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EVALUATION OF THE DYNAMIC CHARACTERISTICS FOR SEISMIC DESIGN OF MULTI-STORY BUILDINGS

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The fundamental period of vibration is a critical structural dynamic characteristic in seismic design. Several expressions for the calculation of the fundamental period have been recommended by different building codes and previous studies. However, further studies are still needed to evaluate the design expressions used for the calculation of the fundamental periods and assess the need for further refinement. In this study, comprehensive fundamental period data from two sources is collected and compared with different formulas from building codes and previous studies. The first data set is obtained from 147 instrumented buildings with various lateral force resisting systems (LFRSs). The second set of period data are collected from the dynamic response simulations of selected structures. Different LFRSs are considered, including steel moment resisting frames (SMRFs), reinforced concrete moment resisting frames (RCMRFs), reinforced concrete shear walls (RCSWs), concentrically braced frames (CBFs), eccentrically braced frames (EBFs), masonry structures and pre-cast structures. The correlations between the derived period expressions with those recommended by the design provisions show that the code approach is conservative enough for SMRFs, CBFs, masonry buildings and pre-cast structures. For RCMRFs, EBFs and RCSWs, the design code is slightly unconservative for low-rise buildings. The outcomes of the study help to arrive at more efficient and cost-effective seismic design of buildings with different characteristics.

Keywords: Fundamental period, Dynamic response, Design standards, Instrumented structures, Structural systems.

1 INTRODUCTION

Evaluating the dynamic characteristics of structures is an essential step for the design of buildings when subjected to earthquake loads. As the fundamental period of vibration cannot be precisely calculated before the design of buildings, several empirical formulas for the calculation of this crucial parameter have been recommended by seismic codes and previous studies. The code provisions specify formulas to estimate the fundamental vibration periods according to LFRS (e.g., EN 1998–1 2004, ASCE/SEI-7 2016). Moreover, several previous studies evaluated the fundamental vibration periods of buildings according to the structural LFRS (e.g., Goel and Chopra 1997, 1998, Kwon and Kim 2010). For instance, Goel and Chopra (1997) evaluated the fundamental period formulas of MRFs for the design of buildings. The same authors also proposed a vibration period formula for RCSW buildings (Goel and Chopra 1998). More recently, Kwon and Kim (2010) assessed the fundamental period for different LFRSs and recommended few changes in the code formulas related to certain structural systems.

It is important to note that the data needed to estimate the period of vibration is continuously updated and enriched due to: (i) instrumenting more buildings all over the world, (ii) recording additional data from recent earthquakes for previously instrument structures, and (iii) conducting extensive dynamic response simulation of more realistic building models (Mwafy 2013, Mwafy *et al.* 2015, Ashri and Mwafy 2017). Further assessment studies are still needed for the estimation of the fundamental vibration period of buildings to provide more reliable formulas for the design, considering the diverse vibration period data from both instrumented and simulated structures representing different LFRSs. Therefore, this study aims to collect and classify data representing the dynamic characteristics of instrumented and simulated structures, evaluate the fundamental periods based on different LFRSs, and compare the calculated period database with the current formulas specified by the seismic design code (ASCE/SEI-7 2016).

2 DATA COLLECTION AND PROCESSING

The dynamic characteristics data of this study is collected from two main sources. The first set of data is gathered from the California Geological Survey (CGS) of the California Strong Motion Instrumentation Program (CSMIP 2018). The second data set is obtained from selected simulated structures (Mwafy and Elnashai 2008, Mwafy 2011, Issa and Mwafy 2014, Ashri and Mwafy 2017). In the following sections, the process of collecting and calculating the fundamental periods from each of the above sources is described in more details.

2.1 Period Data from Instrumented Structures

The instrumented period data is collected in this study from CSMIP (2018). A total of 147 instrumented structures with different LFRSs and heights are considered. These structures are classified according to the following LFRSs: (i) SMFRs, (ii) RCMRFs, (iii) CBFs, (iv) EBFs, (v) RCSWs, (vi) masonry structures and (vii) pre-cast structures. For each building, the story layouts are used to specify the locations of the sensors on each floor, as shown in Figure 1 for a sample building. The difference in acceleration between the top and bottom sensors is obtained for each instrumented structure. This difference is then used to derive Fourier and power amplitude spectra. The response spectra of each building are used to calculate the fundamental periods from different earthquake events in both orthogonal directions of the building by reading the period corresponding to the peak value. Figure 2 depicts the adopted process for estimating the fundamental period of vibration from the response spectra.

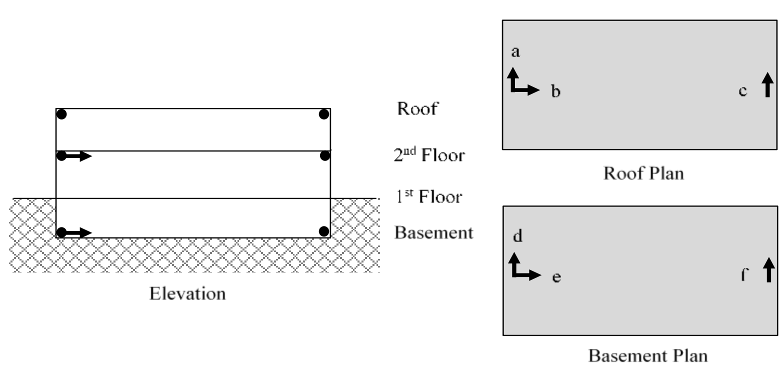

Figure 1. Layout of a building showing examples for the location of sensors.

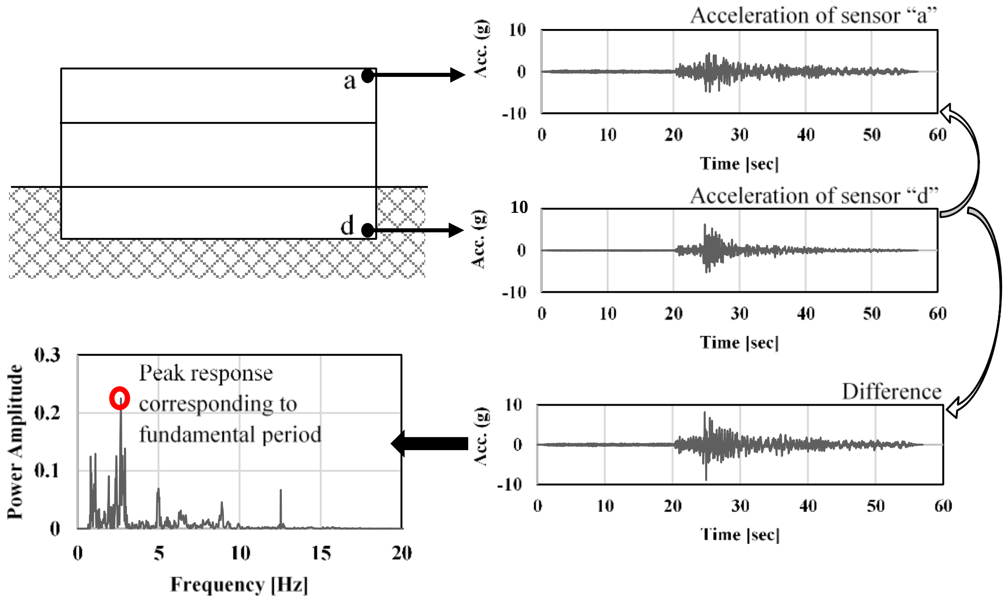

Figure 2. Process of estimating the fundamental period of a sample building.

2.2 Period data from Simulated Structures

A range of simulated structures with different heights and structural systems is also considered in this study. The selected structures are categorized into two main groups, as shown in Table 1. Group A consists of twelve medium-to-high-rise RCSW buildings with different layouts. On the other hand, group B includes low-to-medium-rise RCMRFs. The difference in response between the upper and lower nodes located at the middle interior LFRS of the selected buildings is calculated. The same procedure described previously is then implemented to calculate the fundamental vibration periods of the simulated structures.

Table 1. Characteristics of the simulated structures.

Group	Building reference	No. of stories	Total height (m)	Structural system	Group	Building reference	No. of stories	Total height (m)	Structural system
A	B1	100	321.3	RCSW	B	B13	12	36.0	Special RCMRF
	B2	80	257.3	RCSW		B14	12	36.0	Intermediate RCMRF
	B3	66	212.5	RCSW		B15	12	36.0	Intermediate RCMRF
	B4	60	193.3	RCSW		B16	12	36.0	Ordinary RCMRF
	B5	56	180.5	RCSW		B17	8	25.5	Special RCMRF
	B6	50	161.3	RCSW		B18	8	25.5	Intermediate RCMRF
	B7	40	129.3	RCSW		B19	8	25.5	Intermediate RCMRF
	B8	30	97.3	RCSW		B20	8	25.5	Ordinary RCMRF
	B9	26	84.5	RCSW		B21	2	8	RCMRF
	B10	20	65.3	RCSW		B22	8	28.5	RCMRF
	B11	18	58.9	RCSW		B23	6	24.5	RCMRF
	B12	10	33.3	RCSW		B24	3	13	RCMRF
						B25	2	9.5	RCMRF
						B26	2	9	RCMRF

3 EVALUATION OF DYNAMIC CHARACTERISTICS

Following the calculation of the comprehensive fundamental period data from the CGS database and simulated structures, the results are correlated with the code formulas according to different LFRSs. Two upper bound periods are considered, which represent 1.4xCode and 1.6xCode. These upper bound values were used in previous studies (e.g., Goel and Chopra 1997, Kwon and Kim 2010) and also recommended by design codes for high and medium seismicity regions, respectively (i.e., Sd_1 = 0.3-0.4 and 0.15, respectively, as per ASCE/SEI-7). The calculated periods of MRFs from the instrumented and simulated structures are compared with the code formulas in Figure 3. One building is excluded from the SMRFs database due to its unrealistic period since it was designed for twice the recommended seismic design load, Figure 3(a). Although the code formula is generally conservative for SMRF buildings, it is over-conservative for buildings higher than 60 meters. Hence, the code approach can be refined using the formula presented in Figure 3(a). For RCMRFs, the results of the flat slab-column system are excluded because of their flexible LFRS unlike other instrumented and simulated structures, which consist of efficient beam-column framing systems, Figure 3(b). The envelope of the derived formula is very close to the code formula, which confirm that the design approach is conservative and predicts well the periods of RCMRFs. It is noteworthy that the data used in previous studies included RCMRFs higher than 80 meters, which is uncommon for the RCMRF system. Moreover, two bracing systems are considered in this study, namely CBFs and EBFs. Figure 4(a) shows that the code formula is conservative enough for CBFs. Figure 4(b) also indicates that the design formula is conservative for the EBFs buildings higher than 40 meters, while it slightly overestimates the periods for low-rise structures.

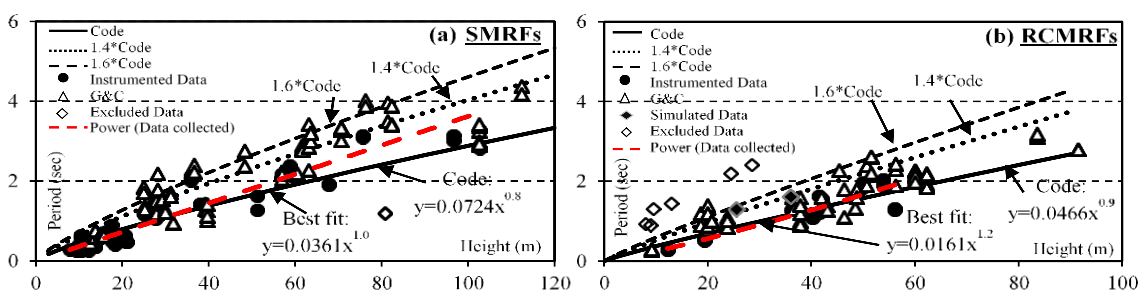

Figure 3. Identified building periods of MRFs along with derived and code recommended formulas: (a) SMRFs, and (b) RCMRFs.

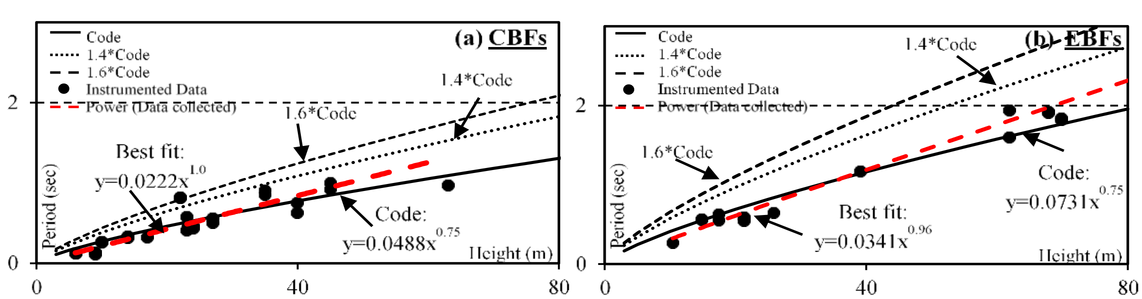

Figure 4. Identified building periods of BFs along with derived and code recommended formulas: (a) CBFs, and (b) EBFs.

Considering the calculated data of the RCSW system, two period points are excluded as the corresponding buildings were designed using the tube-in-tube system (Ashri and Mwafy 2017). The latter LRFS is typically used for super high-rise buildings. In addition to the code approach, the formula suggested by Kwon and Kim (2010) for RCSWs is presented in Figure 5. As the majority of the instrumented building periods is for low-to-mid-rise structures, the corresponding data is magnified in Figure 5(b). It is shown that the code formula is conservative for mid-to-high-rise buildings with heights over 25 meters. For low-rise RCSW buildings, the code approach slightly overestimates the period. It is also shown from the presented results that the suggested formula by Kown and Kim (2010) for RCSWs is over-conservative although it provides a lower bound for this class of structures. It is noteworthy that the simulated data are for buildings designed for medium seismicity regions, while the instrumented data were collected from a high seismic region (CSMIP 2018). Furthermore, the instrumented building data are mainly for RCSW structures lower than 75 meters, which is insufficient data to cover high-rise buildings. Therefore, the results suggest increasing the number of instrumented and simulated high-rise buildings from different regions, which may result in adopting different formulas for RCSWs depending on the seismic regions. Two additional LFRSs are considered in this study, namely masonry structures and pre-cast structures (Figure 6). The period formulas recommended by Kown and Kim (2010) for these two systems are also presented. For both LFRSs, the results show that the code formula provides a conservative lower boundary, while the Kown and Kim (2010) formulas are over-conservative although they may provide a lower bound for these two systems.

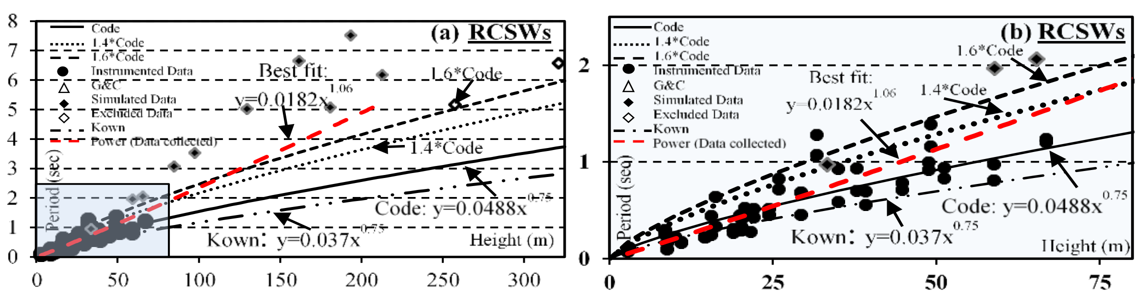

Figure 5. (a) Identified building periods of RCSWs, along with derived and code formulas, and (b) magnified data for the low-mid-rise buildings.

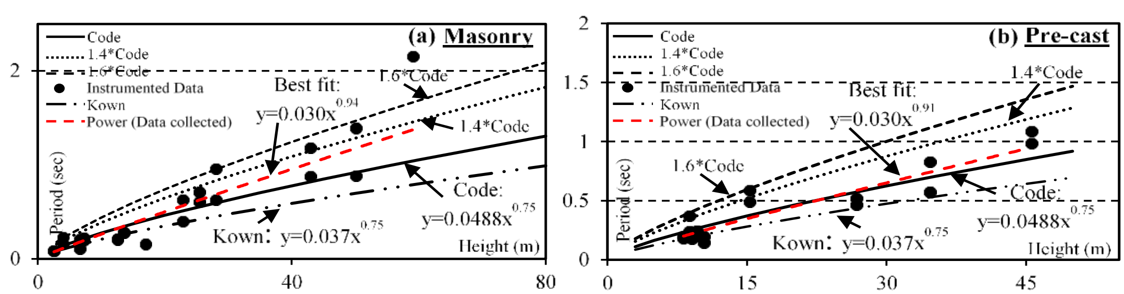

Figure 6. Identified building periods, along with derived and code recommended formulas, for: (a) masonry structures, and (b) pre-cast structures.

4 CONCLUSIONS

This study evaluated the fundamental period data collected and calculated from instrumented and simulated structures by correlating the data with the formulas recommended by design codes and previous studies. Several LFRSs were considered, including SMRFs, RCMRFs, RCSWs, CBFs, EBFs, masonry buildings and pre-cast structures. It is concluded that the design code formulas are conservative in predicting the time periods of SMRFs, CBFs, masonry structures and pre-cast structures. For RCMRFs, EBFs and RCSWs, the code formulas slightly overestimate the fundamental period of low-rise structures while they are conservative enough for mid-rise and high-rise buildings. For RCSW structures, further study is still needed to evaluate the fundamental periods of high-rise buildings located in different seismicity regions. The results of this study, which were obtained from comprehensive database representing instrumented and simulated structures, shed light on the effectiveness of the design codes in estimating the dynamic characteristics of structures, which help to arrive at more efficient and cost-effective seismic design of buildings with different characteristics.

Acknowledgments

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