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Using ambient vibration measurements to generate experimental floor response spectra and inter-story drift curves of Reinforced Concrete (RC) buildings

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Abstract

Achieving the global good seismic performance of a building as required in modern building codes is contingent upon maintaining the integrity and functionality of its structural system as well as its Non-Structural Components (NSCs). Experience of past earthquakes has shown that many buildings have suffered from the failure of NSCs, which caused life safety hazards, costly property damages, and significantly impacted the building functionality. Avoiding these undesired consequences is of great importance particularly in post-disaster buildings that have to remain operational during and after earthquakes. In spite of advances in seismic analysis of NSCs, there is still a need for a simple, practical and yet reasonably accurate approach for seismic design of NSCs. To gain acceptance in practice, this approach must be capable of circumventing the shortcomings of existing analytical approaches as well as of current building code provisions. This study proposes an original experimental approach to generate the Floor Response Spectra (FRS) and Inter-Story Drift (ISD) curves based on Ambient Vibration Measurements (AVM) in buildings. These outputs provide robust tools for the seismic evaluation of NSCs. This paper presents the application of the proposed method to a RC building. It addresses the dependence of the output results on NSC response parameters such as NSC location in the building, NSC dynamic properties (internal damping and natural periods), and natural periods of the building. The comparison of the results with the NBCC 2015 (National Building Code of Canada) provisions for NSCs shows that these empirical recommendations typically underestimate the seismic demands on NSCs.

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

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1. Introduction

Observations of damage caused by seismic events of the last several decades have shed more light on the importance and necessity of seismic design and analysis of Non-Structural Components (NSCs) to: 1- mitigate any possible life-safety hazards arising from NSCs failure [1]; 2- guarantee the continuous functionality of post-disaster facilities such as hospitals, emergency shelters and etc. to meet their performance objective; 3- prevent significant economic losses caused, directly, by damage to NSCs or, indirectly, by facility downtime due to NSCs failure/malfunction. Therefore, rational assessment of NSC seismic performance has been the focus of many researchers during the past few decades by whom several analytical approaches were developed (see for example [2-6]). These methods can be categorized into two general groups based on the assumption of decoupling/coupling of NSCs (secondary system) from/with structural components (primary system). The two groups of methods are: 1- Floor Response Spectra (FRS) approaches, which decouple two systems and analyze them independently; 2- Combined Primary-Secondary System (CPSS) approaches, which consider them as a coupled system and analyze them together. Decoupling primary and secondary systems makes the FRS approach a lot simpler, faster, and computationally more economical than CPSS approach. However, it also makes FRS less accurate because of it cannot take into account: 1- dynamic interactions between the primary and secondary systems; 2- non-classical damping effects; 3- cross-correlation of response for multi-supported NSCs; and 4- impact of the torsional behavior of the primary system on NSCs' response. The CPSS approach can overcome the aforementioned limitations by capturing the coupling effects and dynamic interactions but will typically result in a coupled system with a large number of degrees-of-freedom and non-classical damping characteristics, which has to be reanalyzed entirely every time a change is made in the NSC parameters. Moreover, the CPSS approach has limited practicality for new building designs, as the design of the structural (primary) system is rarely synchronized with the design of NSCs, s since these two tasks involve different teams of professionals, in most instances [7-9].

Beside these two analytical methods, recent building codes and standards provide engineers with recommendations for seismic risk mitigation of NSCs in existing buildings as well as empirical equations for seismic design of NSCs in new structures. In Canada, there are two available sources including: the National Building Code of Canada (NBCC) [10] applicable to new building designs, and CSA S832-14 [11] applicable to both existing and new buildings. The current NBCC edition includes two set of seismic requirements for NSCs design: 1-seismic force requirements in which the lateral equivalent static force required for design of NSCs and their anchoring systems is calculated using an empirical equation based on the same Uniform Hazard Spectrum (UHS) approach that is used for structural components; and 2-seismic displacement requirements in terms of building inter-story drift limits. CSA-S832 [11] is the Canadian standard for "Seismic risk reduction of Operational and Functional Components (OFCs) of buildings" that should be used in conjunction with the NBCC to seismically address seismic design or evaluation of NSCs in both new and existing buildings.

The empirical equations recommended in most of the codes and standards share some common limitations such as: 1- disregarding the effect of NSCs' damping when estimating the seismic acceleration demand; 2- neglecting the effect of higher building modes on NSCs response which can be significant in high-rise buildings [2]; 3- ignoring the torsional behavior of the building that affects NSCs response particularly in irregular structures; 4- assuming linear variation of floor acceleration over building height which is convenient but not quite accurate, especially in mid-rise and tall buildings [12, 13]; 5- calculating equivalent lateral seismic forces acting on NSCs based on spectral design acceleration at short period (0.2 s) assuming that most of NSCs are stiff or rigidly connected, whereas a more accurate approach is to consider the natural periods of NSCs to account for any tuning and detuning effects.

Despite the development of these analytical and empirical approaches, a generally accepted method has not yet been attained. However, the use of Floor Design Spectra (FDS) for seismic design of NSCs still remains among the most rational and practical methods available today. Modern building codes include earthquake hazard data for structural component design in the form of design spectra, whereas, FDS for seismic design of NSCs are not currently available in the codes. This study proposes an original approach to generate FDS based on experimental data extracted from ambient vibration measurements (AVM) in buildings. Briefly, in AVM the floor velocities induced by ambient excitations are recorded in two horizontal and along the vertical directions of the building by sensors positioned at selected locations. The recorded data are then analyzed using different frequency/time domain techniques to extract the modal properties of the building. Here, two frequency-domain techniques, namely Frequency Domain