IDENTIFICATION AND VALIDATION OF NATURAL PERIODS AND MODAL DAMPING RATIOS FOR STEEL AND REINFORCED CONCRETE BUILDINGS IN CALIFORNIA

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Abstract

Sixty-four buildings, with a total of 693 distinct seismic event and building direction records, are selected from the CSMIP database to identify modal quantities (i.e., natural periods and equivalent viscous damping ratios). The selected buildings include steel and reinforced concrete moment resisting frames (i.e., SMRF, and RCMRF), and reinforced concrete walls (RCW). Variation of modal quantities to structural system types, building height, amplitude of excitation, and system identification technique is studied. Results, tentatively, show median values for modal damping ratio are %2.7, %3.1, and %3.6 for RCW, RCMRF, and SMRF structures, with COVs in the order of 50%.

Introduction

Except for seismic design methods that are explicitly based on equivalent linearization, such as the Capacity Spectrum Method contained in ATC-40 (Applied Technology Council, 1996) or the Direct Displacement-Based Seismic Design (Priestly, Calvi and Kowalski, 2006), the use of equivalent damping in seismic design has been at best ambiguous and not well defined. This is a major issue for seismic design of new buildings, and retrofit of existing structures alike, because no matter what design method is implemented, an estimate of equivalent modal viscous damping is necessary for the structural design process. In the prescriptive (code-based) structural design approach the reduction in design forces attributable to expected nonlinear behavior of the structure, and the structural system's expected or assumed ductility, is primarily considered using the Response Modification Coefficient (i.e. *R*). In modern performance-based design (PBD), which relies on explicit nonlinear analyses of structures, the energy dissipated in the structure due to nonlinear hysteretic behavior of structural components is explicitly modeled.

In the modern PBD context the term structural damping refers not to the energy dissipated in the structure due to its nonlinear response, but, refers to sources of energy dissipation that are not explicitly considered in the structural model. There is an extensive body of research currently available on characterization and modeling of structural damping. A detailed literature review is presented in publications such as Spence & Kareem (2013) and ATC (2010). The research summarized here is in contrast with previous efforts in that it aims to use the vast data available from the network of CSMIP instrumented buildings to identify meaningful, and practical, structural period and damping coefficients to improve both the seismic design provisions of the building codes and the practice of performance-based design and retrofit of structures. The main focus here is on three types of lateral load resisting systems: (1) Reinforced Concrete Walls (RCW), (2) Reinforced Concrete Moment Resisting Frames (RCMRF), and (3) Steel Moment Resisting Frames (SMRF). The results presented herein are preliminary and work is in progress to finalize the main objectives of this research.

Proper modeling of the structural damping must consider the effect of variables that are fundamental to energy dissipation in structures. These factors include, but are not limited to, the building height, building construction materials, cladding and other nonstructural components, characteristics of the structure-soil-foundation interface, and excitation amplitude (Jeary, 1986; 1997). For all practical purposes structural damping is currently modeled using equivalent linear viscous damping (ASCE, 2010; ATC, 2010; ASCE, 2007). This approach is considered largely due to its modeling convenience where damping is often expressed as a percentage of the critical damping (i.e., damping ratio) in one or more vibration modes– Rayleigh Damping, Caughey Damping–(Chopra, 2001). The effect of damping is accounted for at a global scale and through modal properties. It is general practice to use a damping ratio between 2% and 5% for the first mode of vibration; damping ratios for other modes are a matter of judgment. There have been efforts to provide guidelines for proper assignment of damping ratio by relating this parameter to building type (ASCE, 2007). For example, using a damping ratio as high as 10% for wood-frame construction are allowed based on ASCE (2007); however, the same standard restricts damping in most structures to 5% or less.

In the contemporary practice, equivalent viscous damping forces are assumed to be proportional to velocities and not dependent on the amplitude of excitation. However, experimental data shows that damping is primarily a function of displacement rather than velocity. In addition, the use of a linear viscous damping model in many cases produces inaccurate estimates of displacements and internal forces in members (Bernal, 1994; Charney, 2006; Hall, 2005; Zareian & Medina, 2010). These inaccurate estimates of internal forces are related to responses in which static equilibrium is not satisfied. Despite these implications, the benefits of using a simple, applied, and practical equivalent viscous damping for modeling energy dissipation in structural systems seems to outweigh its shortcomings.

Data Collection and Description

CSMIP database of instrumented buildings contains structural records from more than166 events (including main shocks and aftershocks) ranging in date from 1979 to 2015. Due to the recent move to digital recording, the data is skewed towards more recent earthquakes resulting in a sharp increase in the number of records obtained from more recent events. For the research study presented herein, a subset of the CSMIP database with the following constraints are utilized:

1. Only buildings whose lateral load resisting system contains Reinforced Concrete Walls (RCW), Reinforced Concrete Moment Resisting Frames (RCMRF), and Steel Moment Resisting Frames (SMRF) are considered.
2. Data sets corresponding to cases where noticeable structural damage was observed were eliminated. This includes notable building-record sets for the Van Nuys 7-story Hotel (CSMIP ID: 24386), Sherman Oaks 13-story Commercial Bldg. (CSMIP ID: 24322), El

Centro - Imperial County Services Building (CSMIP ID: 1260), and Los Angeles 19-story Office Bldg. (CSMIP ID: 24643).

3. The building-record sets corresponding to systems that utilized energy dissipating devices such as dampers and seismic isolation systems were eliminated.

Our selection process has resulted in a dataset that includes 64 buildings with a total of 693 distinct seismic event and building direction records. The list of the CSMIP instrumented buildings used in this study is presented in Appendix A (Table A.1). Among the 64 buildings used in this study, there are 30 RCW, 11 RCMRF, and 23 SMRF buildings with 370, 121, and 202 distinct seismic event and building direction records. Figure 1 provides further information on the statistics of the dataset used in this study; it illustrates the number of distinct seismic event and building direction records for each lateral load resisting system and building height category.

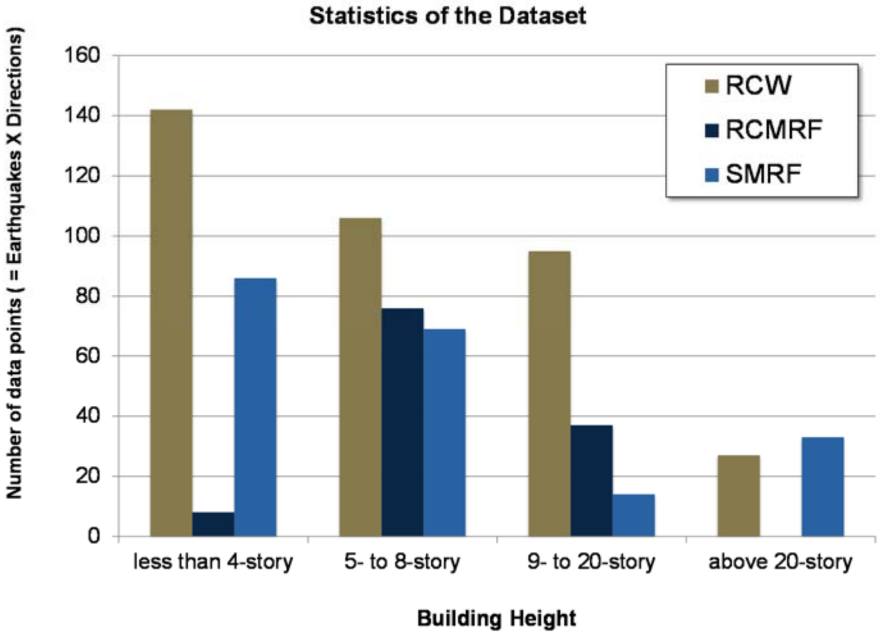


Figure 1. Statistics of the dataset used in this study

System Identification

Three system identification methods are used for assessing natural periods and structural damping of the dataset. These system identification methods include: (1) ERA-OKID method, (2) SRIM method, and (3) EFDD method. ERA-OKID and SRIM methods are input-output methods whereas EFDD is an output only method. A brief description of each methods is provided in the following.

ERA-OKID Method

ERA-OKID is an input-output time-domain system identification method which consists of two steps: (1) Eigensystem Realization Algorithm (ERA) to identify modal parameters, and (2) Observer/Kalman Identification (OKID) to increase the efficiency of the identification process. The ERA methodology is based on the discrete state-space model of the system represented with two equations: $\mathbf{x}_{k+1} = \mathbf{\Phi x}_k - \mathbf{\Gamma u}_k$, and $\mathbf{y}_{k+1} = \mathbf{Cx}_k - \mathbf{Du}_k$, where $\mathbf{\Phi}$, $\mathbf{\Gamma}$, $\mathbf{C}$ and $\mathbf{D}$ are Markov parameters of the system that embody natural period and modal damping information, $\mathbf{x}$ and $\mathbf{y}$ are the state and output vectors, and k denotes time steps. A Hankel matrix is formed by packaging the output data $\mathbf{y}$ at every time step from k to $k+2s-2$ where integers k and s represent the beginning time step, and the number of following steps used for identification, respectively. Since $\mathbf{y}_k$ is generated by Markov parameters $\mathbf{\Phi}$, $\mathbf{\Gamma}$, $\mathbf{C}$ and $\mathbf{D}$, the Hankel matrix is expressed by Markov parameters as well. By the factorization of the Hankel matrix using singular value decomposition, a minimum realization of Markov parameters is derived from which modal parameters are estimated. The OKID approach aims to increase the stability of the system identification by eliminating the redundant part of the Hankel matrix from information obtained from input excitation. Detail description of the ERA-OKID system identification methods can be found in Luş *et al.* (1999).

SRIM Method

System Realization using Information Matrix (SRIM) is an algorithm based on the concept of data correlation. In this method, a state-space vector equation in the form of $\mathbf{y}_p(k) = \mathbf{O}_p\mathbf{x}(k) + \mathbf{T}_p\mathbf{u}_p(k)$ is developed where $\mathbf{y}_p(k)$ and $\mathbf{u}_p(k)$ are stacked output and input data from time step k to $k+p-1$ respectively, and the observability matrix $\mathbf{O}_p$ and the Toeplitz matrix $\mathbf{T}_p$ are stacked system matrices that embody $\mathbf{\Phi}$, $\mathbf{\Gamma}$, $\mathbf{C}$ and $\mathbf{D}$ by the order from 1 to p-1. The integer p is chosen such that $p \geq n/m+1$, where n is the order of the system and m is the number of outputs. $\mathbf{O}_p$ and $\mathbf{T}_p$ are estimated from the auto-correlation and cross-correlation matrices of input and output data from which $\mathbf{\Phi}$, $\mathbf{\Gamma}$, $\mathbf{C}$ and $\mathbf{D}$ and ultimately modal properties of the system are estimated. Detail description of the SRIM system identification methods can be found in Juang (1997).

EFFD Method

Enhanced Frequency Domain Decomposition (EFDD) is an output-only frequency domain system identification method (Ghahari *et al.* 2014). In this system identification method, response signals are decomposed into contributions from each mode by modal coordinates: $\mathbf{y}(t) = \phi\mathbf{q}(t)$. Preliminary mode shapes are estimated from the singular vectors of the correlation matrix of output signals in the frequency domain. These preliminary mode shapes are utilized to select meaningful regions of the correlation matrix of output signals in the frequency domain via a Modal Assurance Criterion. The select regions of the output correlation matrix in the frequency domain is transformed into the time domain from which modal properties can be estimated using logarithmic decrement technique.

Identified Natural Periods & Modal damping ratios for buildings

This section focuses on assessing the variation of modal properties with structural system types, construction materials, building height, amplitude of excitation. Only the data obtained from the SRIM system identification method is used—a short sensitivity study on variation of modal properties to system identification method is described. A separate investigation, using the system identification toolbox developed by Chang *et al.* (2012) called *SMIT*, was used to demonstrate that the SRIM system identification method provides a more stable and reasonable result compared to other system identification methods. *SMIT* was used to implement the SRIM method to identify modal properties of the buildings described in Table A.1.

A subset of the identified modal properties that this research group deemed reliable was selected for further analysis and discussion presented in this paper. The information that was temporarily discarded include 7 data-points for the Oakland - 24-story Residential Bldg. (CSMIP ID: 58483), and one data-point for the Hemet - 4-story Hospital (CSMIP ID: 12267).

Modal Properties and building Height

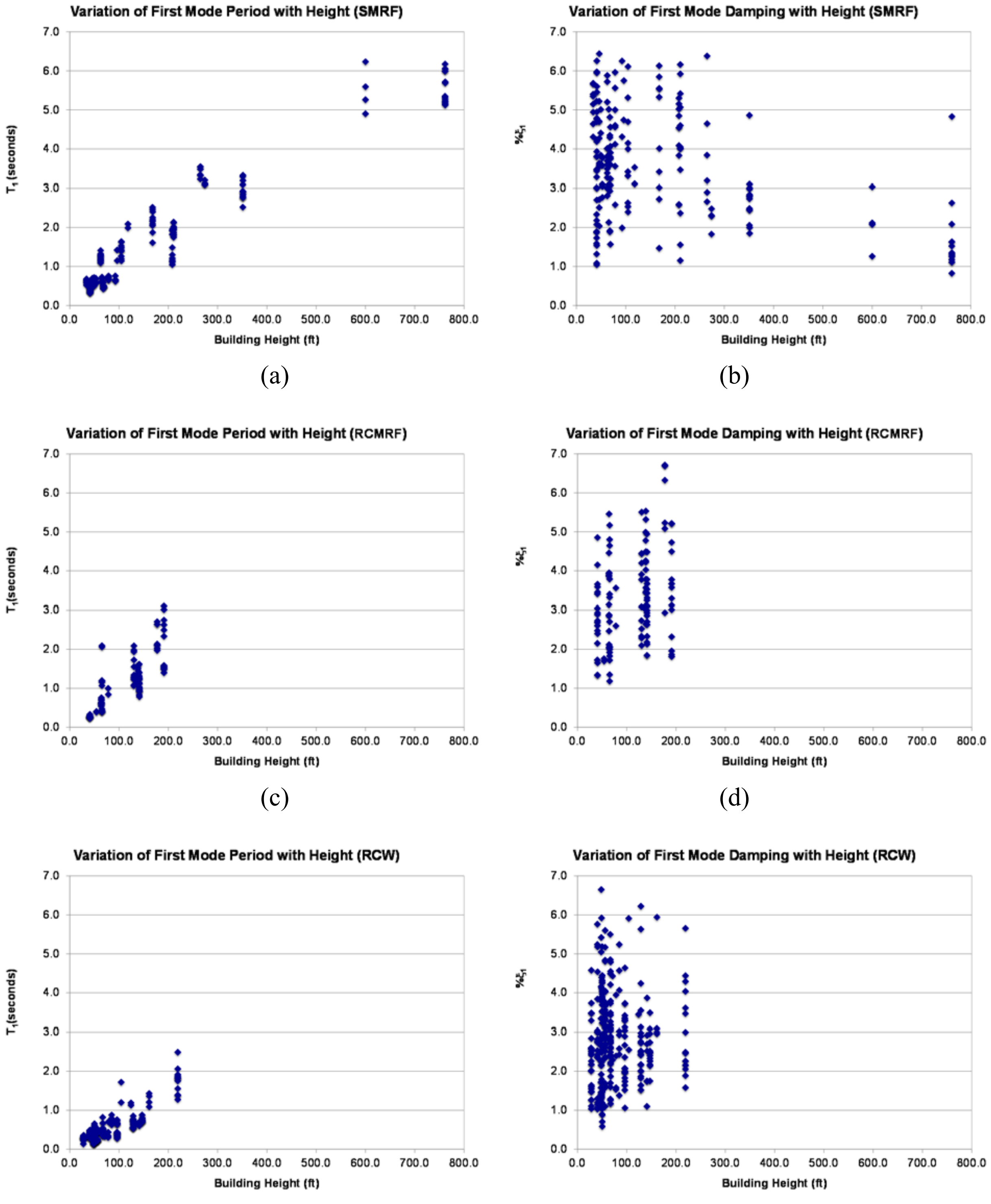
In general, the identified first mode period, T_1, and equivalent viscous damping ratio, ξ_1, follow the trend observed in previous research (Goel and Chopra, 1997, 1998; Satake et al., 2003; Bernal *et al*., 2012). Figure 2 shows the variation of T_1 and ξ_1 to building height. It is evident from the figure that estimation of both modal values is associated with high level of variability. Nevertheless, some of the trends identified by other researchers can be observed in the present data.

Figure 2a, 2c, and 2e shows that T_1 increases with building height for SMRF, RCMRF, and RCW structures. This increase saturates for taller buildings as illustrated in Figure 2a for SMRF buildings. The data was discriminated against amplitude of vibration, represented by PGA, and no specific trend was observed. ξ_1 in SMRF structures tends to decrease with increase in building height. This trend was observed by other researchers such as Jeary (1986), Satake *et al.* (2003), and Bernal *et al.* (2003). However, the same trend is not evident for RCMRF and RCW buildings. This is mostly due to high level of scatter in the estimated data especially information from low amplitude excitation (i.e. PGA < 0.01g).

Modal Properties and Ground Motion Intensity Measure

T_1 is slightly correlated with the recorded PGA at the location of the building; similar trend was observed in previous research by Satake et al. (2003) and Bernal *et al.* (2012). To show the sensitivity of T_1 to PGA, the data obtained from system identification is presented in a format that can be utilized for validation of ASCE 7-10 (2010) equation for estimation of building's period. According to ASCE 7-10, building period, denoted as T_a, is estimated as: $T_a = C_t {h_n}^x$ where C_t and x are coefficients specific to the building's lateral load resisting system, and h_n is the height of the building. ASCE 7-10 suggests that (C_t, x) is equal to $(0.028, 0.8)$ for RCMRF, $(0.016, 0.9)$ for SMRF, and $(0.02, 0.75)$ for RCW. Figures 3a, 3c, and 3e show the variation of coefficient C_t estimated from the data identified for this study (i.e. $C_t = T_1/H^x$) in which H is the height of the building from the CSMIP database, and x is equal to the value suggested by ASCE 7-10 for each lateral load resisting system. Despite large variability in estimated values of C_t, one can postulate that the code values, depicted with dash lines in Figures 3a, 3c, and 3e, mimic the central tendency of the data.

Sensitivity of ξ_1 to PGA is less than what one may expect. Figures 3b, 3d, and 3f show the variation of ξ_1 with PGA for SMRF, RCMRF, and RCW buildings. The expectation is that higher levels of excitation would lead to further energy dissipation, hence, larger value for ξ_1. One can postulate, however, that higher levels of excitation will result in reduction of the contribution of nonstructural elements in the energy dissipation effort, which are mostly coulomb-based, and increase the contribution of structural elements. The authors are currently studying this phenomenon. At this time, results show median values for modal damping ratio are %2.7, %3.1, and %3.6 for RCW, RCMRF, and SMRF structures, respectively, with COVs in the order of 50%.

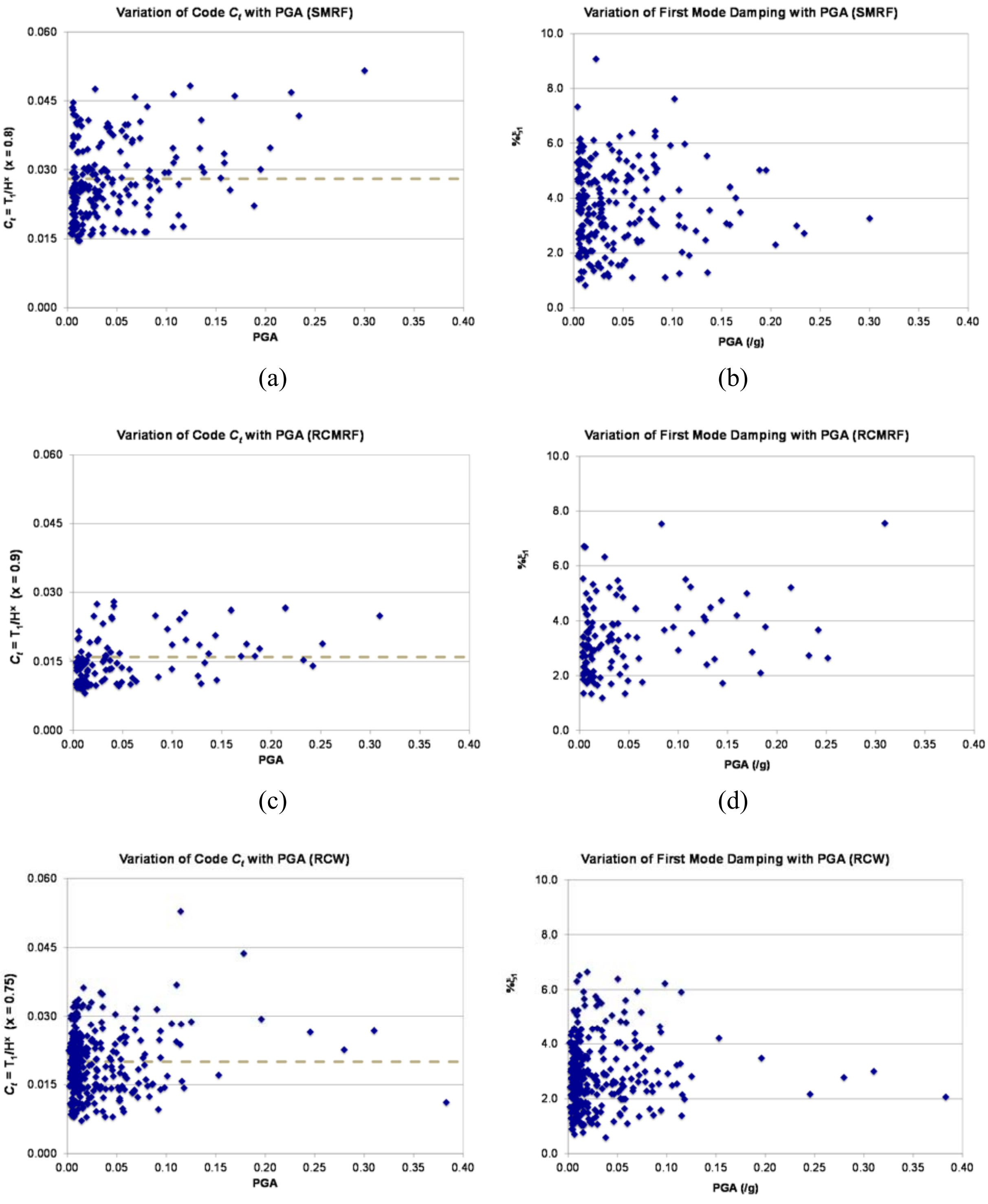


(a) (b)

(c) (d)

(e) (f)

Figure 2. Variation of first mode period and damping ratio to building height: a,b) SMRF; c,d) RCMRF; and e,f) RCW (Identification method: SRIM)

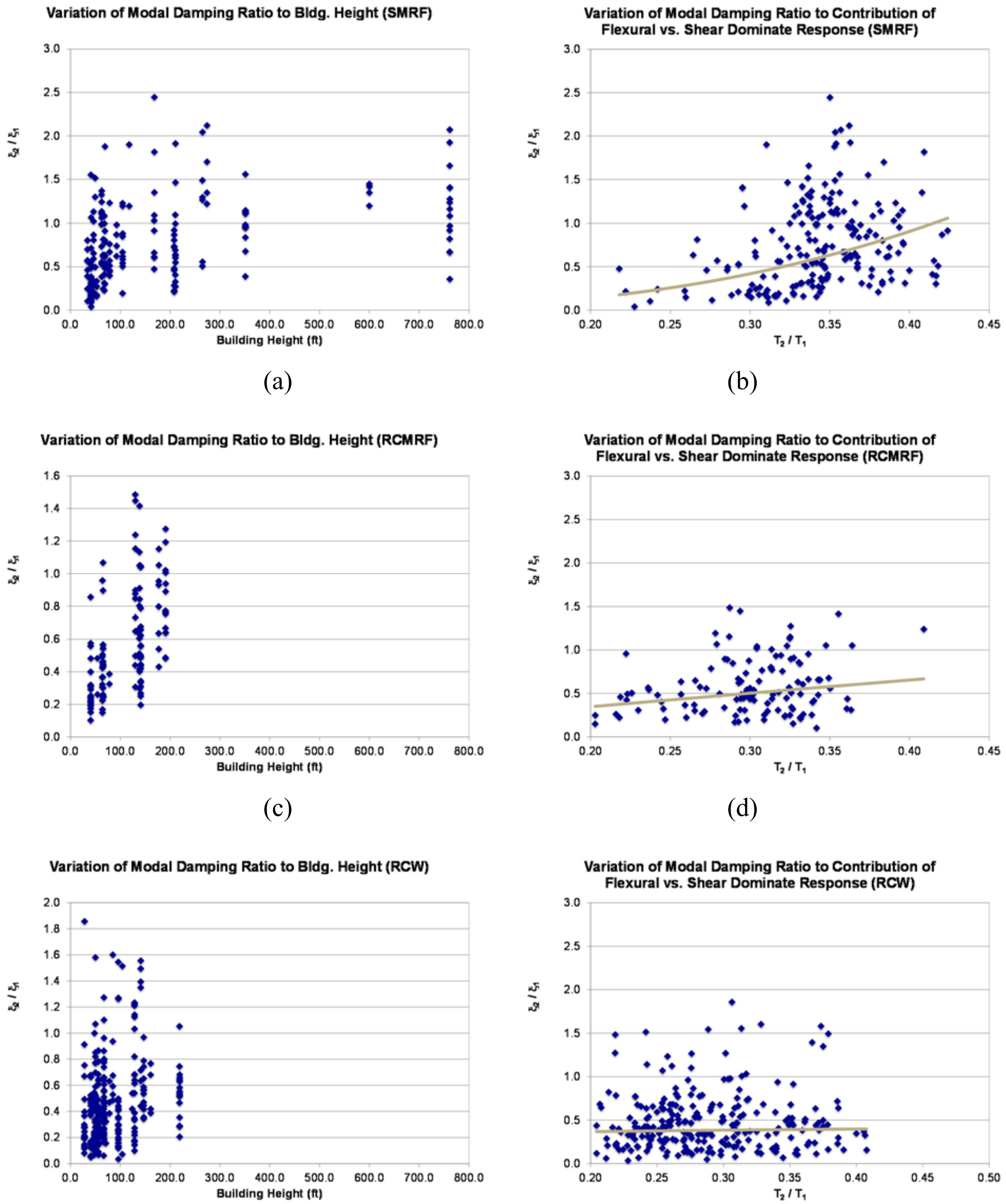


(a) (b)

(c) (d)

(e) (f)

Figure 3. Variation of first mode period and damping ratio to PGA: a,b) SMRF; c,d) RCMRF; and e,f) RCW



(a) (b)

(c) (d)

(e) (f)

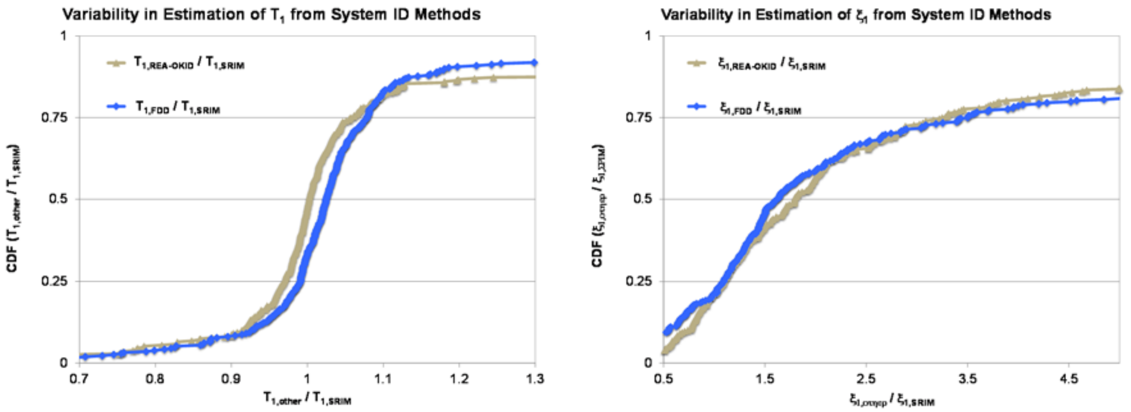
Figure 4. Sensitivity of first to second mode damping ratio to building height and ratio of first to second mode period: a,b) SMRF; c,d) RCMRF; and e,f) RCW (Identification method: SRIM)

Equivalent Viscous Damping at Higher Modes

Contrary to the suggestion by Satake et al. (2003), the results obtained in this research indicate that in average, the damping ratio of higher modes is smaller than the damping ratio of the first mode. Figures 4a, 4c, and 4e show the variation of ξ_2/ξ_1 with building height. The median of ξ_2/ξ_1 is 0.2, 0.3, and 0.4 for RCW, RCMRF, and SMRF structures, respectively. Bernal *et al.* (2010) suggests that ξ_n/ξ_1 is a function of the lateral load resisting systems behavior; it is expected that buildings with dominant flexural response (e.g. shear wall buildings, tall frame buildings) have different a trend in ξ_n/ξ_1 compared with buildings with dominant shear response (e.g. short frame buildings). In this study, relative contribution of flexural and shear response is measured with T_2/T_1 ratio; small values of T_2/T_1 (e.g. $T_2/T_1 < 0.3$) represents high levels of contribution from flexural mode to the building response, and otherwise. Figures 4b, 4d, and 4f show the variation of ξ_2/ξ_1 with T_2/T_1. It is evident from these plots that there is a positive correlation between ξ_2/ξ_1 with T_2/T_1. Large T_2/T_1 represents dominance of the shear mode of response to the total response and leads to further engagement of mechanisms that result in energy dissipation in higher modes.

Sensitivity of Identified Modal Properties to System Identification Method

Variability in estimated modal properties for a given building and ground motion is large and deserves further investigation. Figure 5a shows the statistics of the ratio of T_1 obtained from other system identification methods (i.e., ERA-OKID, and EFDD) to T_1 obtained from SRIM method for RCW structures. Figure 5b shows similar statistics for ξ_1. It is evident from these plots that estimation of T_1 is stable and relatively independent from the identification method. However, estimation of ξ_1 is highly variable and dependent on the system identification method.



(a) (b)

Figure 5. Sensitivity of first to second modal properties to system identification technique: a)first mode period, b)first modal damping ratio

Future Work

The results presented herein are preliminary and work is in progress to finalize the main objectives of this research. The authors plan to further investigate the sources of variability in estimation of modal damping, and utilize new methods for system identification. Within this setting, Spence and Kareem (2013) have proposed a new method for identification of structural damping where it assumes that the total energy dissipated in a building has viscous and frictional nature. Results of their study shows that including the amplitude dependent energy dissipation term in calculation of structural damping coefficient increases the accuracy of such estimates and is in line with the physics of the building response.

The authors plan to compare the natural periods and structural damping ratios obtained for a subset of buildings obtained herein with the results obtained from previous CSMIP sponsored study (Naeim et al, 2005; 2006). In a previous CSMIP sponsored study (Naeim *et al.*, 2004), a set of 75 buildings were carefully selected to highlight CSMIP instrumented buildings and value of seismic instrumentation in a database system and a visualization software titled CSMIP-3DV. A subset of 40 CSMIP-3DV buildings were utilized in a subsequent CSMIP sponsored study for development of damage detection techniques (Naeim *et al.*, 2005; 2006) and development of modal identification techniques using genetic algorithms (Alimoradi *et al.*, 2006; Alimoradi & Naeim, 2006).

Ultimately, the authors envision developing simplified/practical equations for estimation of natural periods and structural damping coefficient based on building information

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Appendix A

Table A.1. Set of buildings used in this study

Index	Building Station	Primary VLLR	Building Height (ft)	Number of Stories	Number of Eqs X Dir
1	58224	RCW	28.0	2	24
2	58334	RCW	49.0	3	18
3	58348	RCW	40.6	3	20
4	58503	RCW	47.5	3	12
5	12267	RCW	48.0	4	10
6	12284	RCW	50.0	4	20
7	58488	RCW	50.0	4	10
8	68387	RCW	50.0	4	2
9	68489	RCW	50.0	4	2
10	89770	RCW	50.0	4	24
11	13620	RCW	67.0	5	2
12	14311	RCW	67.0	5	2
13	23285	RCW	67.0	5	28
14	23287	RCW	56.0	6	36
15	24514	RCW	96.0	6	10
16	24655	RCW	67.0	6	12
17	58394	RCW	84.8	6	2
18	58462	RCW	84.8	6	8
19	13329	RCW	0.0	8	6
20	47459	RCW	141.0	10	4
21	57355	RCW	141.0	10	7
22	57356	RCW	96.0	10	14
23	58364	RCW	128.5	10	22
24	13589	RCW	146.9	11	14
25	58337	RCW	0.0	11	14
26	24680	RCW	114.9	12	4
27	25339	RCW	114.9	12	12
28	58479	RCW	241.0	18	4
29	58480	RCW	219.0	24	4
30	58483	RCW	219.0	24	23
31	57355	RCMRF	64.0	4	6
32	24454	RCMRF	64.0	4	2
33	23511	RCMRF	138.5	5	20
34	24579	RCMRF	65.2	7	14
35	24463	RCMRF	65.2	7	16
36	24322	RCMRF	65.2	7	14
37	24571	RCMRF	65.2	7	12
38	24464	RCMRF	130.0	9	8
39	58490	RCMRF	141.0	10	2
40	12493	RCMRF	191.0	13	12
41	24386	RCMRF	191.0	13	15
42	13312	SMRF	41.0	2	10
43	24288	SMRF	41.0	2	16
44	24609	SMRF	41.0	2	8
45	58532	SMRF	41.0	2	4
46	23516	SMRF	46.2	3	18
47	24104	SMRF	34.0	3	16
48	14533	SMRF	46.2	3	6
49	14323	SMRF	46.2	3	2
50	58261	SMRF	52.5	4	6
51	24198	SMRF	78.5	5	8
52	24629	SMRF	78.5	5	14
53	23515	SMRF	69.0	5	2
54	58506	SMRF	62.5	6	12
55	24370	SMRF	92.5	6	13
56	24566	SMRF	62.5	6	10
57	57562	SMRF	62.5	6	4
58	68669	SMRF	104.5	7	6
59	58755	SMRF	208.0	13	4
60	23634	SMRF	208.0	13	10
61	57357	SMRF	351.2	32	12
62	23481	SMRF	600.0	47	10
63	12299	SMRF	761.5	57	7
64	24569	SMRF	761.5	57	4