DYNAMIC CHARACTERIZATION OF URM SCHOOL BUILDINGS IN QUEBEC

M. Boutin[1], J. Proulx[1], M. Mestar[2], M.J. Nollet[2], H. Tisher[3], G. McClure[3] and P. Paultre[1]
[1] Department of Civil Engineering, Université de Sherbrooke, Sherbrooke, QC, J1K 2R1, Canada,
jean.proulx@usherbrooke.ca
[2] Department of Construction Engineering, École de technologie supérieure, Montréal QC, H3C 1K3, Canada,
marie-jose.nollet@etsmtl.ca
[3] Department of Civil Engineering and Applied Mechanics, McGill University, Montréal QC, H3A 0C3,
ghyslaine.mcclure@mcgill.ca

ABSTRACT

This paper presents an ongoing collaborative research program on the dynamic characterization of unreinforced masonry (URM) buildings, which typically comprise steel or reinforced concrete framing systems with nominal ductility and URM infill walls. Past earthquakes, most notably the 1988 Saguenay earthquake for eastern Canada, have shown the hazards associated with the seismic performance of URM. This material is commonly found in high importance structures such as schools and hospitals built in the first half of the 20th century before the introduction of any seismic provisions in the National Building Code of Canada (NBCC) and structural design codes. Retrofitting programs for these structures rely both on the evaluation of their seismic capacity and a realistic estimation of the seismic demand. However, the equations of the NBCC for estimating the fundamental period of URM buildings neglect the contribution of the infill walls. Infills increase the lateral stiffness of the building and as a result decrease its fundamental period, resulting in underestimated seismic loads. This research is part of an initiative to establish a database on the seismic vulnerability and dynamic characteristics of existing URM buildings. Ambient vibration tests were carried out by three research groups (Sherbrooke, ETS, McGill) on school buildings in different areas of the province of Quebec. This paper focuses on a particular sample of reinforced concrete frames with infill walls. It is hoped that the dynamic properties collected will contribute to the determination of more precise formulas for the fundamental vibration periods of such buildings in view of seismic demand estimations for URM seismic rehabilitation projects or new building constructions using masonry walls.

KEYWORDS: structural dynamics, seismic design, unreinforced masonry, ambient vibration, fundamental period, natural frequency.

INTRODUCTION

The 2010 edition of the National Building Code of Canada (NBCC) classifies all school buildings in the high importance category; some of these buildings are also designated as post-disaster shelters. Past earthquake experience in eastern Canada, most notably during the 1988 Saguenay earthquake ($M_w = 5.9$), has shown the high seismic vulnerability of school buildings [1]. This weakness is primarily linked to the fact that the majority of school structures were built before the implementation of rational seismic design in construction codes. Another factor contributing to the high vulnerability of school buildings is the abundant use of unreinforced masonry (URM) as wall partitions and frame infills. To mitigate this vulnerability, governmental programs have been established, prominently in the province of British Columbia, for the rehabilitation of school structures for which performances under seismic forces have been judged unsatisfactory [2]. Rehabilitation procedures require the evaluation of the seismic force demand on buildings, which relies on the identification or estimation of their fundamental dynamic properties, and most importantly their fundamental period. The main issue is that current building code equations to estimate the fundamental period of low-rise concrete frames with unreinforced masonry infill are inaccurate and underestimate seismic forces. [3].

It is therefore of utmost importance to obtain reliable experimental data to characterize the dynamic behaviour of school buildings, particularly those with extensive use of URM. Ambient vibration tests are being carried out on different types of high importance buildings as part of a collaborative effort between three research groups (McGill University, École de technologie supérieure and University of Sherbrooke), focusing on post-earthquake operational functionality. These buildings include different types of schools built before 1970. This paper describes the testing procedures, and reports the salient features of the results and compares the estimated natural frequencies with those calculated with NBCC equations. While more than 100 buildings were tested, this paper presents the results obtained in 2011 [4] and 2012 on 18 reinforced concrete moment-resisting frame buildings with URM infill walls located in central Quebec.

OVERVIEW OF THE NBCC FUNDAMENTAL PERIOD EQUATIONS

The fundamental period of vibration of a structure (T expressed in seconds) is the main parameter in defining the design seismic forces applied to a structure during ground motion. Currently, the NBCC 2010 proposes empirical period formulas depending on the lateral force resisting system and based on the height (h in meters) or number of storeys of the structure. Equation (1) refers to steel moment-resisting frames and equation (2) to concrete moment-resisting frames [5].

$$T = 0.085h^{3/4} \tag{1}$$

$$T = 0.075h^{3/4} \tag{2}$$

These equations were first introduced in the 2005 edition of NBCC and were based on the analysis of 40 buildings in California during the San Fernando earthquake of 1971 [6]. Ambient vibration testing programs have shown that these equations are not always adequate for reinforced concrete moment resisting frame buildings over 45 meters in height as well as most reinforced concrete buildings with URM infills [7]. Similar discrepancies were observed for low-rise commercial steel structures [8]. This was also corroborated by one of the research groups in this program, having recently completed their analysis of 80 school buildings through ambient vibration testing in the Montreal region [3] and Equation (3) was proposed for the prediction of the fundamental lateral period specifically for concrete frames with masonry infill walls.

$$T = (0.035 \pm 0.007)h^{3/4} \tag{3}$$

This equation is also used with the set of buildings tested in central Quebec and compared with experimental results below. The main purpose of predicting the fundamental lateral period of structures is to estimate lateral seismic forces through the equivalent static force procedure (ESFP). Even when using a more complete dynamic analysis, the NBCC limits the minimum base shear forces to 80% of the values obtained with the ESFP. Equation (4) shows the relation between the fundamental period and the resulting equivalent static force. [5]

$$V = \frac{I_E W M_V S(T_a)}{R_d R_o} \tag{4}$$

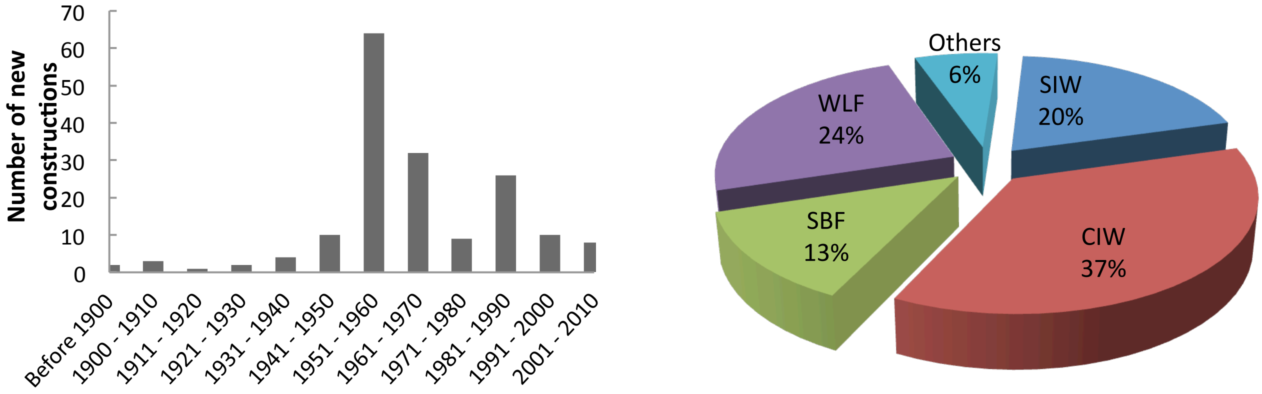
in which $S(T_a)$ refers to the design spectral acceleration at the fundamental period T_a in the uniform hazard spectrum (UHS) defined in the NBCC. As the UHS for most cities varies greatly for periods of one second and lower, overestimating the fundamental period can lead to a non-negligible underestimation of the equivalent lateral forces.

FEATURES TYPICAL TO URM SCHOOL BUILDINGS

Investigation of the dynamic characteristics of school buildings requires the participation of local school boards. The basic information supplied allows the classification of buildings according to year of construction or structural system. Features specific to the individual school building can then be deduced and on-site testing can be planned accordingly.

In the participating school boards in central/southern Quebec, officials supplied architectural and engineering drawings and provided access to selected buildings. The data presented below relates to two school boards (named SB1 and SB2) and comprises 171 buildings or expansions, built between 1882 and 2010. The distribution of the construction year of the structures is presented in Fig. 1a, with most constructions occurring between 1951 and 1970. This distribution is deemed typical of south-central Quebec, with a post-war boom first taking place in the 1950s and more projects in the 1960s through the 1970s. A similar distribution is also observed at the larger provincial scale [9]. Larger schools and sports complex expansions were built in the 1980s and 1990s. In some older structures, unclear or missing engineering drawings limited the identification of the lateral force resisting system (LFRS). The buildings classification according to LFRS is based on the types defined in the 1993 *Guidelines for the Seismic Evaluation of Existing Buildings* [10]. The distribution of this sample is presented in Figure 1b. Building types considered include *Concrete frames with infill shear walls* (CIW), *Steel Frames with infill shear walls* (SIW), *Steel Braced Frames* (SBF) and *Wood Light Frames* (WLF). Other structural types observed in negligible quantities include reinforced and unreinforced masonry bearing walls.

Figure 1b shows that more than one third of the structures built in these school boards are reinforced concrete frames with URM infill walls (CIW). Two typical CIW building in school board SB2 with peripheral masonry infill walls and outer brick cladding are presented at Figure 2. The investigated buildings often featured elevation and plan irregularities due to a higher roofed gymnasium or an L-shape extension. All buildings analysed had rigid floor diaphragms consisting of concrete slabs at every storey. However, for drainage and ventilation purposes, the roof structure was often composed of a wood assembly lying on top of the masonry walls, one meter above the ceiling slab, as shown in Figure 3a. Because it was not possible to position the sensors directly on the ceiling concrete slab, they were placed on top of the wood structure. This did not result in the identification of local roof modal information as ambient vibration data observed at the storey level corroborated with roof data, reflecting the dynamic characteristics of the structure as a whole.



(a) (b)

Figure 1: Sample from SB1 and SB2: a) Distribution according to year of construction. b) Distribution according to lateral force resisting system.

Some buildings featured shear damage to non-structural exterior brick cladding, as seen in Figure 3b. Observed URM walls were composed of either structural clay tiles (terracotta) or concrete blocks. Irregularities in the disposition of the blocks, as shown in Figure 4, were found in both types of masonry.

(a) (b)

Figure 2: Typical exterior of CIW buildings:
a) SB2-1, built in the early 1960s. b) SB2-2, built in the late 1940s

EXPERIMENTAL PROCEDURE

Ambient vibration tests requires the acquisition of data through acceleration or velocity sensors. Unidirectional Syscom velocity sensors [11] (Figure 5a) were used by one of the Sherbrooke research team for the SB1 and SB2 school boards. The other two teams used tri-axial wireless Micromed Tromino tromographs [12] in the Montreal region.

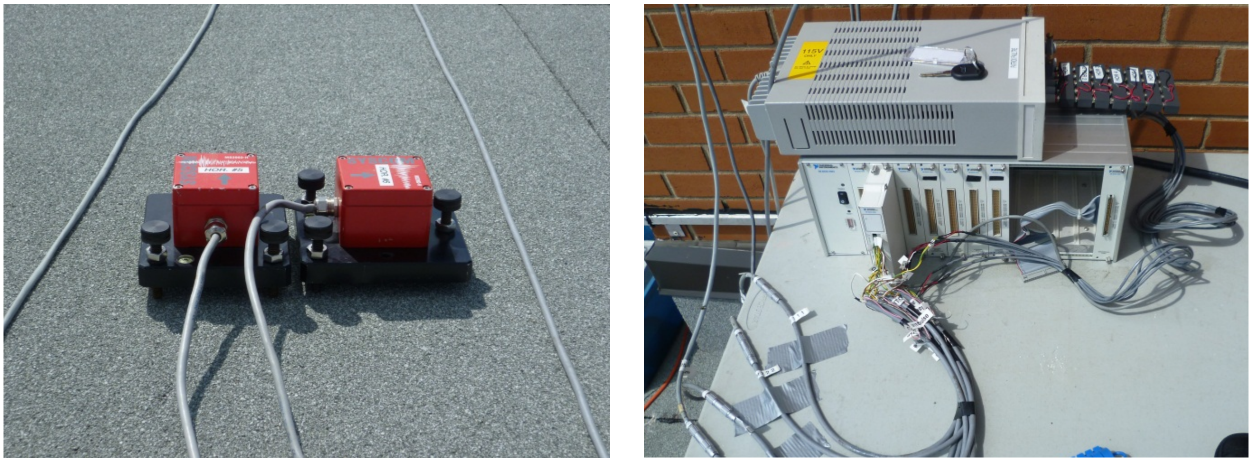
(a) (b)

Figure 3: a) Ventilation area in roof supported by URM wall b) Observed shear damage to non-structural masonry brick veneer

(a) (b)

Figure 4: Irregularities in masonry placement for: a) concrete blocks b) structural clay (terra-cotta) tiles

Experimental results for the SB1 and SB2 school boards (CIW buildings only) are presented in Table 1. In a typical configuration, sensors were placed along the peripheral walls and at key points, depending on the building structure, as seen in Figure 6. In order to cover a reasonable number of locations on the structure, multiple configurations were used which required two reference sensors and four roving sensors. These configurations were selected to consider both elevation and plan mode shapes. Ambient vibrations were recorded for seven minutes per configuration on a National Instruments acquisition system (Figure 5b). The acquisition frequency was 200 Hz with a low-pass filter using a cut-off frequency of 50 Hz.



(a) (b)

Figure 5: a) Syscom velocity sensor b) National Instruments DAQ

DATA PROCESSING

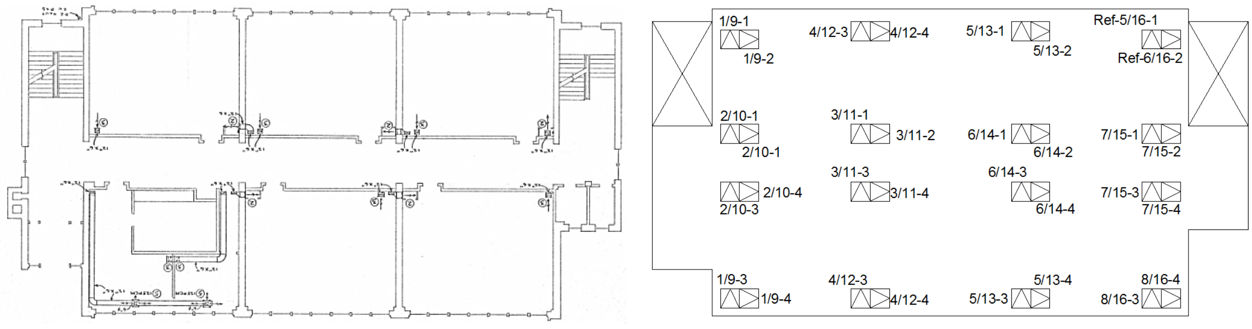
The dynamic characteristics were identified using the Frequency Domain Decomposition (FDD) method [13] on the ARTeMIS extractor software [14]. Ambient vibration signals are composed of a modal structural response and a random external excitation. Statistical treatment of the recorded signals is carried out using an autocorrelation function. This function is then transposed to the frequency domain through a Fast Fourier Transform (FFT), resulting in a Power Spectral Density function (PSD). Power spectral density matrices are then calculated at every discrete frequency (for example, in the case of the SB1 and SB2 samples, 2048 data points were used). Singular value decomposition (SVD) is carried out on the PSD matrices. Natural frequencies can then be found using the Peak Picking technique on the singular value plot. Finally, the enhanced FDD method allows the identification of damping for each selected frequency. An equivalent single degree of freedom (SDOF) spectral bell function is defined for each frequency "peak" identified on the singular value plot and is then transposed back to the time spectrum where damping is evaluated through logarithmic decrement. Natural frequencies are also verified through the use of the modal assurance criterion (MAC) [8].

TYPICAL TEST RESULTS

Typical results are shown here for a specific CIW building (SB2-9 Building 9 in school board 2). This primary school was built in the late 1950s and the original engineering drawings were unavailable. Recent mechanical engineering drawings show the location of concrete columns and URM walls (Figure 6a). The relatively small size of the building (36 meters by 19 meters) made it possible to create a precise mesh using two unidirectional sensors at each node, as shown in Figure 6b (arrows indicate the direction of velocity measurement). The sensor grid was setup to capture a significant number of mode shapes (usually up to 4 or 5 mode shapes, including flexure and torsion). A total of 16 roving sensor configurations were used for this building, covering the second storey and the roof of the structure, with reference sensors located on one of the roof corners.

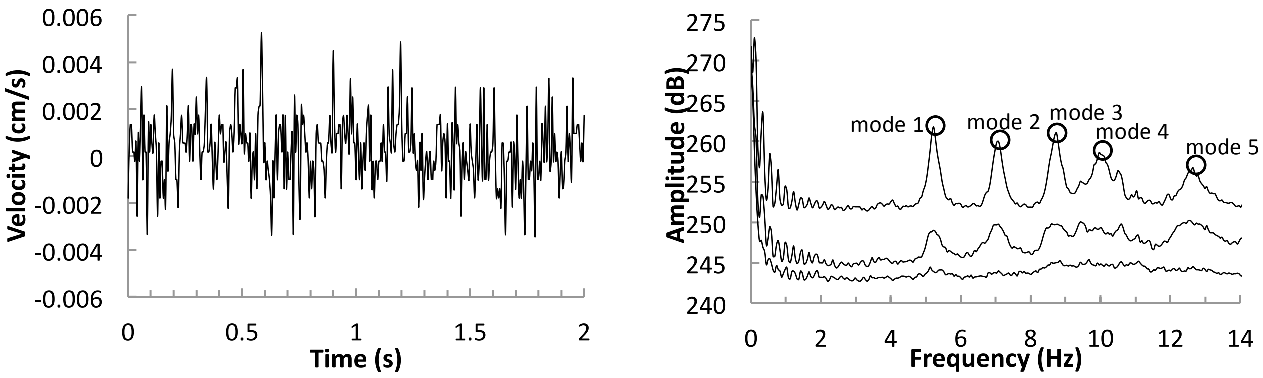
Figure 7a shows a typical time history sample and the resulting EFDD singular value plots where the peaks of the first five modes are identified, and the corresponding mode shapes are presented in Figure 8. Modes 1 and 2 show flexural sway modes in orthogonal directions, with a period of

0.19 s and 0.14 s respectively, while mode 3 shows the fundamental torsional mode with a period of 0.11 s. The fourth mode shows local flexure of the URM partition walls dividing each classroom on the second storey. Finally mode 5 shows the second flexural sway mode.



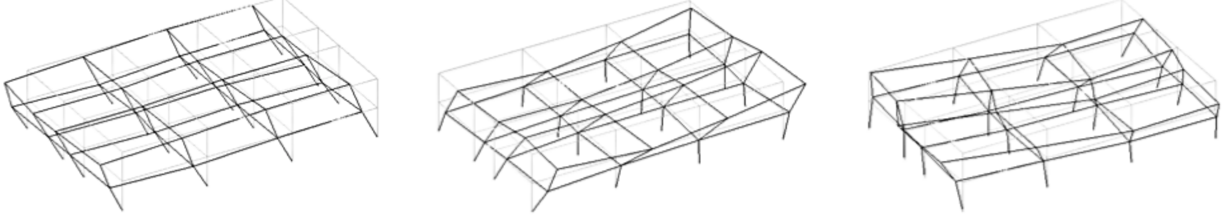
(a) (b)

Figure 6: a) Mechanical engineering plans b) Instrumentation details



(a) (b)

Figure 7: a) 2-second time history sample of recorded velocities.
b) Spectral density curves after data processing.



Mode 1 : (T_1 = 0.19 s, f = 5.2 Hz) *Mode 2 : (T_2 = 0.14 s, f = 7.1 Hz)* *Mode 3 : (T_3 = 0.11 s, f = 8.7 Hz)*

Mode 4 : (T_4 = 0.10 s, f = 10 Hz) *Mode 5 : (T_5 = 0.08 s, f = 13 Hz)*

Figure 9: Modal shapes obtained for SB2-9

DYNAMIC CHARACTERISTICS

Results obtained for the fundamental modes of 17 CIW buildings in the SB1 and SB2 school boards in 2011-2012 are presented in Table 1, as well as an additional CIW building from another school board (SB3) in the Montreal region, tested in 2012. The extracted dynamic characteristics include mode shapes, natural frequencies and equivalent viscous damping ratios. The fundamental sway modes were obtained for each orthogonal direction of the buildings. In some cases, modal information could only be extracted for one direction due to the lack of distinct mode shapes in the perpendicular direction. Building SB2-4 features a detached, single-storey extension to the original building which was therefore evaluated individually (buildings SB2-4.1 and SB2-4.2).

Table 1: Ambient vibration test results for CIW buildings in central Quebec

	Height (m)	Frequency (Hz)	Damping (%)	Period (s)	NBCC Period (s)	Tischer eq.3 max (s)	Tischer eq.3 min (s)
SB1-1	7.3	4.3	0.6	0.23	0.33	0.19	0.12
	7.3	6.0	0.4	0.17	0.33	0.19	0.12
SB1-2	7.1	3.2	2.2	0.31	0.33	0.18	0.12
	7.1	3.5	1.5	0.29	0.33	0.18	0.12
SB1-3	7.3	4.8	1.2	0.21	0.33	0.19	0.12
SB1-4	11.5	3.9	N/A	0.26	0.47	0.26	0.17
	11.5	5.8	N/A	0.17	0.47	0.26	0.17
SB1-5	11.5	6.0	0.4	0.17	0.47	0.26	0.17
SB1-6	6.7	6.0	1.8	0.17	0.31	0.17	0.12
SB2-1	7.9	7.0	1.2	0.14	0.35	0.20	0.13
	7.9	7.2	0.7	0.14	0.35	0.20	0.13
SB2-2	12.5	4.9	0.6	0.20	0.50	0.28	0.19
	12.5	5.1	0.9	0.20	0.50	0.28	0.19
SB2-3	8.7	6.6	0.8	0.15	0.38	0.21	0.14
	8.7	6.8	0.6	0.15	0.38	0.21	0.14
SB2-4.1	13.4	5.3	0.7	0.19	0.53	0.29	0.20
	13.4	5.1	1.2	0.20	0.53	0.29	0.20
SB2-4.2	3.8	10.2	0.6	0.10	0.20	0.11	0.08
SB2-5	11.5	5.5	1.1	0.18	0.47	0.26	0.17
SB2-6	7.6	8.0	0.8	0.13	0.34	0.19	0.13
	7.6	10.4	0.6	0.10	0.34	0.19	0.13
SB2-7	8.6	6.4	1.0	0.16	0.38	0.21	0.14
	8.6	7.8	0.7	0.13	0.38	0.21	0.14
SB2-8	11.4	5.9	0.7	0.17	0.47	0.26	0.17
	11.4	4.7	0.8	0.21	0.47	0.26	0.17
SB2-9	6.7	5.2	1.0	0.19	0.31	0.17	0.12
	6.7	7.1	0.7	0.14	0.31	0.17	0.12
SB2-10	8.7	5.5	1.0	0.18	0.38	0.21	0.14
SB3-1	13.7	4.25	1.45	0.24	0.53	0.30	0.20

It is interesting to compare the resulting experimental periods to the predictions from empirical equations presented earlier. Figure 10 shows the relationship between the fundamental period and the building height. Results for the CIW buildings in both school boards are shown along with the periods computed from NBCC Equations (1) and (2) as well as predictions from Equation (3) developed by the McGill research group, based on their findings in the Montreal region [3]. Here the systematic overestimation of the fundamental period by the NBCC code provisions is clearly apparent, while Equation (3) more closely fits the data and is also generally conservative.

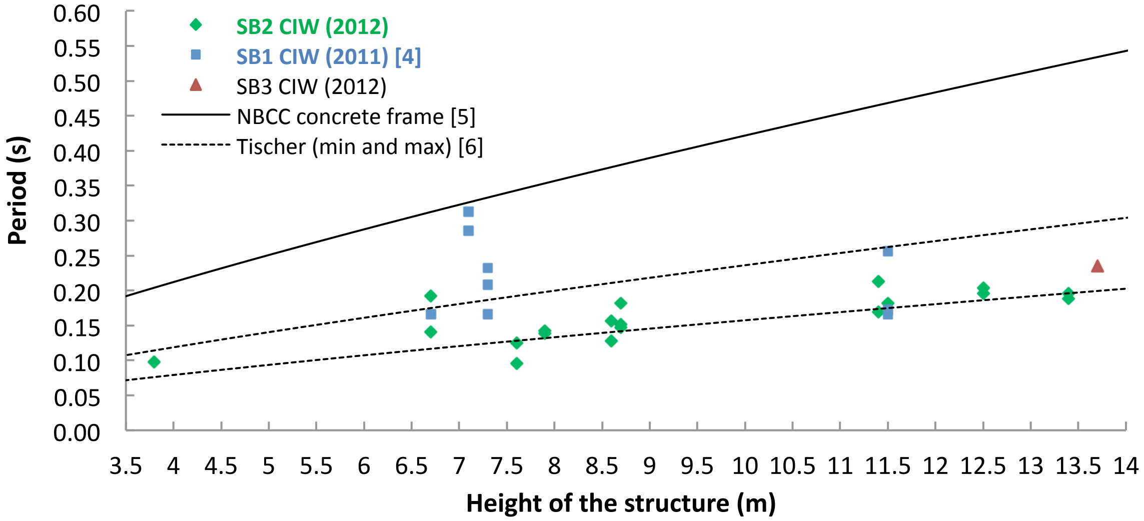


Figure 10: Comparison of the fundamental periods computed from NBCC equations to existing data

CONCLUSIONS

In a collaborative research project, three research teams based in Quebec are studying the seismic vulnerability of high importance buildings, and one of their objectives is to create a dynamic characteristics database for school buildings. Using ambient vibration measurements, natural frequencies, mode shapes and equivalent modal viscous damping ratios were obtained for several buildings in different school boards across the province. This paper focused on a particular sample in two school boards in southern/central Quebec, and results were presented for concrete frames with URM infill (CIW), a very common type of construction in the province. Elements particular to the CIW sample in central Quebec and observed during field testing were discussed, and instrumentation methods and data processing techniques were described. The resulting dynamic characteristics were compared to current NBCC empirical equations, as well as a new equation proposed by Tischer [3], which provided a better and more conservative prediction of the fundamental period for CIW buildings. Damping values were also presented for the sample and are considerably lower than the usual 5% value that is used to compute earthquake responses. It is important to note, however, that ambient vibration testing involves very low excitation levels, and these values therefore do not take nonlinear behaviour into consideration. Further research on the dynamic behaviour of URM infill and non-structural partition walls is currently underway as part of this project, involving large scale cyclic and shake-table tests.

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