected from the reference time-history library developed by Atkinson [22] (available from: www.seismotoolbox.ca) and have been scaled accordingly. The records are synthetically generated using the stochastic finite-fault implementation of Atkinson and Bore [23]. Ground motions for eastern Canada are simulated for moment magnitude of M6 at fault distances from [10-15] km (M6 set 1) and [20-30] km (M6 set 2), and for M7 at [15-25] km (M7 set 1) and [50-100] km (M7 set 2). For each of these record sets, three random components were simulated at 15 randomly drawn locations around the fault for a total of 4 sets × 3 components × 15 realizations = 180 simulations for each site class condition. M6 events in the [10–30] km distance range will match the short-period end of the UHS, whereas an M7 event at a somewhat larger distance (but within the same range) will match the long-period end of the UHS for cities in eastern Canada in regions of moderate-to-high seismicity. As NBCC requires a minimum number of 11 ground motions to be matched with target spectrum or UHS, 20 records comprising 5 records from each set (i.e. M6 sets 1&2 and M7 sets 1&2) have been selected and scaled according to Atkinson [22].

The scaling and selection procedures have been implemented in a MATLAB code. The program takes the period ranges of interest, records sets, and number of records to be selected as the inputs and provides the scaled records to be used in the analysis. The comparison of the average, and average ± standard deviation spectra of the scaled 20 records with the target UHS of Montreal is shown in Fig. 1.

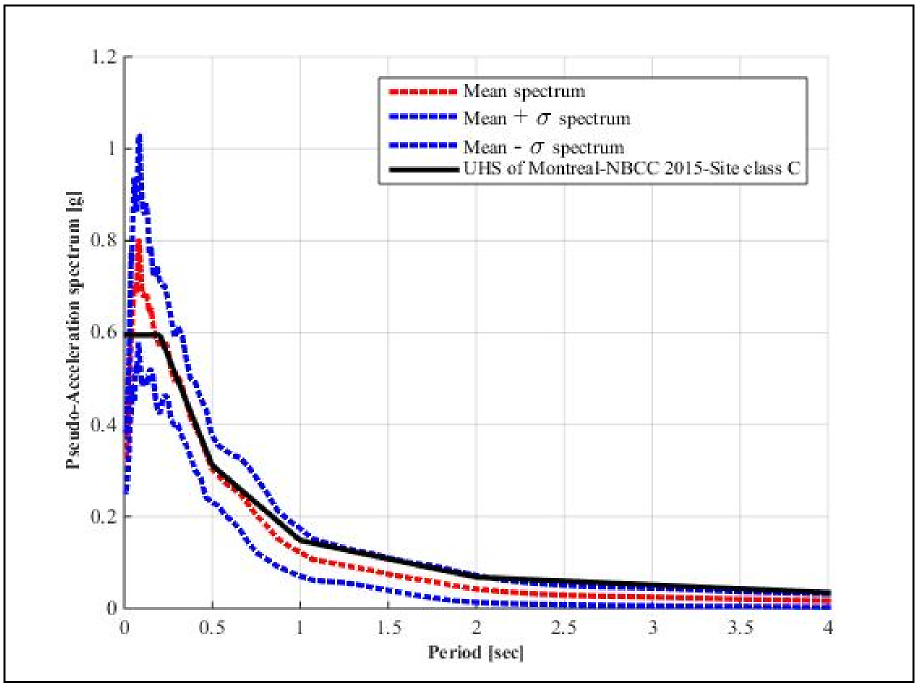


Fig. 1 – Comparison of averaged spectrum of all scaled records with UHS of Montreal for site class C.

3.4. Modification of building modal parameters for higher-amplitude ground motions

Modal properties including natural frequencies, modal damping ratios and mode shapes are the essential factors in predicting the dynamic response of the primary system (building structure) and, subsequently, its NSCs (secondary system). It has been shown by numerous studies such as Celebi [24-26], Todorovska et al [27, 28], Dunand et al [29] to name a few, that these parameters vary with respect to the intensity/amplitude of the input excitation. These variations are called as "wandering" of natural frequencies of the structure in the literature [30]. Hence, the dynamic properties extracted from low-amplitude excitations (PGA<10^{-5}g) such as AVM are expected to be different from those derived from high-amplitude shakings (PGA > 0.1g) such as in real seismic events. In general, by increasing the intensity level of seismic excitation, the natural frequencies of the building are decreased and modal damping ratios are increased while the mode shapes are not altered much as long as no localized damage happens. Wandering of natural frequencies and damping ratios can be attributed to: 1- softening of the building due to damage and non-linear behaviour of the building (e.g. micro-cracking of concrete at foundation and superstructure), 2- possible soil-structure interactions, 3- slippage of steel connections, and 4- interaction between structural and NSCs. It should be also pointed out that slight changes in modal parameters, in the range of 1-4 % difference, can be caused by ambient conditions, being weather variables such as temperature, wind, rainfall, etc., and traffic [30, 31].

Decreased natural frequencies during the main shock have been observed to increase again and being recovered partly or completely during the aftershocks; suggesting system recovery. This increase can be associated with: 1- changes in the bond between soil and foundation, 2- dynamic compaction of the soil and dynamic settlement, 3- recovery of the building if remained in the elastic range (undamaged state) [28].

To enable using the dynamic properties of the building extracted from AVM (low-amplitude excitation) for predicting the seismic behaviour of the primary and secondary systems during strong shaking (high-amplitude excitation), a set of appropriate modification factors is required. These modification factors can be derived by using the data collected in permanently instrumented buildings during past and recent seismic events where the building has not suffered visible structural damage. The variation of modal parameters of instrumented buildings before, during, and after earthquakes has been the subject matter of many studies such as: Çelebi(1996, 2007, 2009) [24-26], Çelebi et al. (1993) [32], Trifunac et al. (2001) [33], Hao et al. (2004) [34], Todorovska et al. (2006) [28], Todorovska et al. (2004) [27], Dunand (2005) [35], Dunand et al. (2004, 2006) [29, 36], Clinton et al. (2006)[30], Boroschek and Lazcano (2008)[37]; Carreño and Boroschek (2011) [31], Singh et al. (2014)[38]. Careful review of the variations innatural frequencies and damping ratios of RC buildings covered in these studies have led to the following conclusions:

1- For the range of weak-to-strong ground motions, a decrease of 24 % and an increase by a factor of 4.0, on average, have been observed in natural frequency and modal damping ratio, respectively, for the first mode of vibration.

2- For the second mode of vibration, the range of variation is 19% decrease for natural frequency and an increase by a factor of 3.3 for modal damping ratio.

3- The mode shapes have not been altered noticeably from ambient to strong vibration levels contingent upon avoiding visual damages in the structure.

Considering these observations, four different sets of modification factors have been defined in this study to evaluate the impact of variation in natural frequencies and damping ratios of the primary system (caused by various intensity-level of ground motions) on the response of its NSCs. It should be noted that the modification factors are applied to the natural frequencies and damping ratios extracted originally from AVM. These four scenarios are described below:

Case 1 - No modification factor: which means the original modal properties (i.e. natural frequencies and damping ratios) extracted from AVM are used without any alteration.

Case 2 - Decreasing natural frequencies by 10% and increasing modal damping ratios by a factor of 2.

Case 3 - Decreasing natural frequencies by 20% and increasing modal damping ratios by a factor of 3.

Case 4 - Decreasing natural frequencies by 30% and increasing modal damping ratios by a factor of 4.

Building#15 of the database (see Table 1) has been selected to study the effect of these four different cases. The building has been subjected to the ensemble of seismic records described in section 3.3 Then, FRS and inter-story drift curves have been generated for each scenario and compared to each other. The results are discussed in the next section.

4. Results and discussions

4.1. Building description

Building#15 is a reinforced concrete moment frame (RCMF) structure constructed in 1975 and comprising five stories including one basement. The building has a total height of 21 m above foundation level and 18.6 m above ground. The AVM of the building was previously done by Mirshafiei [2]. Fig. 2 shows the typical plan and elevation views of the building. It should be noted that the floor plan changes at various levels of the building and typical width and length are as shown. The global coordinate system and adopted north direction (N) for measurements are illustrated in Fig. 2. From the AVM data, the first three fundamental modes of the building have been extracted including: 1- First translation mode in X direction with *f=3.38 Hz & ξ=2.0%*, 2- First translation mode in Y direction with *f =4.52Hz & ξ=2.3%*, 3- First torsional mode with *f=5.47 Hz & ξ=1.6%*.

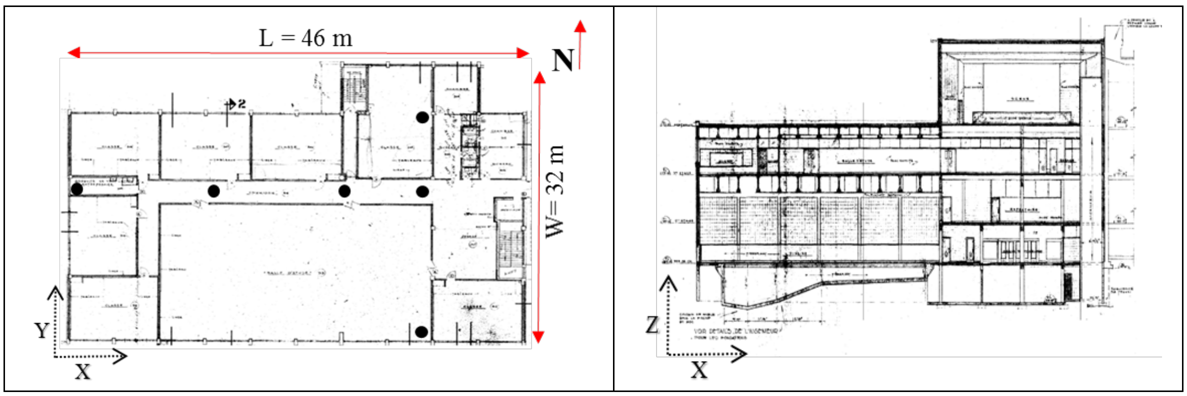
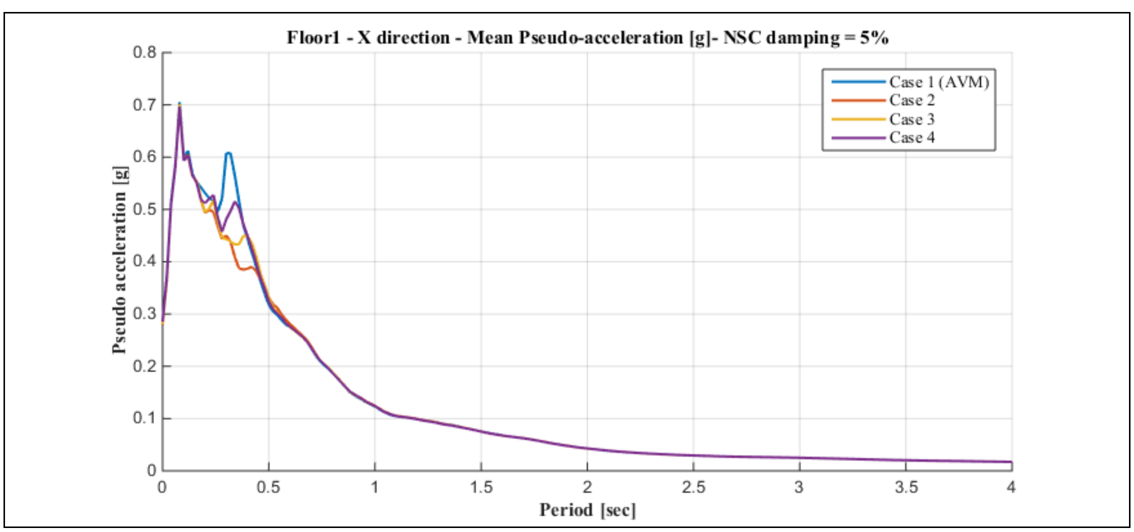


Fig. 2 – Typical plan and elevation views of building #15.

4.2. Pseudo-acceleration FRS and inter-story drift curves

The modal properties of building #15 (i.e. natural frequencies and modal damping ratios extracted from AVM) have been modified according to cases 1 through 4. For each case, the building has been subjected to the ensemble of 20 seismic records (described in section 3.3) in both orthogonal horizontal directions (i.e. X and Y) independently. The FRS curves in terms of displacement, velocity, acceleration, pseudo-velocity, and pseudo-acceleration and inter-story drift curves have been generated at every floor of the building, in both X and Y directions, for each seismic input considering different NSC damping ratios. Due to space limitation, selected results for the 1st and 4th stories are illustrated next, comprising only pseudo-acceleration FRS and Inter-story curves, at 5% NSC damping. Fig. 3 and 4 show the average response due to the ensemble of 20 records.



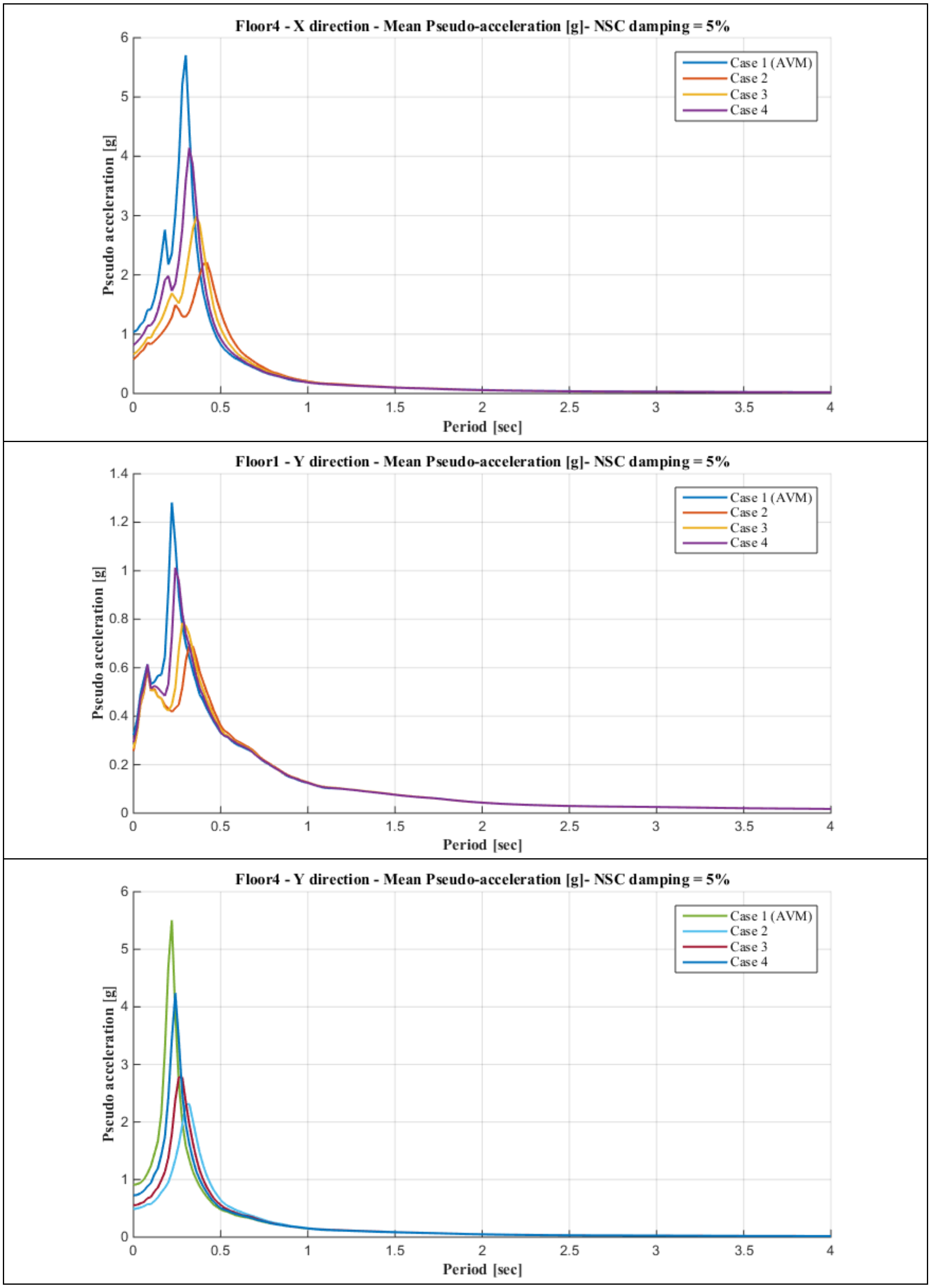


Fig. 3 – Averaged pseudo-acceleration FRS curves of 1st and 4th floors of building #15 in X and Y directions for Case 1 through Case 4, NSC damping = 5 %.

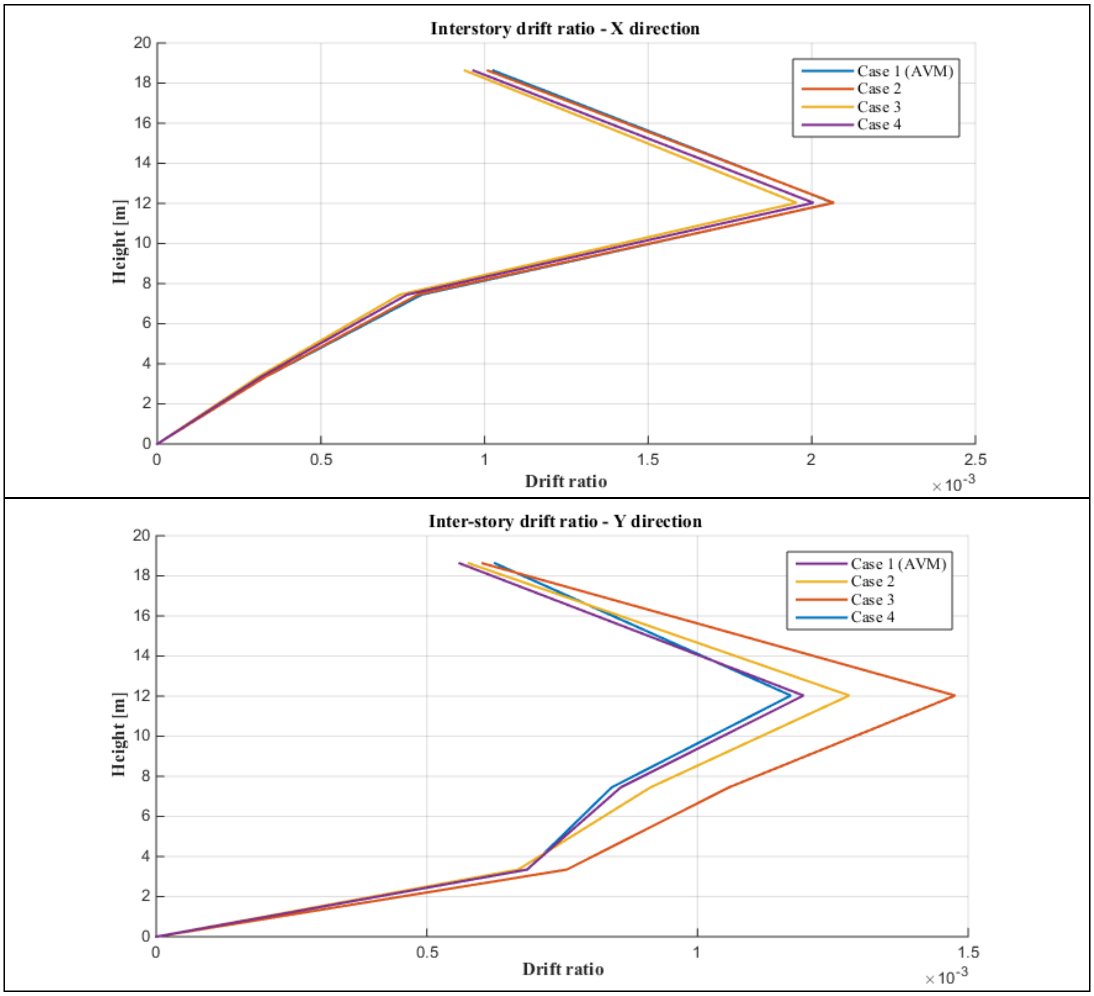


Fig. 4 – Average inter-story drift curves for building #15 in X and Y directions, NSC damping = 5%.

Looking at Fig. 3 and 4, the following observations can be made:

- The peaks of the FRS curves (Fig. 3) are caused by resonance at frequencies close to the natural frequencies of the building. The peaks are shifted toward lower frequencies (longer periods) and their amplitude are decreased due to increasing the damping ratios (i.e. increasing the energy dissipation) and decreasing the global lateral stiffness of the building (i.e. decreasing the fundamental natural frequency) moving from cases 1 to 4.
- Regarding inter-story drift curves (Fig. 4), decreasing the fundamental natural frequencies and increasing the damping ratios will have opposite and counteracting effects. The drift response is increased by decreasing natural frequencies (softening the building) and decreased by increasing the damping ratios (increasing energy dissipation). Therefore, smaller differences can be observed for drift than for acceleration responses in cases 1 to 4.

The database mostly comprises post-disaster buildings that should not undergo severe damage in order to remain operational during and after a design-level earthquake. In addition, the buildings are all located in Montreal, a region with low-to-moderate seismicity. Therefore, case 4, associated with severe damage during high intensity ground motions is not representative. Eliminating case 4 and considering the slight difference between cases 2 and 3 in terms of drift responses, it was decided to adopt the modification factors of case 2 as it results in more conservative accelerations to apply to the rest of the database.

5. Conclusion

The study has proposed an original approach to generate FRS and inter-story drift curves based on modal properties extracted from AVM in buildings. As AVM is conducted during the normal operation time of the building when all components are in place, if there is any dynamic interaction between primary and secondary systems, it would be captured in the test. This is a significant improvement over the conventional FRS method that does not consider dynamic coupling effects. The proposed method is very efficient and fast compared to more time-consuming numerical simulations and it is a practical approach to assess NSCs in existing buildings which may have changed properties with time, changes which cannot be easily captured in numerical simulations. Using response modification factors, the response of NSCs can be predicted at higher levels of shaking as long as no visual damage is happening in the structure.

6. Acknowledgements

This work has received financial support from the Natural Sciences and Engineering Research Council of Canada, strategic grant project STPGP-396464, and McGill University's MEDA program for the first author in the form of a doctoral fellowship.

7. References

[1]. Taghavi, S. (2003): Response Assessment of Nonstructural Building Elements. in Department of Civil and Environmental Engineering, Stanford University: Stanford, California. p. 96.

[2]. Mirshafiei, F. and G. McClure (2016): Modified three-dimensional seismic assessment method for buildings based on ambient vibration tests: extrapolation to higher shaking levels and measuring the dynamic amplification portion of natural torsion. Earthquake Engineering & Structural Dynamics.

[3]. National Research Council of Canada (NRC), Institute for Research in Construction (IRC) (2015): National Building Code of Canada (NBCC). Ottawa, ON, Canada.

[4]. Canadian Standard Association (CSA) (2006): CAN/CSA-S832-06: Guidline for seismic risk reduction of operational and functional components (OFCs) of buildings. Rexdale, ON, Canada.

[5]. Villaverde, R. (2009): Fundamental concepts of earthquake engineering. Boca Raton, FL: Taylor & Francis Group.

[6]. Charleson, A. (2007): Architectural design for earthquakes–a guide to the design of non-structural elements. New Zealand Society for Earthquake Engineering (NZSEE), Wellington.

[7]. Chen, Y. and T. Soong (1988): Seismic response of secondary systems. Engineering Structures, 10(4): p. 218-228.

[8]. Singh, M. (1988): Seismic design of secondary systems. Probabilistic engineering mechanics, 3(3): p. 151-158.

[9]. UBC (1935): Uniform building code. International Conference of Building Officials (ICBO): Whittier, California.

[10]. National Earthquake Hazard Reduction Program (NEHRP) (2000): Recommended provisions for seismic regulations for new buildings and other structures. Building Seismic Safety Council: Washington, D.C.

[11]. American Society of Civil Engineers (2010): ASCE Standard 7-10: Minimum Design Loads for Buildings and Other Structures. American Society of Civil Engineers: Reston, VA.

[12]. Sullivan, T.J., P.M. Calvi, and R. Nascimbene (2013): Towards improved floor spectra estimates for seismic design. Earthquake and Structures, 4(1): p. 109-132.

[13]. Brincker, R. and C. Ventura (2015): Introduction to operational modal analysis. John Wiley & Sons.

[14]. Oppenheim, A.V., R.W. Schafer, and J.R. Buck (1989): Discrete-time signal processing. Vol. 1999. Prentice hall Englewood Cliffs, NJ.

[15]. Asgarian, A. (2012): Impact of seismic retrofit and presence of terra cotta masonry walls on the dynamic properties of a hospital building in Montreal, Canada. in Department of Civil Engineering and Applied Mechanics, McGill Univeristy: Montreal, Canada. p. 156.

[16]. Structural Vibration Solution (2010): ARTeMIS Extractor, Software for Operational Modal Analysis.

[17]. Sensequake (2016): 3D-SAM 0.1v. Montreal, QC.

[18]. The MathWorks Inc. (2014): MATLAB. Natick, MA.

[19]. Chopra, A.K. and F. Naeim (2007): Dynamics of Structures—Theory and Applications to Earthquake Engineering. Earthquake Spectra. Vol. 23. 491.

[20]. Computers and Structures, I.C. (2009): SAP 2000-advanced 14.0.0. Berkeley. California.

[21]. Asgarian, A., F. Mirshafiei, and G. McClure (2014): Experimental floor response spectra for seismic evaluation of operation and functional components of building. in CSCE 2014, 4th International Structural Specialty Conference: Halifax, NS, May 28 to 31. p. 10.

[22]. Atkinson, G.M. (2009): Earthquake time histories compatible with the 2005 National building code of Canada uniform hazard spectrum. Canadian Journal of Civil Engineering, 36(6): p. 991-1000.

[23]. Atkinson, G.M. and D.M. Boore (2006): Earthquake ground-motion prediction equations for eastern North America. Bulletin of the Seismological Society of America, 96(6): p. 2181-2205.

[24]. Çelebi, M. (1996): Comparison of damping in buildings under low-amplitude and strong motions. Journal of wind engineering and industrial aerodynamics, 59(2): p. 309-323.

[25]. Çelebi, M. (2007): On the variation of fundamental frequency (period) of an undamaged building–a continuing discussion. in Proceedings of International conference on Experimental Vibration Analysis for Civil Engineering Structures (EVACES07), Porto, Portugal, October 24-27.

[26]. Çelebi, M. (2009): Comparison of recorded dynamic characteristics of structures and ground during strong and weak shaking, in Increasing Seismic Safety by Combining Engineering Technologies and Seismological Data, Springer. p. 99-115.

[27]. Todorovska, M., T. Hao, and M. Trifunac (2004): Building periods for use in earthquake resistant design codes earthquake response data compilation and analysis of time and amplitude variations. in Report CE 04-02: Department of Civil Engineering, University of Southern California, Los Angeles, California,.

[28]. Todorovska, M., M. Trifunac, and T.-Y. Hao (2006): Variations of apparent building frequencies-lessons from full-scale earthquake observations. in 1st European conference of earthquake engineering and seismology: Geneva, Switzerland, September 3-8.

[29]. Dunand, F., P.-y. Bard, and J. Rodgers (2006): Comparison of the dynamic parameters extracted from weak, moderate and strong motion recorded in buildings. in 1st European conference of earthquake engineering and seismology: Geneva, Switzerland, September 3-8.

[30]. Clinton, J.F., et al. (2006): The observed wander of the natural frequencies in a structure. Bulletin of the Seismological Society of America, 96(1): p. 237-257.

[31]. Carreño, R.P. and R.L. Boroschek (2011): Modal parameter variations due to earthquakes of different intensities, in Civil Engineering Topics, Volume 4, Springer. p. 321-333.

[32]. Çelebi, M., L. Phan, and R. Marshall (1993): Dynamic characteristics of five tall buildings during strong and low-amplitude motions. The structural design of tall buildings, 2(1): p. 1-15.

[33]. Trifunac, M.D., T. Hao, and M. Todorovska (2001): Response of a 14-story reinforced concrete structure to nine earthquakes: 61 years of observation in the Hollywood storage building. in Report CE01-02: Department of Civil Engineering, University of Southern California, Los Angeles, California,.

[34]. Hao, T., M. Trifunac, and M. Todorovska (2004): Instrumented buildings of University of Southern California—strong motion data, metadata and soil-structure system frequencies. in Report CE04-01: Department of Civil Engineering, University of Southern California, Los Angeles, California,.

[35]. Dunand, F. (2005): Pertinence du bruit de fond sismique pour la caractérisation dynamique et l'aide au diagnostic sismique des structures de génie civil. Université Joseph-Fourier-Grenoble: Grenoble, France.

[36]. Dunand, F., et al. (2004): Ambient vibration and earthquake strong-motion data sets for selected USGS extensively instrumented buildings. In USGS Open-File Report 2004-1375.

[37]. Boroschek, R. and P. Lazcano (2008): Non-damage modal parameter variations on a 22 story reinforced concrete building. in International Modal Analysis Conference, IMAC XXVI, Orlando, FL.

[38]. Singh, J., et al. (2014): Identification of modal parameters of a multistoried RC building using ambient vibration and strong vibration records of Bhuj earthquake, 2001. Journal of earthquake engineering, 18(3): p. 444-457.