Predicting Collapse of Steel and Reinforced-Concrete Frame Buildings in Different Types of Ground Motions

S. Song & T.H. Heaton
California Institute of Technology, Pasadena, CA, USA

SUMMARY:
An efficient method is developed to predict P-Δ collapse of frame buildings in earthquakes. The method incorporates two types of buildings (steel and RC moment-frame buildings) and three types of ground motions (near-source ramp-pulse-like motions, long-period motions, and short-period motions). To predict whether a building will collapse in response to a given ground motion, the ground acceleration time history is first filtered using a Butterworth low-pass filter with suggested order and cutoff frequency; the order depends on the type of ground motion, and the cutoff frequency depends on the building's natural frequency and ductility. Then, the peak value of the filtered acceleration record is compared with the maximum base shear (fraction of seismic weight) obtained from a pushover analysis. If the peak of the filtered acceleration (PFA) exceeds the maximum pushover strength, then the building is expected to collapse. The method greatly reduces computational complexity but still achieves good accuracy.

Keywords: collapse, Butterworth filter, 70.7% damped response spectrum

1. INTRODUCTION

There have been numerous collapses of multi-story buildings in earthquakes. These include examples from near-source ground motions that are characterized by strong displacement pulses and ramps (1995 Kobe, 1999 Izmit, 2008 Kobe), examples from long-duration harmonic motions that occurred at relatively large distance (1985 Mexico City), and examples from large broad band motions with large duration (2008 Wenchuan, 2010 Chile). In addition to real earthquakes, simulations of the behavior of tall buildings in simulated ground motions from large earthquakes suggest that numerous tall buildings could collapse in future large earthquakes. These studies include a simulation of the 1906 San Francisco earthquake (Olsen, 2008), simulations of a large earthquake on the San Andreas fault in southern California (Lynch et al., 2011; Muto & Krishnan, 2011) and simulations of long-duration motion in the Seattle region from a giant earthquake on the Cascadia subduction zone (Yang, 2009). These studies have demonstrated that ground motions of quite different characteristics can all pose a serious threat to multi-story buildings. In this study, a simple procedure that approximately predicts collapse for buildings simulated using fully nonlinear simulations is demonstrated.

Several research groups have studied building collapse in earthquakes. For example, Hall et al. (1995) examined the effects of near-source ground motion on the collapse of flexible steel frame buildings. Liel et al. (2011), Haselton et al. (2011), and Champion and Liel (2012) have all studied the collapse of non-ductile and ductile concrete frame buildings in earthquakes. Baker and Cornell (2008) proposed the use of response spectral acceleration and ε as a vector intensity measure and used it to predict building collapse. Olsen (2008) proposed a regression model based on a vector measure (PGD, PGV) to predict the collapse of steel moment-resisting frame buildings. Krawinkler et al. (2009) determined a collapse fragility curve that incorporates aleatoric uncertainty due to record-to-record variability.

In this work, a collapse prediction method based on a new parameter (peak filtered ground acceleration or PFA) is proposed. This method covers 2 types of buildings (steel and RC moment-resisting frame buildings) and 3 types of ground motions (ramp-pulse-like, long-period, and short-period ground motions). To predict whether a building will collapse when subjected to a given ground motion, the maximum lateral capacity of the building is first estimated. Then the ground acceleration time history is filtered using a low-pass Butterworth filter and the result is compared to the building capacity (see Fig. 1.1).

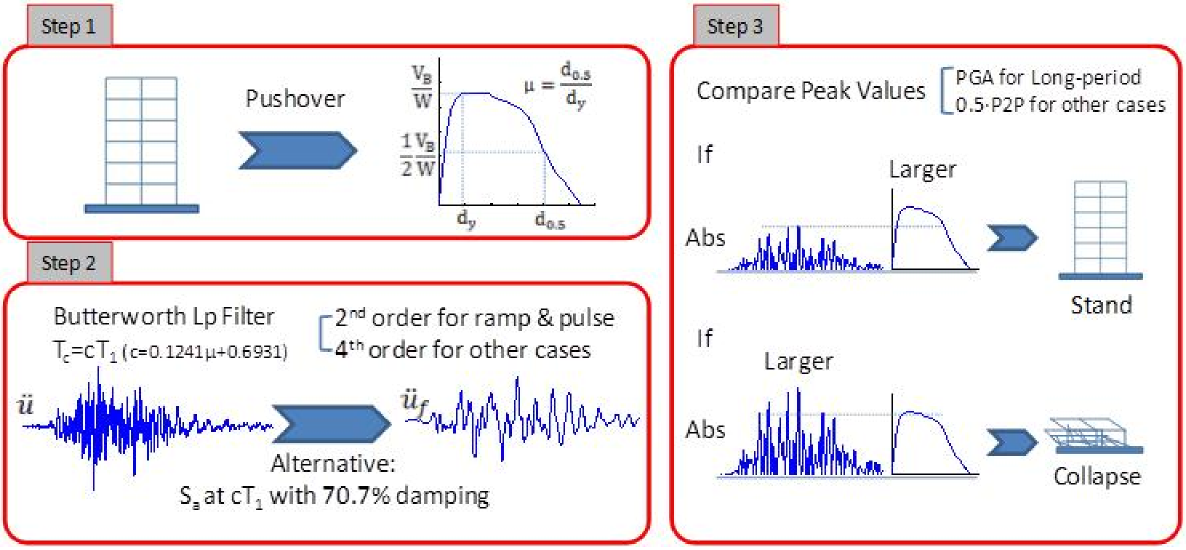


Figure 1.1. Procedure of prediction (T_1-fundamental period, T_c-cutoff period of Butterworth filter, c-developed coefficient which depends on the global ductility and ranges between 0.9 and 2.0)

There are two reasons why the Butterworth filter is chosen: 1) compared to short-period ground accelerations, much smaller long-period ground accelerations cause buildings to collapse. Hence to predict collapse, the unnecessary short-period component is neglected and the long-period component which is dominant is extracted; 2) the peak acceleration from a 2nd order Butterworth filtered record is equivalent to a 70.7% damped pseudo-acceleration response spectrum. 70.7% is the smallest damping at which an oscillator loses resonance behavior. When a building collapses due to P-Δ instability, the drift predominantly increases in only one direction; it no longer oscillates about an equilibrium position and it tends to lose its resonant behavior. Hence, a collapsing building does not respond to a particular frequency and will not have a resonance peak as is assumed in a traditional response spectrum.

2. METHODOLOGY OF THE PROPOSED METHOD

Earthquake ground motions display great variety; some are best characterized as pulse-like, others appear to be more like random noise, and yet others seems to resonate at characteristic frequencies. When a building is close to collapse instability, its behavior is extremely nonlinear and it is not possible to decompose the solution into a linear sum of responses at a spectrum of frequencies. Nevertheless, it can be quite instructive to investigate a building's response to harmonic ground motion that is large enough to cause collapse. Towards that end, a series of sinusoidal ground motions of different periods and durations are generated. Incremental dynamic analysis (IDA) is applied to determine the threshold of collapse. This threshold is denoted with minimum collapse peak ground acceleration (MinCPGA). This analysis is conducted on all 10 building models. The period of sinusoidal ground motion varies from 0.5 to 4 times the fundamental period of each building and three ground motion durations (20s, 40s, and 100s) are chosen for the analysis. An example of this analysis for a six-story steel building with perfect welds is shown in Fig. 2.1; MinCPGA is plotted verses T_s/T_1 (T_s is the period of sinusoidal ground motion and T_1 is the fundamental period of the building, 1.54 s).

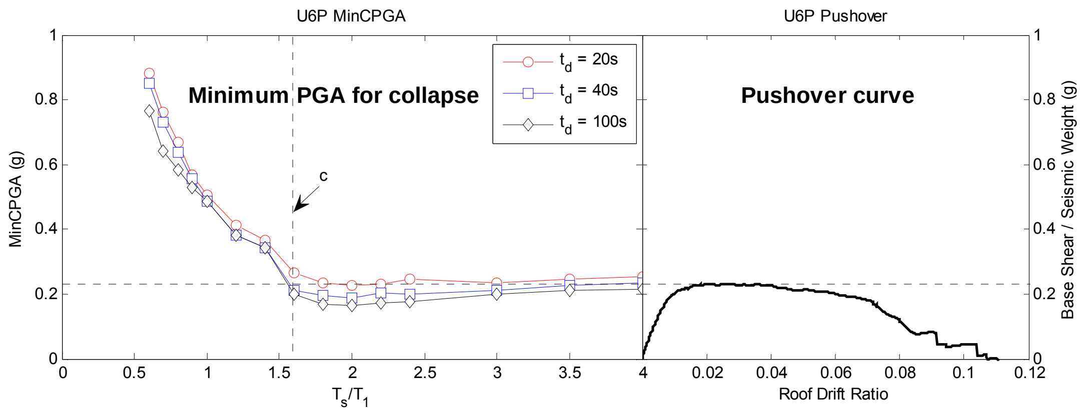


Figure 2.1. Example of minimum collapse PGA in sinusoidal ground motions for a US code six-story steel building (U6P) is shown on the left. The pushover curve is shown on the right. A common vertical axis is used for both panels.

From Fig. 2.1, it can be concluded that much smaller amplitudes are needed at long-period ground motions (T_s/T_1>c) to cause collapse, and these long-period amplitudes are close to the maximum lateral strength calculated in the pushover analysis. This analysis implies that we should pay special attention to the long-period parts of the ground motion. A low-pass Butterworth filter is used to remove the high-frequency parts of the record that seem to have little overall effect on collapse.

3. DETERMINING THE PARAMETERS USED IN THE PROPOSED METHOD

A low-pass Butterworth filter is fully described by two parameters: cutoff frequency (or cutoff period) and filter order, *n*, where the response decays as f^{-n}. A series of tests is conducted to determine these parameters. In addition, the measurement of the maximum size of the filtered acceleration can be determined by either the absolute maximum with respect to zero, or it can be determined by measuring the peak-to-peak amplitude of the largest swing.

3.1. Regression Model for Cutoff Period Coefficient c

The cutoff period is determined from the MinCPGA spectrum for each of the different building models considered in this study. It is chosen as the lowest period (T_s/T_1=c in Fig. 2.1) where the MinCPGA spectrum approaches a constant. It is found that the cutoff period is not necessarily the building's fundamental period (see Fig. 2.1). Furthermore, it is related to building's ductility ratio. In this study, the ductility ratio is defined to be $d_{0.5}/d_y$, where d_y denotes the roof displacement at which building starts to yield globally, and $d_{0.5}$ denotes the roof displacement at which the building loses 50% of the maximum strength. A linear equation is used to find the regression model between the cutoff period coefficient c and the ductility ratio. The result is shown in Fig. 3.1 and Eqn. 3.1.

$$c = 0.1241\frac{d_{0.5}}{d_y} + 0.6931 \tag{3.1}$$

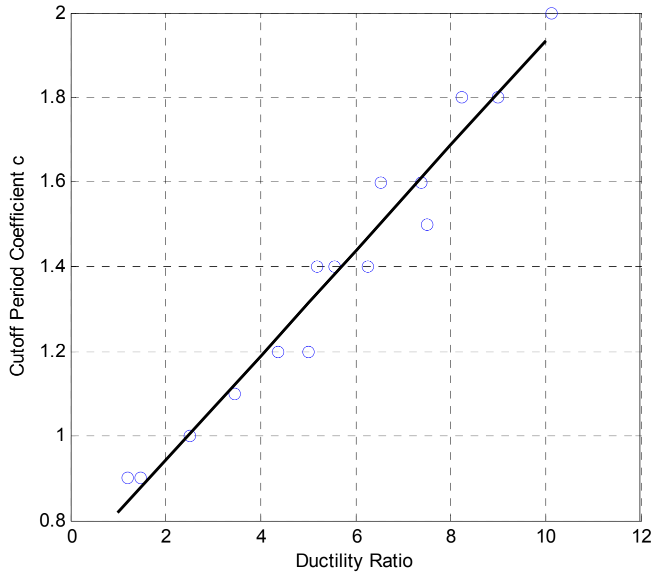


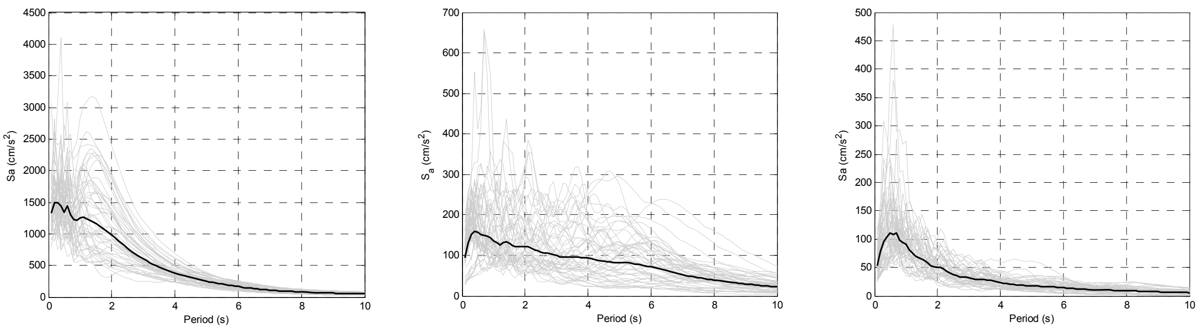
Figure 3.1. Regression model of cutoff period coefficient c

3.2. Adjusting Order of Butterworth Filters and Peak Value of Ground Motions

After obtaining the cutoff period, the order of the Butterworth filter is still need to be decided, and it is also need to decide between methods to determine the peak motion (single peak or half of the peak-to-peak). To make our study more systematic, 1) 3 ground motion sets of 150 records are selected. 2) Nonlinear finite element simulations are used for incremental dynamic analysis to compute the collapse thresholds of 10 building models (see appendix for detail) for the 3 ground motion sets. Then the filter order and amplitude determination method best fit the finite element predictions for each class of ground motion is determined.

3.2.1. Ground motions

Researchers have shown that different types of ground motions have different impacts on building response. To ensure the proposed model covers a wide range of ground motions, they are divided into three groups: 1. Ramp-pulse-like (RP) ground motions, 2. Long-period (LP) ground motions, 3. Short-period (SP) ground motions. Ramp-pulse-like records are selected from a study by Graves and Somerville (2006). Long-period and short-period records are selected from the 1999 M 7.6 Chi-Chi earthquake. The corresponding response spectra are plotted in Fig. 3.2.

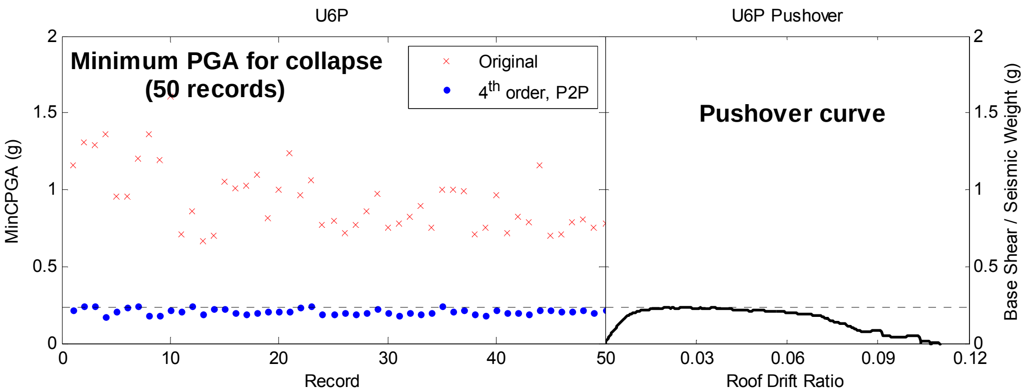


(a) Ramp-pulse-like (b) Long-period (c) Short-period

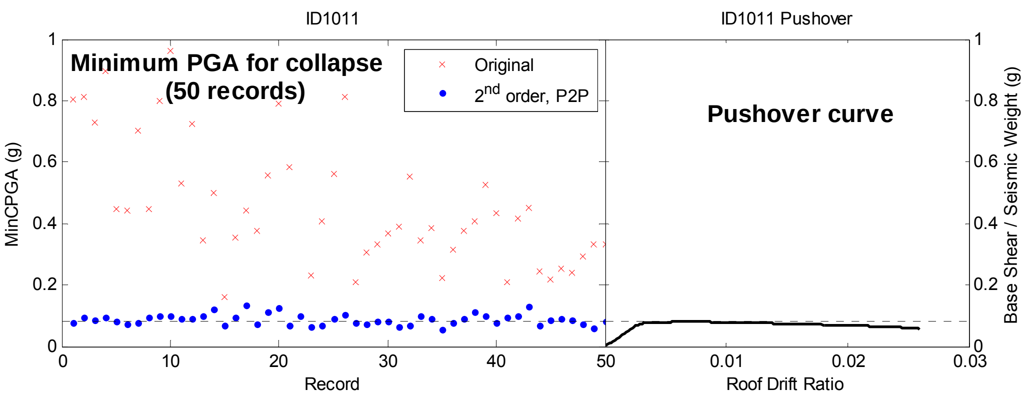
Figure 3.2. 2% damped response spectra of selected ground motions
(black lines represent the geometric mean spectrum in each figure)

3.2.2. Result of filter order and peak representative value

After linearly scaling all 150 records so that they are just large enough to induce collapse (IDA analysis), the scaled records is Butterworth filtered and then the maximum value of the filtered record is determined. This filtering process is repeated several times, each time with a different order Butterworth filter. While a 2nd order filter seems to work best for most records, a 4th order filter works better than 2nd order for ramp-pulse-like ground motions. Furthermore measuring half peak-to-peak filtered acceleration seems to provide more consistent results for ramp-pulse-like and short-period ground motions, while peak ground acceleration works better for long-period ground motions. Interestingly, determining the peak value of a 2nd order Butterworth filter acceleration record is identical to obtaining the linear acceleration spectral value at the cutoff period and with 70.7% damping. The result is shown in Table 3.1, Table 3.2, and Fig. 3.3.



(a) U6P building in ramp & pulse-like ground motions



(b) ID1011 building in short-period ground motions

Figure 3.3. Comparison of peak values of original records, filtered records at thresholds of collapse with maximum values of pushover curves. In the left panels each record is represented by the PGA of the scaled motion that caused collapse (red) and the ½ peak-to-peak amplitude of the filtered acceleration (blue). The right panel shows a pushover curve for the building where the vertical scale (acceleration) is common to both panels.

Table 3.1. Calibrated Order and Intensity Measure

Ground Motion Set	Order of Butterworth Filter	Intensity Measure
RP	4	Half peak-to-peak acceleration
LP	2	Peak ground acceleration
SP	2	Half peak-to-peak acceleration

Table 3.2. Geometric Mean Values of Collapse Thresholds (g)

Building	Ramp-pulse-like	Long-period	Short-period	Pushover
U6P	0.207	0.230	0.212	0.232
U6B	0.173	0.162	0.164	0.163
U13P	0.123	0.139	0.139	0.139
U13B	0.072	0.086	0.081	0.084
U20P	0.119	0.106	0.110	0.106
U20B	0.062	0.063	0.062	0.063
ID1003	0.155	0.134	0.122	0.147
ID1011	0.072	0.081	0.086	0.080
ID1013	0.066	0.078	0.081	0.075
ID1021	0.091	0.088	0.087	0.088

4. SUMMARY OF THE METHOD

To make the method more practical, the result in this study is summarized into a standard procedure to predict the collapse of steel and RC frame buildings. Given a target building and a ground motion record, 7 steps should be followed to predict whether the building will collapse.

(1) Obtain the fundamental period T_1 of the building.
(2) Compute the maximum base shear force V_{max} that the building can resist and its ductility in pushover analysis.
(3) Compute the seismic weight W of the building.
(4) Compute the cutoff period coefficient c for the building with Eqn. 3.1.
(5) Identify the type of the ground motion as one of the following:
    a. Ramp-pulse-like ground motion (RP).
    b. Long-period ground motion (LP).
    c. Short-period ground motion (SP).
(6) Filter the acceleration time history using Butterworth filter with the order and the cutoff frequency given in Table 4.1.

Table 4.1. Parameters of Butterworth Filter

Type of ground motion	Order	Cutoff frequency
RP	4	$1/cT_1$
LP & SP	2	$1/cT_1$

(7) Predict the building behavior with Table 4.2.

Table 4.2. Chart of Collapse Prediction (g is gravity acceleration)

Type of ground motion	Intensity measure	Condition	Prediction
RP	Half of peak-to-peak acceleration	$>V_{max}/W \cdot g$	Collapse
		$<V_{max}/W \cdot g$	Standing
LP	Peak ground acceleration	$>V_{max}/W \cdot g$	Collapse
		$<V_{max}/W \cdot g$	Standing
SP	Half of peak-to-peak acceleration	$>V_{max}/W \cdot g$	Collapse
		$<V_{max}/W \cdot g$	Standing

5. COMPARISON WITH OTHER GROUND MOTION INTENSITY MEASURES

In Figure 5.1, the performance of PFA, PGA, PGV, PGD and S_a in collapse prediction are compared. It can be concluded that PFA has the best performance with smallest standard deviation.

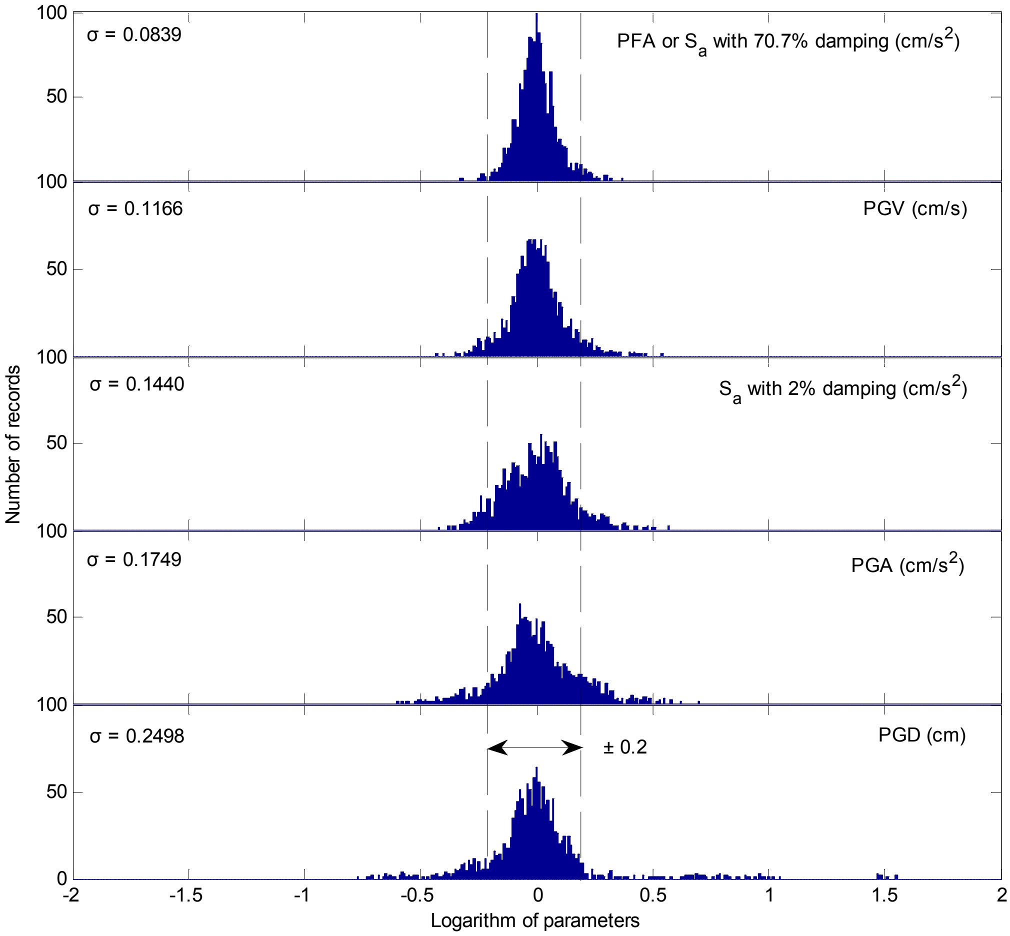


Figure 5.1. Comparison of performance of PFA, PGA, PGV, PGD and S_a in collapse prediction, the intensity measures are normalized by their geometric mean values and plotted in log scale.

6. CONCLUSIONS

In this study, a collapse prediction method is developed for steel and RC frame buildings subjected to ramp-pulse-like, long-period and short-period ground motions. To predict whether a building will collapse in a given ground motion, first long-period component is extracted from the ground motion using Butterworth low-pass filter with suggested order and cutoff frequency. Then the peak value of the filtered acceleration record is compared with the maximum lateral strength calculated in the pushover analysis. If the ground motion intensity exceeds the building's capacity, the building is predicted to collapse. Otherwise, it is expected to survive the ground motion. The method is calibrated by 10 building models and 150 ground motion records. The method has a clear physical meaning, greatly reduces computational effort but still achieves good accuracy.

7. APPENDIX - BUILDING MODELS USED IN THIS STUDY

7 building designs are used in this study. U6 and U20 are 6-story and 20-story steel moment-resisting frame (MRF) buildings designed by Hall (1997). The design of the lateral force-resisting system conforms to 1994 Uniform Building Code (UBC) seismic provisions for zone IV and site class C. U13 is a 13-story steel MRF building designed by the authors using the same seismic provisions (UBC 94). In this study, each steel frame building could have perfect welds (denoted with P) or brittle welds (denoted with B). A Fiber beam-column model is used to simulate the weld condition. Fibers in

perfect welds will never fracture during the dynamic simulation, while fibers in brittle welds will fracture at a random strain generated from the statistical distribution given by Hall (1997). ID1003, ID1011, ID1013 and ID1021 are reinforced-concrete (RC) special moment frame (SMF) buildings designed by Haselton (2006) according to ASCE7-02 (2002) and ACI318-02 (2002). The numbers of stories are 4, 8, 12 and 20, respectively. Detail information of the building models is listed in Table 7.1.

Table 7.1. Information of the building models

Building	No. of Stories	Material	T_1 (s)*	Max Strength **	ductility	Welds
U6P	6	Steel	1.54	0.2319	6.67	Perfect
U6B	6	Steel	1.54	0.1629	7.50	Brittle
U13P	13	Steel	2.63	0.1387	8.00	Perfect
U13B	13	Steel	2.63	0.0844	6.86	Brittle
U20P	20	Steel	3.47	0.1060	4.25	Perfect
U20B	20	Steel	3.47	0.0630	4.50	Brittle
ID1003	4	RC	1.12	0.1472	8.50	
ID1011	8	RC	1.71	0.0800	7.40	
ID1013	12	RC	2.01	0.0748	7.55	
ID1021	20	RC	2.36	0.0880	6.80	

*- Fundamental period

** - The maximum base shear in pushover analysis, normalized by seismic weight of the building

The steel frame buildings are modeled in Frame 2D programmed by Hall (1997) and the RC frame buildings are modeled in OpenSees. Considering different weld conditions, we have 10 building models in total and all of them are modeled in 2D space.

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