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SOLUTIONS TO THE SHORT-PERIOD BUILDING PERFORMANCE PARADOX

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Abstract

This paper presents a summary of the lessons learned from studies of the ATC-116 Project to investigate solutions to the short-period building seismic performance paradox – *Why do analytical models of code compliant designs predict high probabilities of collapse for short-period buildings contrary to damage observed in actual earthquakes and the judgement of earthquake engineers?* The ATC-116 Project, now in its sixth and final year, is being conducted by the Applied Technology Council (ATC) with funding provided by the Federal Emergency Management Agency.

The ATC-116 Project studies are: (1) investigating the major causes of the short-period building performance paradox; (2) improving, calibrating, and validating analytical modeling methods with observed performance of buildings in recent earthquakes and full-scale shake table building tests; and (3) developing practical recommendations for improving seismic design practice and requirements in building codes and standards. These studies have rigorously modeled and evaluated the earthquake collapse performance of the most common types of short-period residential and commercial buildings, including wood light-frame construction, typically used for single-family and multi-family dwellings, and reinforced-masonry shear wall and steel braced-frame buildings commonly used for commercial occupancies. The results of the study provide a better understanding of the seismic risk and resiliency of these types of short-period buildings which represent over 90 percent of the building inventory of the United States.

1. Introduction

This paper summarizes the approach, analyses, findings, and conclusions of a series of studies into the gaps between analytically predicted and historically observed earthquake-induced collapse rates of short-period buildings. The Applied Technology Council (ATC) was commissioned by the Federal Emergency Management Agency (FEMA) to conduct these studies as part of a multi-year project, *Developing Solutions to the Short-Period Building Seismic Performance Paradox.* Interim results of these studies were previously reported in a paper at the 11NCEE [1].

Short-period buildings, such as low-rise residential and commercial buildings, comprise a major portion of the building stocks in high-seismic-hazard communities in the United States. The gaps between analytically predicted and historically observed collapse rates of short-period buildings exist across many seismic-force-resisting systems and construction materials. Therefore, it is believed that the seismic performance of such buildings is not accurately predicted by current analytical models. Following a review of previous studies, available research results and data, the project team selected three structural systems to investigate: light-frame wood, reinforced masonry shear wall, and steel braced frame systems. The project also compared results from each of these studies to identify commonalities for the possible extension of the findings and conclusions to other construction materials and seismic-force-resisting systems.

Reports documenting project work are expected to be published in 2020 and will include the individual studies of wood light-frame buildings, reinforced masonry shear wall buildings, and steel braced frame buildings and a separate report on the commonalities found across the material-specific studies. Collectively, these four reports will provide a comprehensive evaluation of the collapse performance of short-period buildings.

2. Approach and Scope

At the time this study began, commercial buildings in the United States were designed in accordance with ASCE/SEI 7-10, *Minimum Design Loads for Buildings and Other Structures* [2], which was adopted by reference in the 2015 edition of the *International Building Code* (IBC) [3]. Design seismic loads in ASCE/SEI 7-10 are based on the risk-targeted maximum considered earthquake (MCE_R) ground motions, which were introduced in FEMA P-750, *NEHRP Recommended Seismic Provisions for New Buildings and Other Structures* [4]. Like other new buildings, short-period buildings that are designed and constructed in accordance with national design standards and codes (e.g., ASCE/SEI 7-10) are expected to meet the general seismic performance targets of these standards and codes, described in terms of not exceeding a specified percent probability of collapse given MCE_R ground motions. For reference, a collapse probability of 10 percent, given MCE_R ground motions, is the anticipated reliability in ASCE/SEI 7 for Risk Category II buildings, which constitute the vast majority of all buildings. Further, the use of MCE_R ground motions in building design is intended to provide a reasonable assurance of seismic performance for all buildings—regardless of building period, seismic-force-resisting system, or other characteristic—designed in accordance with the governing building code.

Studies conducted prior to the start of this project series, such as those described in NIST [5] used the methodology described in FEMA P-695, *Quantification of Building Seismic Performance Factors* [6], to evaluate the collapse performance of a large number of common current code-permitted seismic-force-resisting systems. While these studies found that many common seismic-force-resisting systems achieve the seismic performance target of not exceeding a 10 percent probability of collapse given MCE_R ground motions, these studies also found that most *short-period* buildings have a higher calculated probability of collapse than the 10-percent target. As shown in Fig. 1, for archetypes of structural systems with design periods less than about 0.5 seconds, the FEMA P-695 studies suggest that the probability of collapse given MCE_R ground motions increases significantly as the design period decreases and, in general, exceeds the 10-percent target. If the FEMA P-695 collapse results shown are accurate, then the aim of a reasonable assurance of seismic performance for all systems (at all periods) is not being achieved, and perhaps of greater significance, short-period buildings appear to exceed the 10-percent target of ASCE/SEI 7.

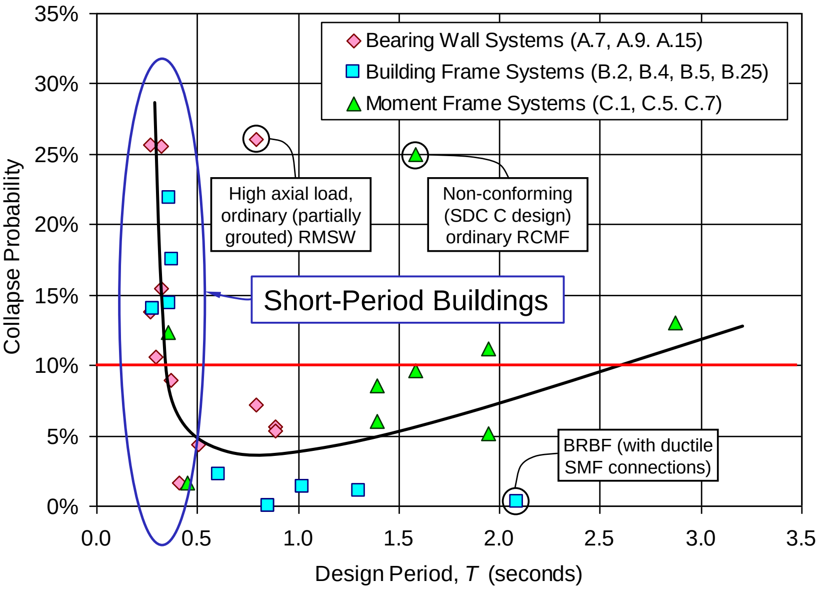

Fig. 1 - Trends in the probability of collapse of selected systems as a function of design period (NIST [5]).

However, trends in observed earthquake damage do not support the high collapse probabilities shown in Fig. 1, and the opinion of many structural engineers suggests that numerical models have overestimated the collapse risk of short-period buildings. For example, as is described in more detail in a later section, relatively few of the short-period buildings that received safety inspections after the 1994 Northridge earthquake were assigned a Red Tag or were observed to have collapsed. This observation does not mean that short-period buildings were not damaged in the 1994 Northridge earthquake; rather, the observation indicates that damage to these buildings was limited and did not cause collapse. This contrast between analytical prediction of collapse performance and the opinions and observations of structural engineers is the short-period building paradox addressed by the ATC-116 project.

Conceptually, the idea that short-period buildings perform worse in earthquakes than buildings with longer periods emerged long before the FEMA P-695 evaluations described in NIST [5]. Analytical studies dating to the 1960s and 1970s by Newmark, Veletsos and others [7] found the ratio of inelastic displacement to elastic displacement of simple, single-degree-of-freedom, numerical models to be period dependent and to increase as the periods of the numerical models shorten, implying worse collapse performance for short-period buildings. Thus, the seeds of the short-period building paradox were planted decades ago, but it is only now - with the advent of a standardized collapse evaluation methodology in FEMA P-695, with additional physical testing of structural elements and assemblies, with advanced numerical modeling techniques, and with the evolution of high-speed computer processing—that we can efficiently investigate and resolve the paradox.

Given this context, a goal of this project series was to improve analytical methods for short-period buildings by developing numerical models that more accurately capture response behavior and that predict collapse rates consistent with post-earthquake observations. The project series also sought to identify the causes of the differences between predicted collapse rates from prior P-695 studies and the collapse rates determined from post-earthquake observations. Finally, goals of this project series were to improve the current understanding of the seismic performance of short-period buildings and to provide recommendations to engineering practitioners and researchers based on this new understanding. Achieving these goals could have significant benefits, including enabling the development of more efficient and effective structural systems to resist seismic forces. A better understanding of the seismic performance of short-period buildings also could lead to improvements in building code provisions, engineering design, and seismic risk assessment methodologies.

3. Observed Response and Performance of Short-Period Buildings

An essential element of this project was the collection of data on short-period building response and collapse performance in past earthquakes, and laboratory tests. This information was used to establish "benchmark" behavior of short-period buildings for verification that numerical models accurately and reliably predict building response. Benchmark metrics include building dynamic response properties (e.g., fundamental period) obtained from instrumental records of wood light-frame building response during earthquakes [8], observations of building performance during shake table tests of full-scale wood buildings [9, 10] and reinforced-masonry buildings [11], and damage and collapse fragility functions determined from post-earthquake damage survey data, e.g., the 1994 Northridge earthquake data [12, 13]. Benchmarking of response, damage and collapse performance were a priority of the project to verify that the enhanced numerical modeling techniques developed during this stage can be used with confidence for implementation of practical solutions to the short-period building paradox.

The three key findings related to the observed collapse performance of short-period buildings are summarized below:

Collapse Failure Mode. In general, collapse was typically a result of P-Δ side-sway failure of the first-story (excluding collapse damage due to foundation failure). Full-scale shake table tests confirm this mode of failure.

Large Lateral Displacements at Incipient Collapse. Severe damage caused either by earthquake ground motions or shake table testing indicate large lateral displacements at the point of incipient collapse (e.g., first-story drift ratios of 10 percent, or greater).

Low Probability of Collapse for MCE$_R$ Ground Motions. Qualitatively, collapse of modern short-period buildings in past earthquakes has been relatively rare. Quantitatively, observed damage (i.e., Red-Tag data) to light-frame wood buildings in the 1994 Northridge earthquake was used to benchmark collapse rates given MCE$_R$ ground motions (i.e., 0.3-second response spectral acceleration of 1.5 g) of not more than 2 percent for one-story, and not more than 5 percent for two-story, or taller, buildings. Similar quantitative collapse rates could not be established specifically for modern reinforced masonry and steel braced frame buildings due to the dearth of collapse data for these buildings.

The relatively low Red Tag rates in the 1994 Northridge earthquake are in stark contrast to the approximate 150,000 buildings (of an estimated 800,000) buildings in the region affected by the 1995 Kobe earthquake that were found by the Architects Institute of Japan to have either severe structural damage or to have collapsed [14]. Differences in construction make direct comparison of building damage impossible, but it may be noted that about 90 percent of the severely damaged or collapsed buildings in the 1995 Kobe earthquake were located within 5 km of fault rupture where ground motions were significantly stronger than those of the 1994 Northridge earthquake.

3.1 Observed Collapse Rates (from 1994 Northridge Earthquake Red-Tag Data)

Red-Tag data from the 1994 Northridge earthquake were used as collapse surrogates to establish target MCE$_R$ collapse probabilities (for benchmarking analytical results). Figure 2 shows Red-Tag percentages (i.e., fraction of all wood buildings with a Red Tag) for each of 186 post-1960 census tracts with a total population of approximately 220,000 newer wood buildings plotted as a function of ground shaking intensity (0.3-second response spectral acceleration). Post-1960 census tracts have an average year of wood building construction of 1960, or later. An example statistic for one of the hardest hit census tracts (Census Tract 11520) shows 23 of 906 post-1960 wood buildings (2.5 percent) were assigned a Red Tag, one of which was the Northridge Meadows apartment complex (shown in photo insert). Sixteen of the 26 building-related fatalities in the 1994 Northridge earthquake were due to collapse of the Northridge Meadows apartment complex [13].

Red-Tag data are assumed to be a feasible reference for comparison of MCE$_R$ collapse probabilities. This assumption may overstate collapse risk since Red-Tag data also includes, to some degree, buildings with significant structural damage deemed to be life-threatening (even if there is no collapse). As such, the Red-Tag data may better represent the likelihood of complete structural damage (i.e., 100 percent financial loss) as characterized, for example, by a large amount of post-earthquake residual drift displacement (e.g., a story drift ratio of 2 percent, or greater) as well as by partial or full collapse of the building structure.

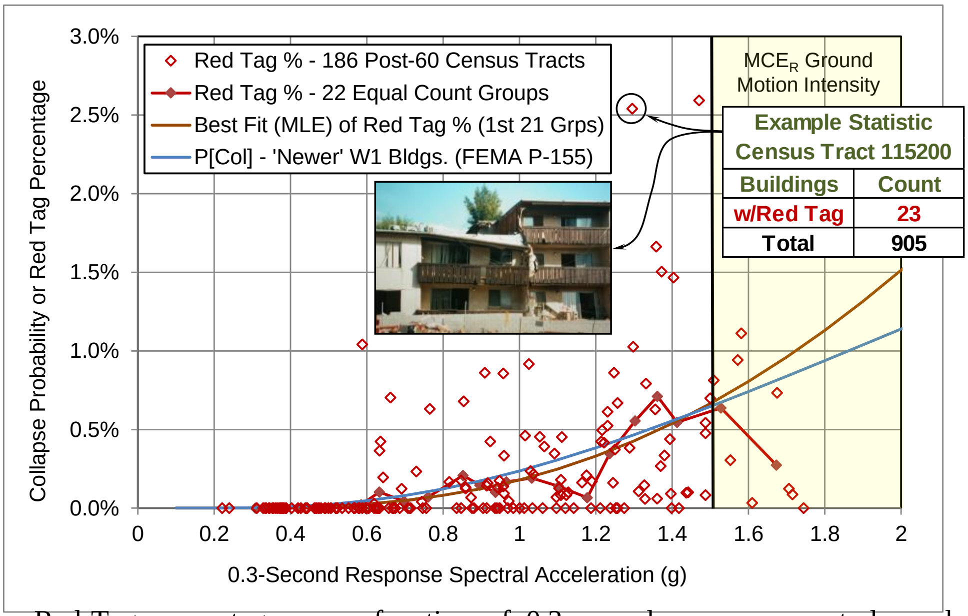

Fig. 2 - Red-Tag percentages as a function of 0.3-second response spectral acceleration developed from post-earthquake safety inspections of post-1960 wood buildings following the 1994 Northridge earthquake.

Also shown in Figure 2 are (1) a lognormal best-fit collapse fragility curve based on census-tract group Red-Tag percentages and (2) a theoretical collapse curve of Newer W1 buildings developed by the ATC-71-6 Project for updating the rapid visual screening procedures of FEMA P-155 [15]. The trend lines show about a 1 percent collapse rate, on average, at a 0.3-second response spectral acceleration of 1.5 g, suggesting a target (high seismic) MCE_R collapse rate of not more than 2 percent considering inherent uncertainties in the underlying data. The 2 percent target collapse rate applies to single-story wood buildings which dominate the Red Tag data. The Red Tag rate for 2-story, or taller, wood buildings was found to be about 2.5 times that of single-story wood buildings, on average, suggesting a target MCE_R collapse rate of not more than 5 percent for multi-story wood buildings. Target MCE_R collapse probabilities, based on Red-Tag percentages, represent building collapse that includes partial collapse as well as full collapse of the building structure, consistent with the ASCE/SEI 7-10 (and FEMA P-695) definition of collapse.

4. Wood Light-Frame Building Studies

To study wood light-frame buildings, the project team identified a suite of archetypes, with variations in use, height and seismic-design level. These archetypes are intended to represent code-compliant modern construction for common commercial office (COM), multi-family dwelling (MFD) and single-family dwelling (SFD) building occupancies that routinely adopt a wood light-frame structural system. The archetype design methods and details represent typical practice exercised in areas of significant seismicity using the normal standard of care. This seismic-force-resisting system is very common in high-seismic areas in the western United States. The SFD building archetypes were configured to meet either the design requirements of ASCE/SEI 7-10 [2] or the conventional construction requirements of the 2010 IRC [16] which are commonly used for most SFD residences. Figure 3 shows an isometric view of the 2-story high seismic MFD wood light-frame building archetype. In this figure, brown shading indicates structural walls of wood panel sheathing. Nonstructural walls (i.e., exterior and interior wall finishes of stucco, gypsum board, etc.) are also included in the modeling of baseline wood light-frame building archetypes.

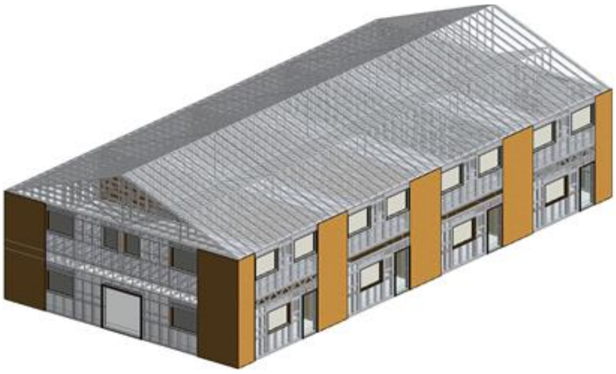

Fig. 3 - Isometric view of the 2-story high seismic MFD wood light-frame building archetype.

Three dimensional nonlinear models of wood light-frame archetypes were developed incorporating nonlinear properties of the walls based on the CUREE formulation of hysteretic properties [17] with properties based on related research, and analyzed using the structural analysis program Timber 3D [22]. Archetype strength and collapse performance were evaluated in accordance with the procedures of FEMA P-695 [10] with the notable modification that baseline archetypes were also designed and evaluated for “very high seismic” ground motions that are 50 percent stronger than the “high seismic” ground motions of FEMA P-695. The best estimate or typical properties of each modeling parameter were incorporated into baseline archetypes. A brief description and summary of key findings are provided below for the parametric study of baseline archetype configurations and the four additional parametric studies that investigated the effects on collapse performance of variant archetype configurations.

Baseline Configuration Parametric Study: investigated the response behavior and collapse performance of different heights and seismic design levels of baseline archetype models of short-period wood light-frame buildings. Table 1 summarizes key model properties and collapse results for each of the six COM, six MFD and eight SFD baseline archetypes of this study and Fig. 4 plots collapse probabilities of the ten high seismic baseline archetypes as a function of average overstrength (i.e., average X-axis and Y-axis overstrength).

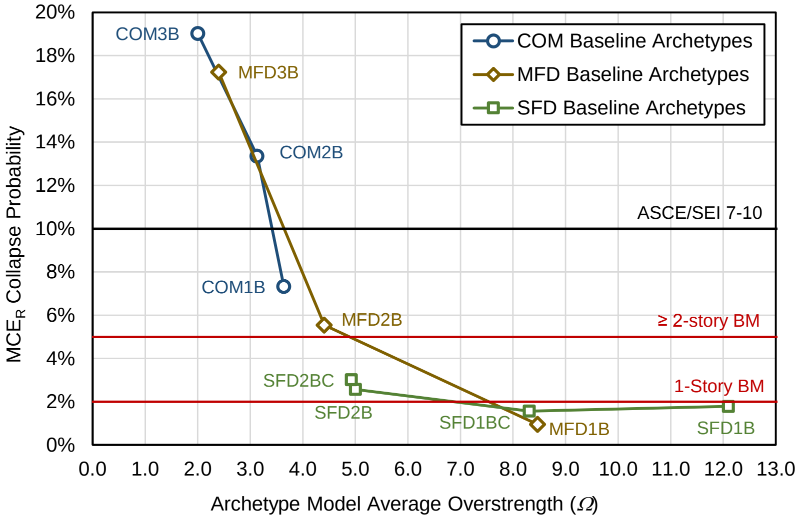

Fig. 4 - MCE$_R$ collapse probabilities of wood light-frame building high seismic baseline archetype models plotted as a function of average archetype model overstrength (Ω).

Key findings. In all cases, collapse was due to P-Δ failure at the 1st-story which is more critical for taller archetypes. 1-story and 2-story high seismic MFD and SFD baseline archetypes comply with collapse benchmarks; COM and 4-story MFD archetypes do not comply, and taller COM and MFD archetypes with overstrength less than about 4.0 also do not comply with the 10 percent collapse safety objective of ASC/SEI

7-10. As shown in Fig. 4, there is a strong correlation of collapse performance and archetype strength (overstrength) which explains the relatively poor collapse performance of the weaker COM and MFD archetypes. In all cases, collapse performance of very high seismic archetypes is appreciably worse than that of the corresponding high seismic archetype due primarily to their lower values of overstrength. Although the structural walls of the very high seismic archetypes were designed with 50 percent greater strength than those of the corresponding high seismic archetype, the strength of the nonstructural walls was the same such that the combined strength of structural and nonstructural walls of very high seismic archetypes was never 50 percent stronger than that of the corresponding high seismic archetype.

Table 1 - Summary of key properties and collapse results of baseline archetype models of wood light-frame buildings

Wood Light-Frame Building Archetype Model ID	Model Properties				Collapse Results				Benchmark Collapse Probability (%)
	No. of Stories	Period T_1 (sec)	Strength		Drift Ratio[1]		CMR_{3D}	P[COL|MCE$_R$] (%)	
			Ω	V_{max}/W	Roof	1st-Story			
Commercial Building High-Seismic (S_{MS} = 1.5 g) Baseline Archetype Models									
COM1B	1	0.29	3.6	0.56	0.082	0.082	1.55	7.3%	0 to 2%
COM2B	2	0.36	3.1	0.48	0.035	0.067	1.31	13.4%	0 to 5%
COM3B	4	0.58	2.0	0.31	0.016	0.046	1.15	19.0%	0 to 5%
Commercial Building Very High-Seismic (S_{MS} = 2.25 g) Baseline Archetype Models									
COM4B	1	0.28	2.9	0.67	0.088	0.088	1.15	19.0%	NA
COM5B	2	0.35	2.4	0.56	0.038	0.074	0.98	29%	NA
COM6B	4	0.52	1.9	0.44	0.020	0.058	0.98	29%	NA
Multi-Family Dwelling High-Seismic (S_{MS} = 1.5 g) Baseline Archetype Models									
MFD1B	1	0.19	8.5	1.30	0.071	0.071	2.43	1.0%	0 to 2%
MFD2B	2	0.28	4.4	0.68	0.046	0.091	1.67	3.3%	0 to 5%
MFD3B	4	0.51	2.4	0.37	0.0164	0.052	1.2	17.2%	0 to 5%
Multi-Family Dwelling Very High-Seismic (S_{MS} = 2.25 g) Baseline Archetype Models									
MFD4B	1	0.17	6.1	1.41	0.102	0.102	1.85	3.5%	NA
MFD5B	2	0.35	3.2	0.73	0.053	0.099	1.23	15.7%	NA
MFD6B	4	0.54	1.9	0.44	0.022	0.054	1.02	26%	NA
Single-Family Dwelling High-Seismic (S_{MS} = 1.5 g) Baseline Archetype Models									
SFD1B	1	0.16	12.1	1.86	0.022	0.022	2.15	1.8%	0 to 2%
SFD1BC	1	0.15	8.3	1.28	0.066	0.066	2.21	1.6%	0 to 2%
SFD2B	2	0.26	5.0	0.77	0.058	0.117	1.99	2.6%	0 to 5%
SFD2BC	2	0.25	4.9	0.76	0.049	0.096	1.92	3.0%	0 to 5%
Single-Family Dwelling Very High-Seismic (S_{MS} = 2.25 g) Baseline Archetype Models									
SFD3B	1	0.15	8.7	2.01	0.028	0.028	1.51	7.0%	NA
SFD3BC	2	0.16	5.5	1.28	0.066	0.066	1.47	8.6%	NA
SFD4B	1	0.26	3.8	0.87	0.055	0.148	1.48	8.4%	NA

1. Median drift ratio at incipient collapse.

Displacement Capacity Parametric Study investigated the effects displacement capacity on response behavior and collapse performance by varying the amount of post-capping residual strength (i.e., from the baseline amount of 30 percent of V_{max}) of 1-story and 2-story high seismic archetypes.

Key findings. Residual strength was found to significantly influence collapse performance of wood light-frame archetype models. The collapse results show a strong trend of lower collapse probabilities with increased collapse displacement capacity that correspond directly to increased post-capping residual strength.

Nonstructural Exterior and Interior Wall Finishes Parametric Study investigated the effects on response behavior and collapse performance of 2-story COM, 2-story MFD and 1-story and 2-story SFD high seismic baseline archetypes modeled without nonstructural exterior and interior wall finishes (i.e., collapse performance based only on the strength of the structural walls).

Key findings. Nonstructural wall finishes were found to significantly influence the collapse performance of wood light-frame building archetypes. In general, collapse probabilities of archetypes without nonstructural wall finishes do not meet collapse benchmarks and where their overstrength is less than about 4.0 also do not comply with the 10 percent collapse safety objective of ASCE/SEI 7-10.

Soil-Structure Interaction (SSI) and Foundation Flexibility Parametric Study investigated the influence of soil-foundation flexibility (inertial SSI effects) on collapse performance by replacing the rigid base of COM and MFD high seismic baseline archetypes with flexible footings supported by nonlinear soils springs and dampers.

Key findings. Modeling soil foundation flexibility was found to have a negligible influence on the collapse performance of wood light-frame building archetypes.

Backbone Curve Shape Parametric Study investigated the influence of the shape of the backbone curve of the nonlinear models of structural walls on response behavior and collapse performance by revising the 4-story COM high seismic baseline archetype to have two variant backbone curve shapes.

Key findings. Backbone curve shape was found to influence collapse performance of the wood-light frame building archetype, although collapse probabilities were found to be comparable for archetype models with backbone curves that have the same peak strength and displacement capacity (i.e., same residual strength).

Lessons Learned – Wood Light-Frame Buildings. The results of these numerical investigations provide valuable insights into the collapse performance of wood light-frame buildings that may be of importance to seismic code development committees and to the improvement of performance-based design methods. For example, nonstructural interior and exterior wall finishes are one of the main reasons that wood light-frame buildings have performed well in past earthquakes, although nonstructural wall finishes are not considered in the design of the seismic force-resisting system (SFRS). That is, good collapse performance in past earthquakes may be as much a function of nonstructural interior and exterior wall finishes as the structural elements of the designated wood light-frame SFRS.

5. Reinforced Masonry Building Studies

To study reinforced masonry buildings, the project team identified a suite of archetypes, with variations in height and seismic-design level. These archetypes are intended to represent code-compliant modern construction for common commercial office (COM) occupancies that routinely adopt a reinforced masonry structural system. The archetype design methods and details represent typical practice exercised in areas of significant seismicity using the normal standard of care. The seismic-force-resisting system for all archetypes is load-bearing, fully grouted, reinforced hollow-unit concrete masonry with cantilever shear walls. This seismic-force-resisting system is common in high-seismic areas in the western United States. Fig. 5 shows an isometric view of the 2-story high seismic COM reinforced masonry building archetype.

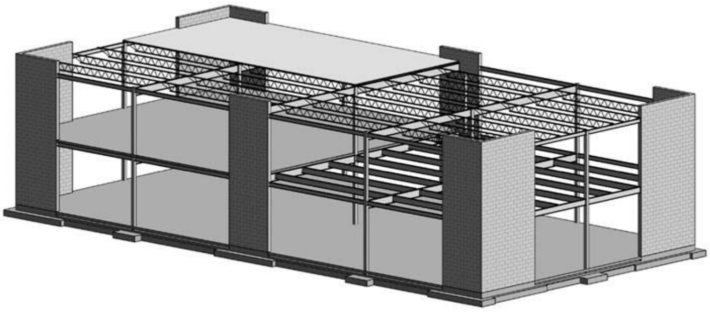

Fig. 5 - Isometric view of the 2-story high seismic COM reinforced masonry building archetype.

Three dimensional nonlinear models of reinforced masonry archetypes were developed using a two-step approach. First, for each building archetype, a refined finite element model was developed and analyzed using commercially available LS-DYNA software to determine pushover strength and dynamic response to selected earthquake records. Second, the results obtained were then used to calibrate computationally efficient frame models for incremental dynamic analysis (IDA) using the nonlinear structural analysis program OpenSEES [19]. Archetype strength and collapse performance were evaluated in accordance with the procedures of FEMA P-695 [6] with the notable modification that baseline archetypes were also designed and evaluated for "very high seismic" ground motions that are 50 percent stronger than the "high seismic" ground motions of FEMA P-695. The best estimate or typical properties of each modeling parameter were incorporated into baseline archetypes. A brief description and summary of key findings are provided below for the parametric study of baseline archetype configurations and the two additional parametric studies that investigated the effects on collapse performance of variant archetype configurations.

Baseline Configuration Parametric Study: investigated variation in the response behavior and collapse performance of different heights and seismic design levels of baseline archetype models of short-period reinforced masonry buildings. Table 2 summarizes key model properties and collapse results for each of the six COM baseline archetypes of this study.

Table 2. Summary of key properties and collapse results of baseline archetype models of reinforced masonry buildings

Reinforced-Masonry Building Archetype Model ID	Model Properties				Collapse Results				Benchmark Collapse Probability (%)
	No. of Stories	Period T_1 (sec)	Strength		Drift Ratio[1]		CMR_{3D}	P[COL|MCE$_R$] (%)	
			Ω	V_{max}/W	Roof	1st-Story			
High-Seismic (S_{MS} = 1.5 g) Baseline Archetype Models									
COM1B	1	0.14	5.6	1.11	0.086	0.086	3.35	0.14%	0 to 2%
COM2B	2	0.19	3.3	0.66	0.035	0.064	1.90	3.2%	0 to 5%
COM3B	4	0.31	2.4	0.47	0.015	0.058	1.43	9.9%	0 to 5%
Very High-Seismic (S_{MS} = 2.25 g) Baseline Archetype Models									
COM4B	1	0.14	4.0	1.19	0.089	0.089	2.42	1.0%	NA
COM5B	2	0.18	2.6	0.77	0.048	0.088	1.56	7.2%	NA
COM6B	4	0.25	2.3	0.68	0.021	0.084	1.46	9.4%	NA

Key findings. In all cases, collapse was due to wall failure at the 1st-story which is more critical for taller archetypes. 1-story and 2-story high seismic baseline archetypes comply with collapse benchmarks; the 4-story high seismic baseline archetype model does not, but this archetype model as well as all very high seismic baseline archetype models comply with the 10 percent collapse safety objective of ASC/SEI 7-10.

Displacement Capacity Parametric Study investigated the effects of displacement capacity on response behavior and collapse performance by varying the post-capping slope of the base shear versus first-story drift curve by plus/minus 30 percent.

Key findings. The displacement capacity was found to have noticeable influence on the collapse performance of reinforced masonry archetype models. The collapse results show a strong trend of lower collapse probabilities with increased collapse displacement capacity.

Soil-Structure Interaction (SSI) and Foundation Flexibility Parametric Study investigated soil-foundation flexibility (inertial SSI effects) by replacing the rigid base of the 2-story archetype model with flexible footings supported by nonlinear soils springs and dampers. Kinematic SSI effects were investigated by filtering records used for the nonlinear analyses to account for kinematic (base slab) averaging effects.

Key findings. Kinematic SSI effects were found to have a negligible influence on collapse performance. Soil=foundation flexibility was found to not significantly impact collapse performance, recognizing that collapse performance could be influenced by foundation flexibility for certain configurations of reinforced masonry archetype where lateral loads overcome gravity loads and cause uplift and rocking of foundations before the walls above fail.

Lessons Learned – Reinforced Masonry Buildings. Although the parametric studies of reinforced masonry buildings were limited in scope, the results of these investigations provide valuable insights into the collapse performance of reinforced masonry buildings that may be of importance to seismic code development committees and to the improvement of performance-based design methods. For example, the large lateral displacement capacity of the reinforced masonry building archetype models of this study (which is consistent with observed shake table test performance), as embodied in cutting-edge nonlinear finite element modeling of reinforced masonry walls, provides a rational basis for the observed good collapse performance of short-period reinforced masonry buildings in past earthquakes, highlighting the importance of considering the performance of a building system as a whole rather than a collection of individual walls.

6. Steel Braced Frame Building Studies

To study steel special concentrically braced frame (SCBF) buildings, the project team identified a suite of archetypes, with variations in height and seismic-design level. These archetypes are intended to represent code-compliant modern construction for commercial office occupancies (COM) that routinely adopt a steel SCBF seismic-force-resisting system. Other occupancies were not studied because occupancy is not believed to have a significant effect on the layout or design of this seismic-force-resisting system. The archetype design methods and details represent typical modern practice exercised in areas of significant seismicity using the normal standard of care. The seismic-force-resisting system for all archetypes is steel special concentrically braced frames, which is common in high-seismic areas in the western United States. Fig. 6 shows an isometric view of the 2-story high seismic commercial steel SCBF building archetype.

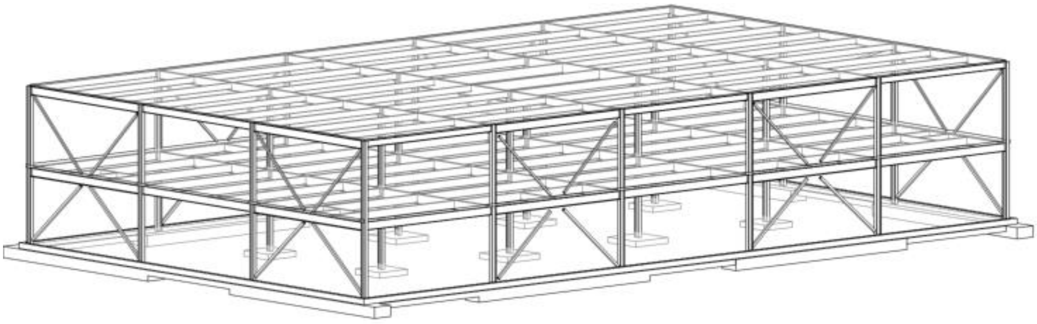

Fig. 6 - Isometric view of the two-story high seismic steel SCBF baseline archetype.

Three dimensional nonlinear models of steel SCBF archetypes were developed using recent research on simulating nonlinear response of SCBFs and analyzed using the nonlinear structural analysis program OpenSEES [19]. Archetype strength and collapse performance were evaluated in accordance with the procedures of FEMA P-695 [6] with the notable modification that baseline archetypes were also designed and evaluated for “very high seismic” ground motions that are 50 percent stronger than the “high seismic” ground motions of FEMA P-695. The best estimate or typical properties of each modeling parameter were incorporated into baseline archetypes. A brief description and summary of key findings are provided below for the parametric study of baseline archetype configurations and the four additional parametric studies that investigated the effects on collapse performance of variant archetype configurations.

Baseline Configuration Parametric Study: investigated variation in the response behavior and collapse performance of different heights and seismic design levels of baseline archetype models of short-period steel SCBF buildings. Table 3 summarizes key model properties and collapse results for each of the six COM baseline archetypes.

Key findings: In all cases, collapse is due to P-Δ failure of 1st-story braces. High seismic baseline archetypes generally comply with collapse benchmarks, but the 2-story and 4-story very high seismic archetypes do not meet the 10 percent collapse safety objective of ASCE/SEI 7-10. Collapse performance is related to both strength and displacement capacity of the steel SCBF building archetype models.

Table 3 - Summary of key properties and collapse results of baseline archetype models of steel SCBF buildings

Steel SCBF Building Archetype Model ID	**Model Properties**				**Collapse Results**				**Benchmark Collapse Probability (%)**
	No. of Stories	**Period T_1 (sec)**	**Strength**		**Drift Ratio[1]**		**CMR_{3D}**	**$P[COL \mid MCE_R]$ (%)**	
			Ω	**V_{max}/W**	**Roof**	**1st-Story**			
High Seismic (S_{MS} = 1.5 g) Baseline Archetype Models									
COM1B	1	0.17	11.0	1.92	0.030	0.030	2.32	1.2%	0 to 2%
COM2B	2	0.27	6.0	1.01	0.033	0.051	1.87	3.4%	0 to 5%
COM3B	4	0.47	3.9	0.66	0.032	0.065	1.83	6.0%	0 to 5%
Very High Seismic (S_{MS} = 2.25 g) Baseline Archetype Models									
COM4B	1	0.16	9.0	2.34	0.058	0.058	1.77	4.0%	NA
COM5B	2	0.25	4.2	1.10	0.022	0.035	1.14	20%	NA
COM6B	4	0.44	2.9	0.74	0.034	0.075	1.21	19%	NA

1. Median drift ratio at incipient collapse.

Brace Configuration Parametric Study: investigated the effects of substituting chevron bracing for the super X-bracing of the 2-story and 4-story high seismic baseline archetype models.

Key findings: The collapse probability of the 2-story model with chevron bracing (6.0%) is roughly consistent with that of the 2-story baseline model; the collapse probability of the 4-story model with chevron bracing (21%) is significantly greater than that of the 4-story baseline model with super X-bracing (due to the unintended consequences of SCBF design) and does not meet the 10 percent collapse safety objective of ASCE/SEI 7-10.

Redundancy Parametric Study: investigated the effects of redundancy on response behavior and collapse performance by reconfiguring the 2-story high seismic baseline model to have only one (non-redundant) bay of bracing on each side of the model.

Key findings: The collapse probability of the model with non-redundant bracing (11.1%) was significantly greater than that of baseline model with redundant bracing. Although designed for 30 percent more base shear ($\rho = 1.3$), the strength of the model with non-redundant bracing was actually less than that of the baseline model with redundant bracing (due to the unintended consequences of SCBF design).

Soil-Structure Interaction (SSI) and Foundation Flexibility Parametric Study: investigated soil-foundation flexibility (inertial SSI effects) by replacing the rigid base of 2-story and 4-story baseline archetype models with flexible footings supported by nonlinear soils springs and dampers. Kinematic SSI effects were investigated by filtering records used for the nonlinear analyses to account for kinematic (base slab) averaging effects.

Key findings: Kinematic SSI effects were found to have a negligible influence on collapse performance. In contrast, collapse performance was significantly influenced by soil-foundation flexibility. Although collapse probabilities of the archetypes modeled with a flexible base were found to be comparable to those of the baseline archetypes with a rigid base, the collapse failure mode was entirely different. In both cases, collapse was due to P-Δ failure. However, rather than 1st-story brace failure, the archetypes modeled with flexible foundation overcame gravity loads, uplifted and rocked before brace failure could occur.

Reserve Moment Frame Parametric Study: investigated the effects of the reserve moment frame action within the braced frames on response behavior and collapse performance by eliminating the moment capacity of the beams at the gusset plate edges, the collector connections within the braced frames, and the column base connections within the braced frames of the 2-story baseline model.

Key findings: The collapse performance of the archetype model without reserve moment frame action was found comparable to that of the baseline model. In these models, the bracing was quite strong and the additional strength provided by reserve moment action increased model strength by only about 15 percent. Reserve moment frame action would be expected to be more influential for steel SCBFs with weaker braces.

Lessons Learned – Steel Braced Frame Buildings

Although the parametric studies of steel SCBF buildings were limited in scope, the results of these investigations provide valuable insights into the collapse performance of steel SCBF buildings that may be of importance to seismic code development committees and to the improvement of performance-based design methods. For example, foundation uplift (prior to brace failure) was found to significantly affect the response behavior and collapse failure mode of certain configurations of steel SCBF buildings (although the collapse performance was also found to be comparable whether governed by lateral instability due to rocking of braced frames or due to the failure of the bracing).

7. Conclusion

With respect to resolving the short-period building performance paradox that the results of prior FEMA P-695 collapse evaluations of numerical models of structural systems designed in accordance with ASCE/SEI 7-10 seem contrary to the judgment of engineering practitioners and observed earthquake damage, the collective findings of the parametric studies of short-period wood light-frame, reinforced masonry and steel SCBF buildings are clear. With improved numerical models of truly representative building archetypes, there is no paradox for short-period buildings with respect to collapse performance. Results of nonlinear analyses of the improved numerical models of short-period wood light-frame, reinforced masonry and steel SCBF buildings, designed and evaluated for high seismic loads (S_{MS} = 1.5 g), show low collapse probabilities for MCE$_R$ ground motions consistent with those observed in past earthquakes (e.g., low rates of Red-Tag postings to wood buildings after the 1994 Northridge earthquake).

In general, modern short-period buildings have performed well in United States earthquakes, recognizing that there is essentially no experience with the collapse performance of modern short-period buildings where recorded ground motions are significantly greater than the high seismic ground motions of this study (i.e., S_{MS} = 1.50 g). Results of nonlinear analyses of the same improved numerical models of short-period buildings, designed and evaluated for very high seismic loads (S_{MS} = 2.25 g) show, in general, collapse probabilities for MCE$_R$ ground motions that are substantially greater than those of the high seismic analyses and, in some cases, do not comply with the 10 percent collapse safety objective of ASCE/SEI 7-10 (e.g., where the overstrength of archetype model is less than about 4.0).

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