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EXPERIMENTAL FLOOR RESPONSE SPECTRA FOR SEISMIC EVALUATION OF OFCS USING AMBIENT VIBRATION TESTS

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ABSTRACT: In very general terms, building components can be classified into two groups: 1- structural components/primary system, and 2-Non-Structural Components (NSCs)/Secondary systems. NSCs are also termed as Operational and Functional Components (OFCs) of buildings in Canadian Standard Association CSA-S832, which implies that their failure can cause the building to lose its functionality, as experienced for example during strong magnitude earthquakes. Functionality is of high importance for post-disaster buildings such as hospitals, schools, and emergency shelters which must be operational after a design-level earthquake. Catastrophic OFC damage observed in past earthquakes, especially in buildings where structural damage was moderate, highlight the fact that OFCs in buildings are far from being secondary in importance and they require a practical and yet reasonably accurate approach to be designed against the seismically induced forces and displacement effects.

Currently available analytical methods for seismic evaluation and design of OFCs and/or their restraints are based on two general approaches: 1- Floor Response Spectra (FRS) approach and 2- Combined Primary-Secondary System (CPSS) approach. Briefly, the FRS approach considers the primary (building structure) and secondary (OFC) systems as dynamically decoupled systems (i.e. no dynamic interaction between them) while the CPSS approach analyses them as a combined coupled system. In this study, an original method is proposed to generate both FRS and inter-story drift curves using building response results derived from 3D-SAM, a three-dimensional experimental method presented in a companion paper (F. Mirshafiei, Asgarian, & McClure,.), which is based on ambient vibration measurements (AVM) in buildings. The proposed method improves the practicality and accuracy of both aforementioned approaches (FRS and CPSS) in several ways.

It is verified through the use of a database of 23 buildings in which AVM were performed and records analysed using 3D-SAM. Floor seismic response histories are derived and then considered as base excitation for OFCs to generate the corresponding OFC response spectra. The next step is to compare the derived OFC-FRS with the corresponding Design Uniform Hazard Spectrum (UHS) specified in the National Building Code of Canada (NBCC 2010) and develop a mathematical model to generate OFC-FRS directly from the UHS and taking into consideration the effects of building height, soil conditions, location of the OFCs in the building, OFC/building fundamental period ratio, and estimated OFC damping.

1. Introduction

Building components can be classified into two main types: 1- Structural components, which comprise the main load-resisting system of the building and are also called “primary systems” or “supporting structure”. 2- Non-Structural Components (NSCs), which are usually not intended to be part of the load-carrying system of the building and, hence, they are called “secondary systems”. NSCs are also termed as Operational and Functional Components of the building in Canadian Standard Association CSA-S832. (CSA, 2006) This terminology emphasizes the fact that OFCs’ damage can limit the functionality of the buildings significantly following moderate to severe seismic events. According to their main function, OFCs can be categorized into the following three sub-groups: Architectural components, Building services (mechanical, electrical, and telecommunication equipment), and Building contents (common and specialized) (CSA, 2006; Villaverde, 2009). Another classification of OFCs can be made in accordance with the nature of their seismic response sensitivity: 1- Inter-storey-drift-sensitive components, 2- Floor-acceleration-sensitive components, and 3- both Interstorey-drift- and floor-acceleration-sensitive components (Taghavi, 2003).

As mentioned above, the functionality and performance of OFCs during and after an earthquake are of great importance especially in post-disaster facilities such as hospitals, emergency shelters, for example, since their failure can considerably affect the overall building functionality, and cause risk to life safety and damage to property even if the structural system has performed well during earthquake. Indeed, the good seismic performance of OFCs is essential to achieve the life-safety performance objective that is mandatory for all buildings in Canada (National Research Council of Canada (NRC), 2010). Possible adverse consequences caused by failure of OFCs during an earthquake can be associated with:

1- Life safety: Movement or failure of OFCs can become a safety hazard, directly threaten the life of building occupants or passers-by, hamper the safe movement of occupants evacuating buildings, or of rescue workers entering buildings.

2- Building functionality: Induced seismic failure or malfunction of some critical OFCs can seriously impair the continuous functionality of post-disaster buildings such as hospitals, emergency shelter, etc. that should be guaranteed by design according to building codes.

3- Property protection: The financial investment in OFCs is far greater than the value of the building structure. As illustrated in Figure 1, OFCs 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), and their damage can result in important economic losses (CSA, 2006; Taghavi, 2003).

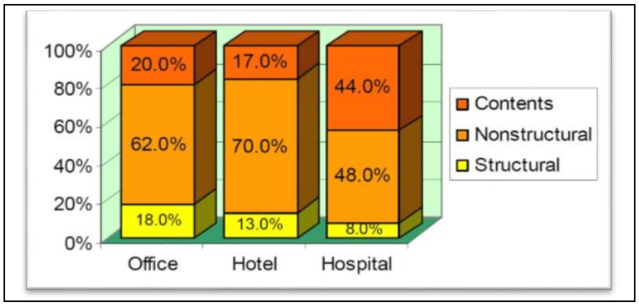


Figure 1 - Typical investments in building construction according to main occupancy (Soong & Lopez Garcia, 2003; Taghavi, 2003)

Experiences from past earthquakes and current understanding of the seismic behaviour of building structures indicate that although OFCs require rational and seismic design and analysis procedures to guarantee their good performance under seismically induced forces and displacements.

2. Background

2.1. Experimental modal analysis: Ambient Vibration Measurements (AVM)

As part of this research, experimental modal analysis is done using the AVM records collected on several post-disaster buildings located in Montreal. In AVM tests, the velocities induced by ambient excitations are recorded in two orthogonal horizontal directions and along the vertical by sensors placed at several locations (typically on floors and rooftop) in each building. Analysis of recorded data is carried out using two different operational modal analysis techniques, namely Frequency Domain Decomposition (FDD) and Enhanced Frequency Domain Decomposition (EFDD),. 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 accompanied with other structural parameters are then used as input to derive the response time-histories and subsequently the FRS for selected building floors under a set of pre-selected earthquake records representative of the site. Further explanations concerning AVM and experimental modal analysis of buildings can be found in (Gilles, 2011).

2.2. Methods of seismic analysis of OFCs

Predicting the seismic response of OFCs is a challenging problem, which has attracted the attention of researchers during the past four decades. Many efforts have been made to develop rational yet practical methods to analyse the seismic response of OFCs, but researchers have not yet reached a consensus on a generally accepted approach. This difficulty arises from the diverse dynamic characteristics of OFCs (themselves with different shapes, sub-components, anchoring systems, etc.) that increase the complexity of the problem compared to predicting the structural response of the building. The currently available analysis approaches for seismic response of OFCs can be classified into two general groups: 1-Floor Response Spectrum (FRS) approach, and 2- Combined Primary-Secondary system (CPSS) approach. The main difference between these two methods is the consideration of the primary and secondary systems as dynamically decoupled or coupled in the analysis. The FRS approach considers the building floor response and the OFC response can be analysed independently (their natural frequencies are well separated) while CPSS analysis accounts for any possible dynamic interaction between the OFC and its supporting structure. The FRS approach, of more traditional application in building structural engineering, avoids the numerical complexities caused by coupling the primary and secondary systems, and is a lot simpler, faster and therefore more economical compared to the CPSS approach. However, it has the shortcomings of neglecting: 1-dynamic interactions between the OFC and its supporting structure, 2- non-classical damping effects, 3- cross-correlation of response for multi-supported OFCs, and 4- possible effects of torsional response of the supporting structure on OFC response. Adopting the CPSS approach will overcome these problems 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, which has to be reanalyzed entirely whenever a change is made in the OFC parameters. The CPSS approach is limited in practicality as the design of the structural (primary) system not synchronized with the design of OFCs, and these two operations may involve different teams of professionals, in most instances. (Chen & Soong, 1988; Singh, 1988; Villaverde, 2009).

2.3. Canadian building code and standards for seismic design of OFCs

In addition to aforementioned analysis approaches, recent building codes and standards include several recommendations, provisions for seismic risk assessment and mitigation of OFCs in existing buildings, and empirical equations for seismic design and analysis of OFCs. In Canada, a set of recommendations and guidelines are presented in the National Building Code(NBCC) (National Research Council of Canada (NRC), 2010) and in CSA S832-14 (CSA, 2006). The current NBCC edition includes two types of seismic requirements for OFC design: 1-Seismic force requirement in which the lateral equivalent static force required for design of the components and their anchoring connections is calculated using an empirical equation that is based on the Uniform Hazard Spectrum (UHS) approach that is used for the design of building structures, 2-Seismic displacement requirements in terms of building inter-story drift limits. CSA-S832 (CSA, 2006) is the Canadian standard for “Seismic risk reduction of operational and functional components (OFCs) of buildings”; it must be used in conjunction with the NBCC seismic requirements for non-structural components, and it is applicable to both new and existing buildings.

In spite of the research effort invested on this problem, the modern building codes and standards still do not reflect the current level of understanding of the seismic behaviour of OFCs and do not incorporate the developed techniques available. This may be attributed to the fact that the developed methods are too complicated and cumbersome to be used in the design of ordinary OFCs housed in conventional buildings. Therefore, a great opportunity exists to develop an analysis method that should be rational and reasonably accurate on the one hand, and simple enough on the other hand, while reflecting the real building characteristics.

3. Description of the proposed method

In currently available building codes and standards, seismic design and analysis provisions for OFCs use empirical methods with several force modification coefficients and are, for the most part, based on past experience, engineering judgment and expert intuitions, rather than on objective experimental and analytical results. A well-known rational approach for seismic design of floor-supported OFCs involves the use of floor design spectra. NBCC 2010 includes the most recent seismic hazard data for building design in the form of a Uniform Hazard Spectrum (UHS). However, floor design spectra for OFC design (OFC-FRS) compatible with the NBCC 2010 UHS are currently not available. The proposed method is an original and practical approach to generate the OFC-FRS based on experimental data obtained from ambient vibration measurements (AVM) in buildings.

The research project consists of two main phases. In the first part, a database of the buildings in which AVT had been conducted was created. As most of the measured buildings in the database were reinforced concrete (RC) structures, the focus was narrowed down to only RC frame buildings covering various height levels (low, medium, and high rise buildings). Data were collected for 156 buildings in total from which a subset of 59 RC buildings met all the initial criteria required for the procedure. More refinements were made to select the most complete cases in the database. As the study is focused on the performance of OFCs in post-disaster buildings, the database is mostly composed of schools, hospitals and community/sport centers designated to serve as emergency shelters.

The AVM data recorded on the selected buildings has been reanalyzed to extract the dynamic properties of the buildings using the commercial software ARTeMIS Extractor^{TM} (Structural Vibration Solution, 2010). The mass and in-plane rotary inertia of the building floors have been estimated using 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 approach described in the companion paper (F. Mirshafiei, Asgarian, & McClure,). The floor response histories of the building subjected to a set of ten ground accelerograms are derived in two perpendicular horizontal directions and are subsequently assumed as base excitations for OFCs to develop their FRS. So far, FRS for 23 buildings have been generated (see Table1).

A MATLAB routine (The MathWorks Inc., 2014) was written to generate the elastic FRS and Inter-storey drift curves at every floor of the building in orthogonal horizontal (X and Y) directions, considering OFCs with several damping ratios (0, 2, 5, 10, and 20 % critical), and a fundamental period range of [0-4] s, with intervals of 0.02 s, for OFCs (damping ratios, period range, and intervals can be set to any valid value in the routine). Direct integration with Newmark's linear method was adopted to solve the equation of motion of OFCs (Chopra & Naeim, 2007), where the Beta and Gamma parameters were set as 0.25 and0.5, respectively to achieve unconditional stability of the operator; other parameters can be selected in the routine. The analysis proceeds over the entire set of seismic records and then the mean, mean + standard deviation, mean - standard deviation results are calculated and represented.

The main advantages of the proposed approach compared to the conventional approaches, codes and standards are as follows:

1) It provides a robust tool to predict the seismic performance of OFCs in existing structures;
2) Elastic FRS and inter-story drift curves can be produced without the need to generate detailed numerical models;
3) The derived FRS is based on the real dynamic properties of the building extracted from AVM which represents the current condition of the structure during its normal operation;
4) As AVM is conducted when all the OFCs are in place, the dynamic interactions between the primary and secondary systems, if any, are captured;
5) The effect of higher modes and torsional motion of the building structure on the seismic response of OFCs is taken into account;
6) The cross-correlation issue concerning the response of multi-supported OFCs is resolved by generating the inter-story drift curves.

Table 1 – Description of the analysed buildings.

Building #	Height above ground (m)	Lateral Load Resisting System (LLRS)	Low rise (1-3 floors)	Medium rise (4-7 floors)	High rise (>8 floors)
Build # 1	18.60	Concrete moment frame		☒	
Build # 2	10.80	Concrete moment frame	☒		
Build # 3	13.00	Concrete moment frame	☒		
Build # 4	8.60	Concrete moment frame	☒		
Build # 5	7.70	Concrete moment frame	☒		
Build # 6	7.46	Concrete moment frame	☒		
Build # 7	7.46	Concrete moment frame	☒		
Build # 8	7.46	Concrete moment frame	☒		
Build # 9	6.50	Concrete shear wall	☒		
Build # 10	6.50	Concrete shear wall	☒		
Build # 11	18.10	Concrete moment frame		☒	
Build # 12	13.00	Concrete moment frame		☒	
Build # 13	36.00	Concrete moment frame			☒
Build # 14	20.18	Concrete moment frame		☒	
Build # 15	20.18	Concrete moment frame		☒	
Build # 16	20.18	Concrete moment frame		☒	
Build # 17	12.00	Concrete moment frame		☒	
Build # 18	27.99	Concrete shear wall		☒	
Build # 19	19.62	Concrete shear wall		☒	
Build # 20	8.40	Concrete moment frame	☒		
Build # 21	8.40	Concrete moment frame	☒		
Build # 22	17.10	Concrete moment frame	☒		
Build # 23	15.90	Concrete moment frame		☒	
Total			**12**	**10**	**1**

The second phase of the project is to compare the generated FRS with the UHS curve corresponding to the building location and the soil site conditions, and derive a relationship between these two. The aim is to generate a model to derive FRS directly from the corresponding UHS taking into consideration the effect of different LLRS types, building height, OFC location, OFC/Building period ratio, damping value, and soil stiffness conditions.

4. Verification of the proposed method

The verification of the proposed approach has been done through the case study of Sainte-Justine Hospital located in Montreal. In a previous study by Asgarian (2012) AVM tests were conducted on block # 8 of the hospital and its dynamic properties were extracted from the AVM records. A detailed linear elastic finite element model of the building had been generated in SAP 2000 v.14.0.0 (Computers and Structures, 2009) and calibrated using experimental results. The results obtained for top floor # 6 and middle floor # 2 have been selected for the sake of validation. On the one hand, FRS and inter-story drift curves were generated using the proposed approach based on AVM results and given a synthetic ground accelerogram compatible to NBCC 2010 UHS corresponding to Montreal. On the other hand, the calibrated FE model of the building was subjected to the same ground accelerogram. Response histories of floors # 2 and # 6 were taken as the input base-excitation for OFCs and FRS and Inter-story drift curves were developed again using Seismosignal software (SeismoSoft Ltd, 2014). Further details of this step and the comparison of the results can be found in (A. Asgarian, Mirshafiei, & McClure, 2014). The comparison indicated that the proposed experimental method is producing accurate and reliable results compared to numerical finite element simulations.

The results obtained for floor #2 of building # 18 of the database (a six-storey reinforced concrete shear wall building, see Table 1) are used to validate the MATLAB code. The same response indicators as calculated with the MATLAB code were generated using SeismoSignal (SeismoSoft Ltd, 2014) and PRISM (Earthquake Engineering Research Group, 2014) software, using the same ground accelerogram used in the MATLAB code (See Fig. 2).

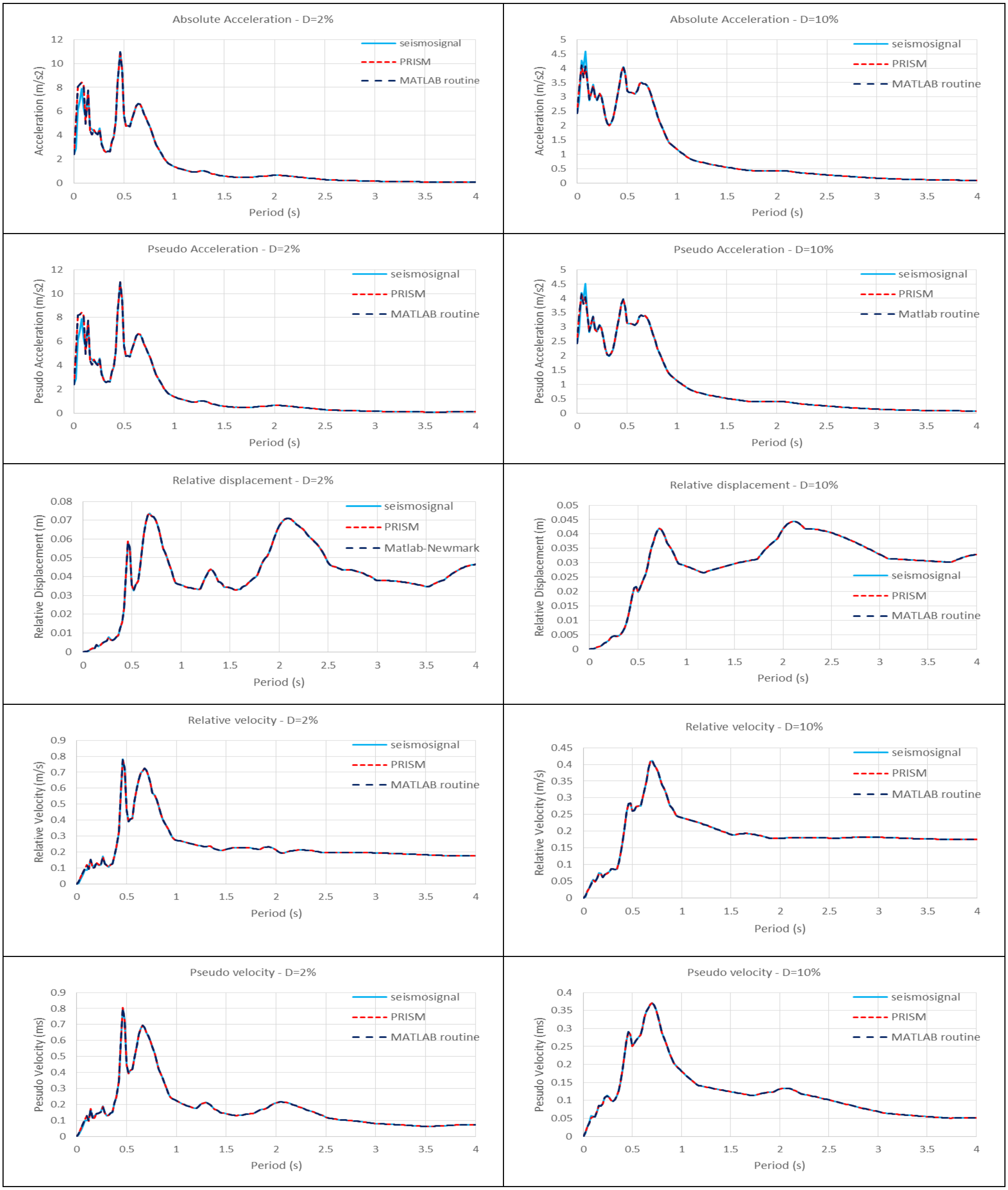


Figure 2 - Comparison of the MATLAB routine results with the SeismoSignal and PRISM results

The comparison of the results in Fig. 2 shows a very good consistency between the code and software results. Although no detailed results are presented herein, further verification of the code was done through another floor using two other accelerograms the same conclusion was reached, showing the accuracy of the MATLAB routine results based on AVM building tests.

5. Results and discussion

Building #18 selected for the sake of this presentation was constructed in 1971 with a RCSW structural system. It has a total height of about 34.70 m including its two basements and of 27.99 m above ground level if excluding the basements. AVM tests were carried out by Gilles (Gilles, 2011) at three point on every building floor of building except at the roof and penthouse levels where access was not granted. The distribution of measurement points, typical floor plan layout and bird's view of the building are as shown in Fig. 3. The AVM records were reanalysed and the building modal properties were extracted (see Fig. 4). Mass/Inertia of every floor was also estimated using the structural and architectural drawings. The building was then assumed to be subjected to a set of ten horizontal ground accelerograms in the X (East-West) and Y (North-South) directions independently. Using the 3D-SAM approach, the floor response histories were generated for the two horizontal earthquake directions, and subsequently the FRS and inter-storey curves were developed using the MATLAB routine at every floor for different damping ratios of OFCs. The results presented below are for floor # 2 of building #18, and due to space limitations, only FRS in terms of pseudo acceleration and inter-storey drift ratio are shown.

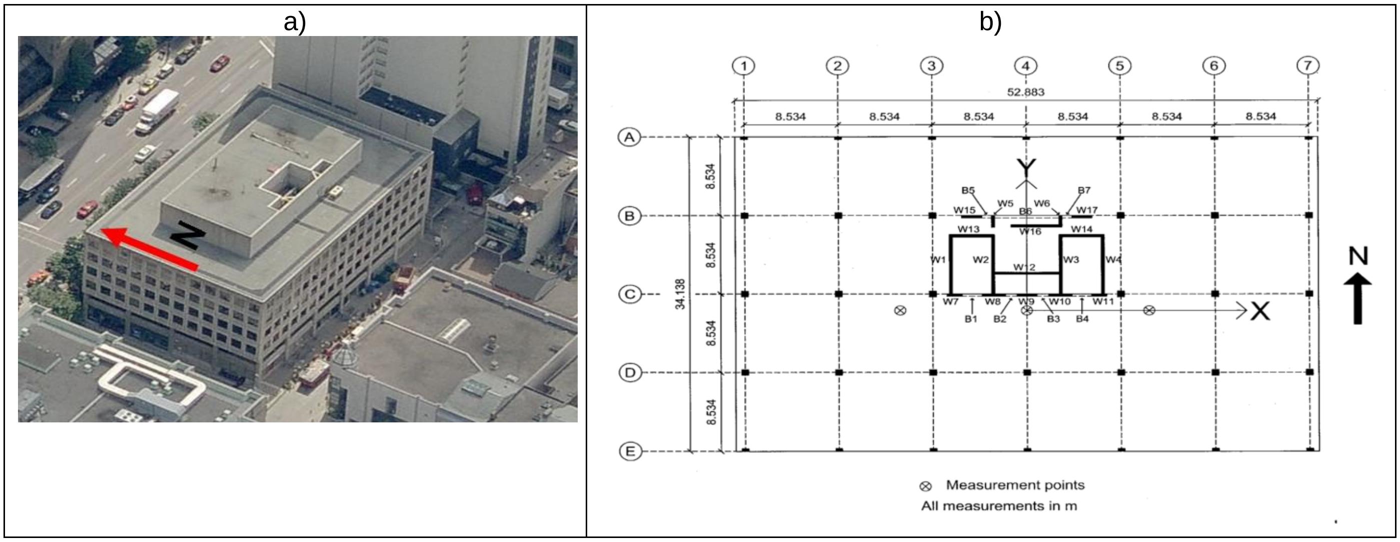
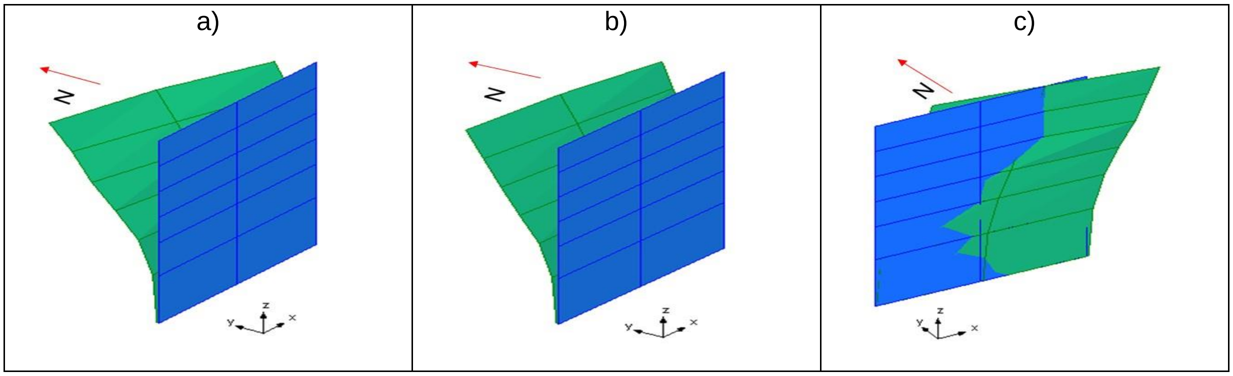

a)
b)

Figure 3 – a) Bird's eye view of building # 18; b) Typical floor plan (Gilles, 2011)


a)
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c)

Figure 4 – Mode shapes a) 1st torsional mode in N-S dir. (T= 0.59 s, damping=3.6%); b) 1st flexural mode in N-S dir. (T=0.46 s, damping =4.4%); c) 1st flexural mode in E-W dir. (T= 0.36 s, damping=1.7%)

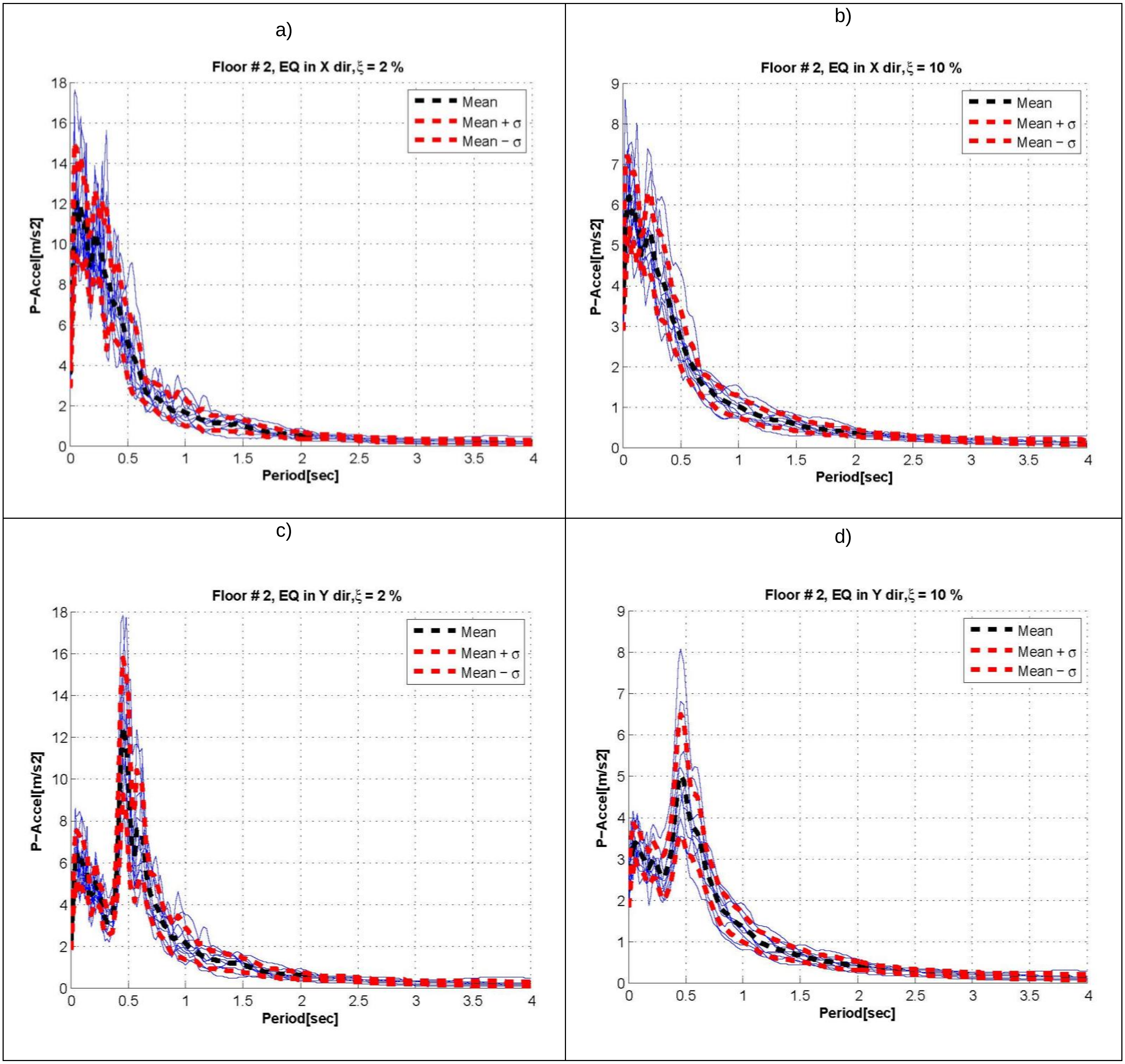
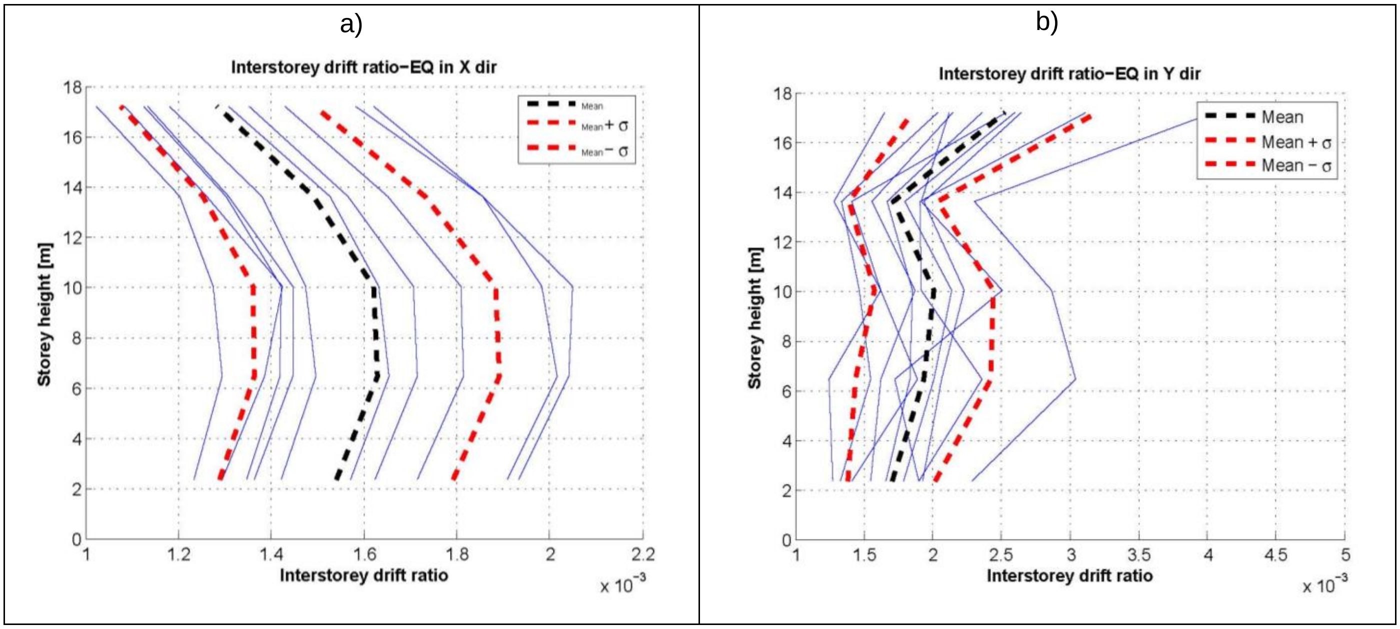


Figure 5 – Pseudo acceleration floor response spectra of floor # 2 of building #18 : a) in X dir with ζ = 2% for OFC; b) in X dir with ζ = 10% for OFC; c) in Y direction ζ = 2% for OFC; d) in Y direction ζ = 10% for OFC.



a)

b)

Figure 6 – Inter-storey drift ratio for building # 18: a) for earthquakes in X direction; b) for earthquakes in y direction.

It is seen that the results obtained from the proposed method without the need for any detailed finite element modeling of the building can be used to evaluate the seismic performance of OFCs in existing post-critical buildings that should remain functional , i.e. suffer only low level damage during a design-level earthquake.

6. Conclusion

We have proposed an original approach to derive the experimental floor response spectra for OFCs based on AVM records measured in the building. The accuracy of the experimentally based method results and their consistency with numerical results obtained from calibrated detailed finite element models were illustrated through a case study of Sainte- Justine Hospital located in Montreal (A. Asgarian et al., 2014). The proposed method is very efficient and fast compared to time-consuming numerical simulations. The method does not require generating numerical models of the buildings (which is of course still necessary for buildings at the design stage). The method is therefore particularly well suited to assess OFC seismic response in existing buildings, which may have changed properties with time, changes that cannot be easily captured in numerical simulations, and in particular in older buildings where structural drawings are not always available or lacking in details.

Contrary to the conventional FRS approach, the proposed method is capable of considering the dynamic interaction between primary and secondary systems as it is based on AVM tests conducted during the normal operation of the buildings when OFCs are in place. This is an important improvement. Moreover, it can resolve the shortcomings of the empirical simplified methods prescribed in building codes and standards by considering the effects of higher building modes and torsional behaviour of the primary system on OFC response. The cross-correlation in floor motions is considered in the inter-story drift curves that are useful to assess the drift-sensitive OFCs. FRS are generated using the real dynamic properties of building (frequencies and damping ratios) extracted from AVM and for different damping ratios assumed for OFCs. The proposed method is a promising tool to evaluate the seismic behaviour and performance of OFCs in existing buildings undergoing low to moderate structural damage. The next step of the project is to develop a mathematical model to derive FRS directly from the corresponding UHS taking into consideration the effect of building height, OFC location, OFC/Building period ratio, OFC damping, and soil stiffness conditions.

7. Acknowledgements

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