Title
Application of the US Resiliency Council Seismic Rating Procedure to Two Dual System Tall Buildings Designed by Alternative Means

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Publication Date
2016

Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA

Los Angeles

Application of the US Resiliency Council Seismic Rating Procedure to Two Dual System Tall Buildings Designed by Alternative Means

A thesis submitted in partial satisfaction

of the requirements for the degree Master of Science

in Civil Engineering

by

Sijin Wang

2017

ABSTRACT OF THE THESIS

Application of the US Resiliency Council Seismic Rating Procedure to Two Dual System Tall Buildings Designed by Alternative Means

by

Sijin Wang

Master of Science in Civil Engineering

University of California, Los Angeles, 2017

Professor Henry J. Burton

This study is focused on assessing the seismic resilience of two 42-story reinforced concrete dual system tall buildings designed by different methods. A systematic rating approach based on the United States Resiliency Council (USRC) Seismic Rating procedure is used as the resilience metric. The two buildings were developed as part of the Pacific Earthquake Engineering Research (PEER) Institute’s Tall Building Initiative (TBI) project. Both buildings were designed based on an assumed site location in Los

Angeles, California. One variant was designed using prescriptive code provisions and the second using the Los Angeles Tall Building Structural Design Council (LATBSDC, 2008) Guidelines. The Seismic Performance Prediction Program (SP3) is used to perform the building rating analysis based on the FEMA P-58 methodology (FEMA, 2012). Ratings are established for the three categories of performance including safety, repair cost and functional recovery time. The results showed that both buildings achieve ratings of five and two stars for the safety and recovery dimensions respectively. However, for damage dimension, 2A gets a four stars rating while 2B has a five stars rating. At the design basis earthquake (*DBE)* level, the mean repair cost normalized by the building replacement value is 5.57% for the code-based building and 4.01% for the *LATBSDC* building. However, at the *MCE* level, the repair costs for the *LATBSDC* building (20%) is about 18% higher than that of the code-based building (17%). This result is explained by the fact that the residual drift demands are significantly higher in *LATBSDC* building and dominates the losses at the *MCE* level. For both buildings, the *REDi* recovery time is dominated by impeding factors which account for more than 75% of the functional recovery time.

The thesis of Sijin Wang is approved.

Scott J. Brandenberg

Thomas Sabol

John W. Wallace

Henry J. Burton, Committee Chair

University of California, Los Angeles
2017

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1. Introduction

For the most part, seismic design codes and guidelines are established with the intent of ensuring life safety in the event of large magnitude earthquakes. However, events like the 2010-2011 Canterbury earthquake sequence have highlighted the critical role of building performance in minimizing the impact on community functionality. While the February 22, 2011 event resulted in a low (relatively speaking) number of fatalities, the central business district was severely disrupted. In the hours immediately following the earthquake, local authorities cordoned off 114 square blocks of the downtown area, eventually reducing the zone to 75 blocks ten days later. This was largely due to the risk of aftershock collapse and falling debris from several mid- and high-rise buildings, which were extensively damaged and subsequently slated for demolition. Moreover, local authorities mandated the closure of surrounding streets during the demolition of these buildings (EERI, 2011).

As demonstrated in the Canterbury earthquake sequence, the physical size and concentration of people and services in tall buildings is such that their seismic performance has strong implications to the resilience of the urban environments that they occupy. As such, an explicit quantification of their seismic performance is crucial to understanding their role in ensuring continued functionality of large city centers following a hazard event.

The performance-based earthquake engineering (*PBEE)* framework provides an alternative to the prescriptive design approach of the building code. Following the development of the *PBEE* methodology, several efforts have been directed towards advancing the implementation of performance-based design of tall buildings in structural engineering practice. One such initiative was the Pacific Earthquake Engineering Research (*PEER)* Center Tall Buildings Initiative (*TBI).* As part of the *TBI* project, three different tall building types (concrete core only, concrete core with reinforced concrete moment frame and steel buckling-restrained braced frame system) were designed using three different approaches including building code prescriptive procedures, the *LATBSCD* (2008) and the *TBI* (2010) draft guidelines. The study included probabilistic seismic hazard analysis and ground motion selection for the building site which is located in Los Angeles, California, structural modeling and response simulation and loss assessment studies that estimated repair costs for future earthquakes.

Another initiative that is focused on meeting the challenge of developing earthquake resilient communities is the United States Resiliency Council (*USRC*) Building Rating System for Earthquake Hazards. By providing a means of quantifying risk, the *USRC* rating system is intended to increase the economic value of buildings designed to higher seismic standards using performance- or resilience-based methods. The current study is focused on applying the *USRC* Seismic Rating to two of the design variants of the 42-story reinforced concrete building developed as part of the *TBI* project including the prescriptive code (code-based) and *LATBSCD* (performance-based) procedures. The Seismic Performance Prediction Program (*SP3)* is used to conduct the building rating analysis based on the FEMA P-58 methodology (FEMA, 2012). Ratings are established for the three categories of performance including safety, repair cost and functional recovery time. However, the aim of this paper is more than to give rating levels of two buildings, the author intended to come up with key design parameters improving performance of structure as well.

2. Description of Case Buildings

2.1 Building Design

The study buildings are assumed to be located at a site in Los Angeles at the longitude = -118.25, latitude = 34.05. The site class of this location is C. Each of the building has 42 stories, all of which are 10.5 feet in height, except for the first story which is 13.67 feet. There are four basement levels and a penthouse at the roof level. The core walls are L-shaped and are connected with coupling beams. An isometric view and plan layout are shown in Figure 1 and Figure 2 respectively. Twelve inches thick reinforced concrete is used for the ground floor slab and 8 inches thick post-tension concrete is used above the floor. There are two 4-bay special moment resisting frames (SMRFs) in each direction of two buildings.

The first variant (identified as Building2A in TBI, 2010) was designed using provisions of the IBC 2006 building code provision, which is based on the criteria of ASCE 7-05 and ACI 318-08. A 5% damped response spectrum was used to obtain the seismic demands. The first, second and third mode periods are 4.46 seconds, 4.03 seconds, 2.48 seconds respectively. For building 2A, the core wall thickness is 24 inches from foundation to 20^{th} floor and 18 inches above 20^{th} floor. The depth of coupling beams is 30 inches at all floors. Building 2A uses 6000 psi concrete strength from foundation to 20th floor and 5000 psi in the floors above. All special moment beams are 30 inches wide and 26 inches deep and all special moment columns frames are 36 inches square in cross section.

Building 2B was designed using the 2008 LATBSDC Guidelines. The period of building 2B is 4.28 seconds for the first mode, 3.88 seconds for the second mode and 2.439 seconds for the third mode. For building 2B, the core wall thickness is 24 inches from foundation to 20th floor and 18 inches from 20th floor to 30th floor and 16 inches above the 30th floor. Building 2B uses 8000 psi specified concrete strength from foundation to the 20th floor and 6000 psi from the 20th to 30th floor and 5000 psi above the 30th floor. The yield strength of the steel reinforcement used in the two buildings is 60 ksi. For both buildings, the expected concrete strength is taken to be 1.3 times the design concrete strength and the expected yield strength of the steel reinforcing is taken to be 1.17 times the design reinforcing strength. Building 2B has less reinforcement in the special moment frame beams and corner columns compared to 2A. Moreover, the amount of boundary reinforcement in the core wall of Building 2B is also reduced compared to 2A.

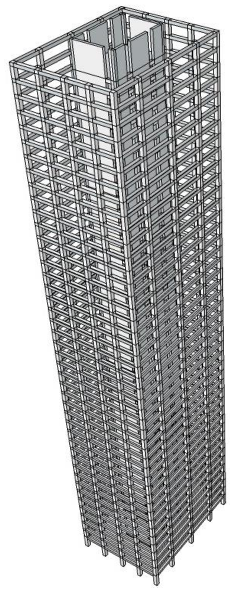


Figure 1 Isometric view of dual moment frame system

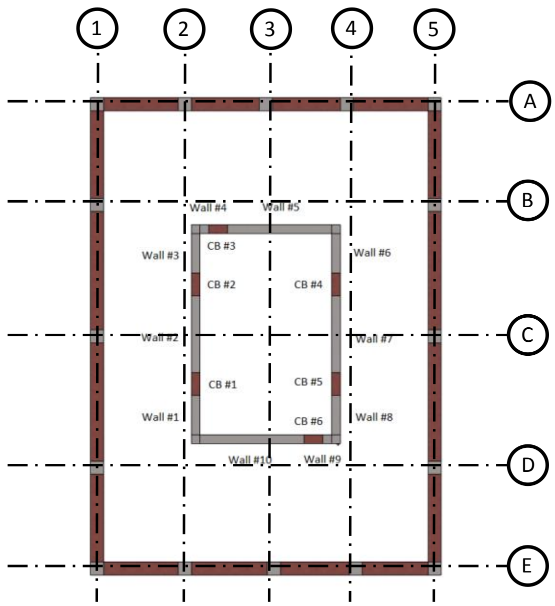


Figure 2 Plan layout of dual moment frame system

2.2 Building Analysis EDPs

The USRC Seismic Rating assessment is performed with the SP3 software tool using the user-defined engineering demand parameters (EDPs). Three-dimensional structural models of the lateral force resisting system (gravity system not included) of the tower (basement levels not included) were constructed and analyzed in OpenSees (Mazzoni et al. 2007) by Yu Zhang (PhD Student in UCLA Structural/Earthquake Engineering program). A rigid diaphragm is incorporated at all suspended floor levels by constraining the horizontal translational degrees of freedom. The seismic mass is lumped at the center of mass at each floor. Expected gravity loads (D + 0.25L) are used in the model. A leaning column is used to account for P-Delta effects resulting from the expected loads on the gravity system. The leaning column is axially rigid, has no lateral stiffness and the horizontal translational degrees of freedom of the end nodes are constrained to the floor nodes. The core walls and moment frame columns are fixed at the base.

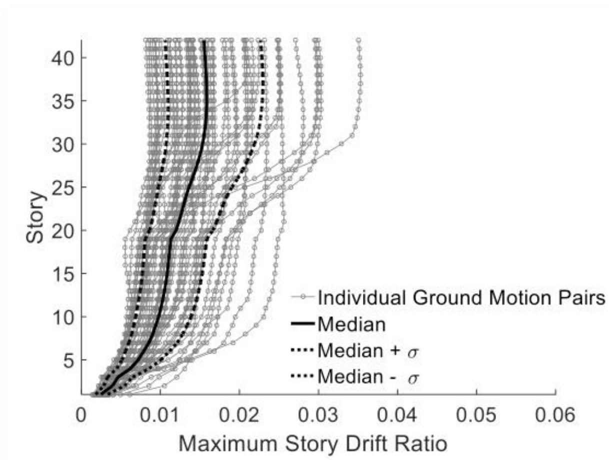
The moment frame elements and coupling beams are defined using elastic beam-column elements with flexural plastic hinges at the ends. The nonlinear behavior of the flexural hinges in the frame beams and columns is based on the Ibarra et al. (2005) peak oriented hysteretic model and the predictive equations developed by Panagiotakos et al. (2001) and Haselton et al. (2008) are used to obtain the backbone parameters. For the coupling beams with diagonal reinforcement, the flexural hinge parameters are based on test results by Naish et al. (2009). A multi-layer shell element (Lu et al., 2015) is used to capture the non-linear behavior of core walls. The cover concrete, confined concrete and vertical and horizontal web reinforcement are modeled using equivalent orthogonal shell layers. The constitutive relation of the concrete material is modeled based on (Loland, 1980) and (Mazars, 1986), and Giuffre-Menegotto-Pinto

(Filippou, 1983) model with isotropic strain hardening is used for steel material. The confinement effects, including increase in strength and ductility of the core concrete, are incorporated using the relations suggested by Mander et al. (1988).

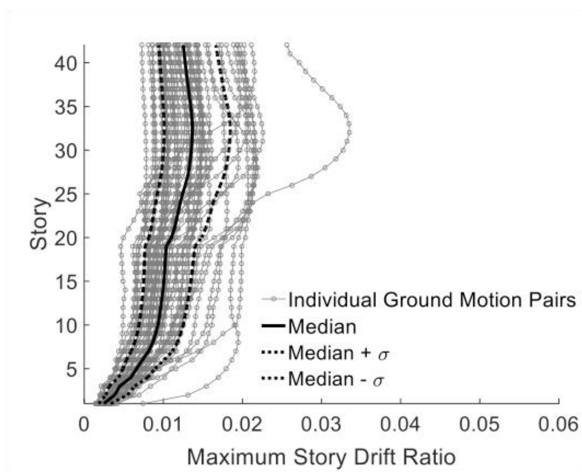
The *EDPs* needed for the SP3 analyses include the peak transient and residual drifts, peak floor accelerations and chord rotations for the shear wall and coupling beams chord rotations. Three sets of analyses are performed: two intensity-based analyses with the ground motions scaled to match the 1st mode period spectral acceleration associated with the 10% in 50-year and 2% in 50-year hazard levels and incremental dynamic analyses (IDA) to collapse. The results from the IDAs are compared with the collapse results obtained using the FEMA 154 approach, which is for the *USRC* rating.

For the purposes of reporting the results of the nonlinear response history analyses and FEMA P-58 assessment, the transverse direction will be referred to as the X-Direction and the longitudinal, the Z-Direction. Figure 3 shows the maximum story drift profile in the X-Direction of Building 2A for the individual ground motion pairs scaled to the design basis earthquake (DBE) (10% in 50-year) and maximum considered earthquake (MCE) (2% in 50-year) spectral acceleration levels. Two analyses are conducted for each ground motion pair by switching the orthogonal direction of each of the motions. The median maximum story drift profile for the two building cases subjected to the *DBE* and *MCE* level ground motions are shown in Figure 4. For both buildings, the drift demands are generally higher in the X-Direction. For example, at the *MCE* level, the median peak drift in the X-Direction of Building 2A is 1.6% (occurring at the 33rd

story) compared to 1.4% (occurring at the 32nd story) in the Z-Direction. The drift demands in Building 2A are generally higher than Building 2B, particularly at the upper stories. At the *MCE* hazard level, the median peak drift in the X-Direction is 1.4% in Building 2B compared to 1.6% in Building 2A. In the Z-Direction, the *MCE* level median peak drift demand is 1.4% and 1.1% in Buildings 2A and 2B respectively. The story drift demands are used to assess damage to several of the deformation-sensitive structural and non-structural components including the gravity and frame beams and columns, interior partitions and exterior cladding.

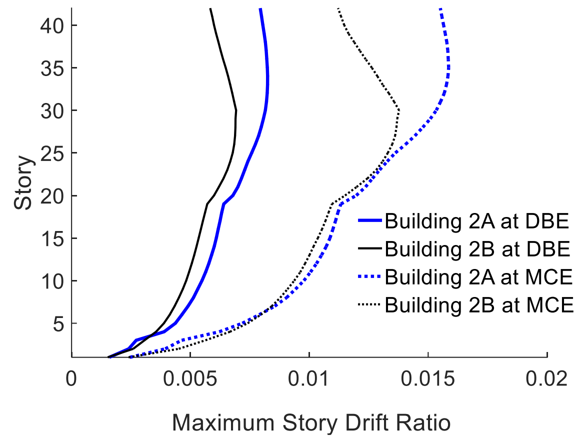


(a)

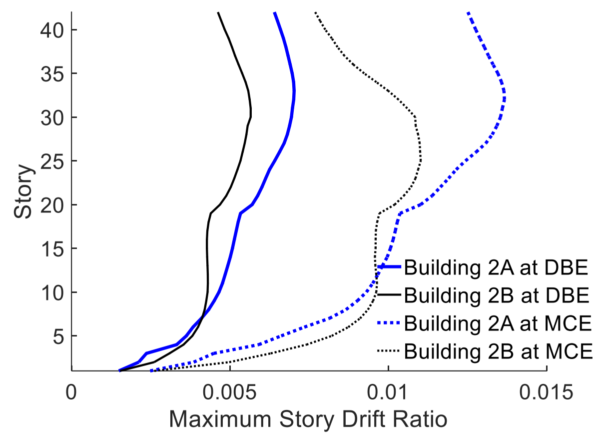


(b)

Figure 3 Maximum story drift profile for Building 2A in the X-Direction for individual ground motion pairs scaled to the (a) DBE and (b) MCE hazard levels



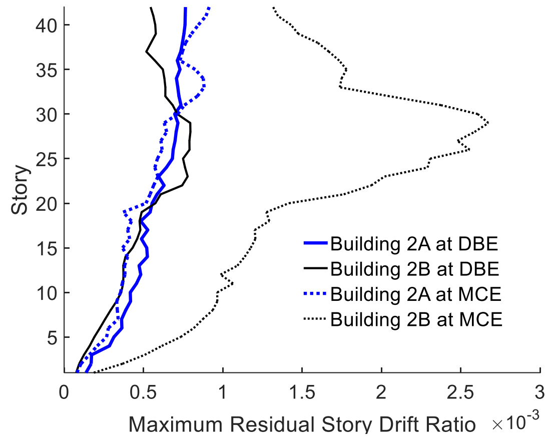
(a)



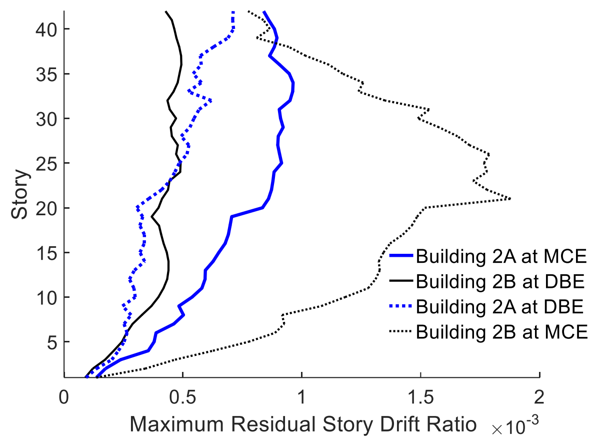
(b)

Figure 4 Median of maximum story drift profile for Buildings 2A and 2B in the (a) X- and (b) Z-Directions for ground motion pairs scaled to the DBE and MCE hazard level

The maximum residual drift demands shown in Figure 5 are relevant to considering the impact of demolition on repair costs and recovery times. The USRC Rating procedure requires that the effect of residual drifts be considered in cases where any of the star ratings is greater than 3. Figure 5 shows that residual drift demands are generally higher in Building 2B. At the MCE hazard level, the median peak residual drift in the X-Direction is 0.27% in Building 2B and 0.09% in Building 2A. This is likely the result of the reduced core wall reinforcement in Building 2B.



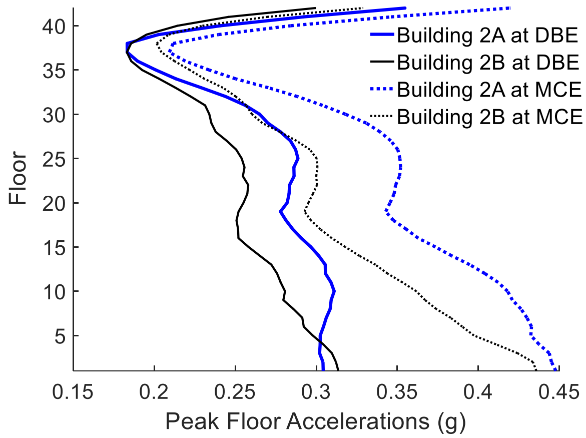
(a)



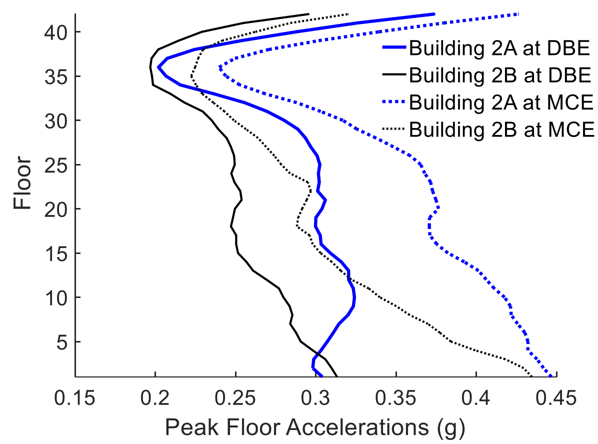
(b)

Figure 5 Median of maximum residual story drift profile for Buildings 2A and 2B in the (a) X- and (b) Z-Directions for ground motion pairs scaled to the DBE and MCE hazard level

Peak floor accelerations are used to simulate damage to acceleration sensitive non-structural components and contents such as ceiling tiles and plumbing lines. Figure 6 shows the median profile of peak floor accelerations for the two building cases. For both buildings, the magnitude and profile of the peak floor accelerations are almost identical in the two orthogonal directions. The demands are generally higher in building 2A.



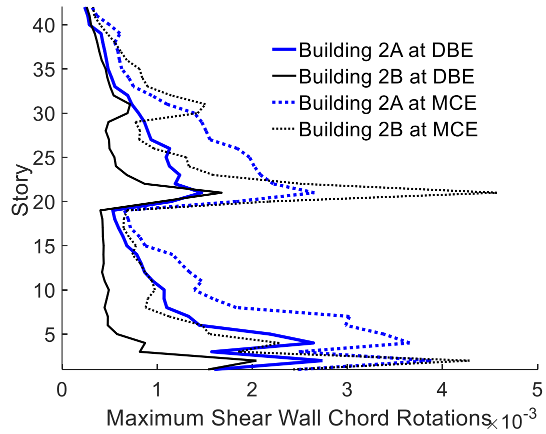
(a)



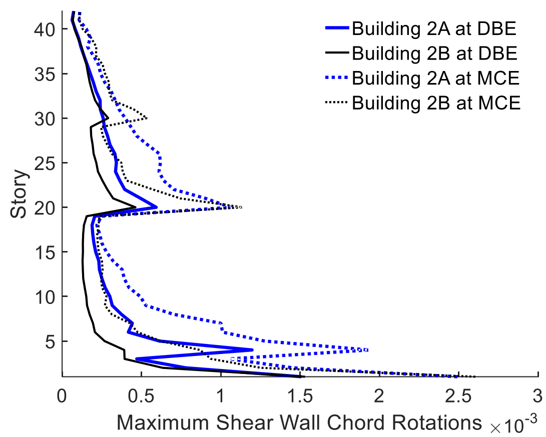
(b)

Figure 6 Median of maximum peak floor acceleration for Buildings 2A and 2B in the (a) X- and (b) Z-Directions for ground motion pairs scaled to the DBE and MCE hazard level

Chord rotations are used to assess damage in the shear wall. The median maximum chord rotation profiles for core walls 5 (X-Direction) and 7 (Z-Direction), which are identified in Figure 1b, are presented in Figure 7. The median chord rotation profiles are generally comparable for the two buildings. For example, in the X-Direction, the median maximum chord rotation at the *MCE* hazard level is 0.0039 for Building 2A and 0.0045 for Building 2B.



(a)

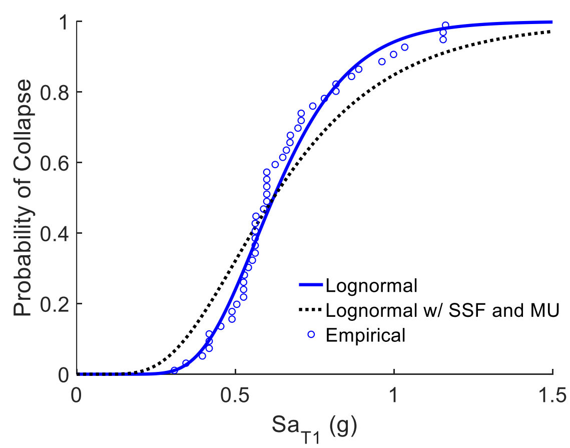


(b)

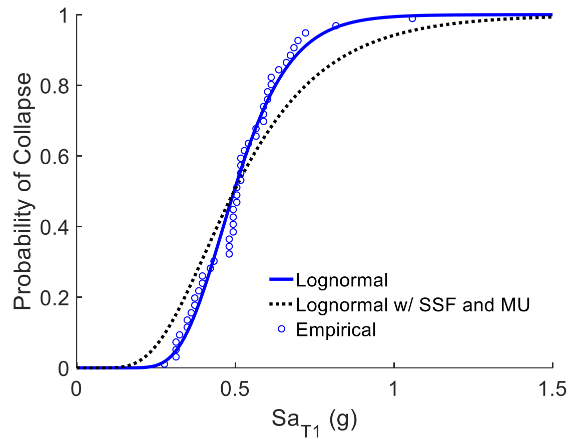
Figure 7 Median of maximum chord rotation profile in shear walls (a) 5 (X-Direction) and (b) 7 (Z-Direction)

The collapse safety of the two building cases is assessed using incremental dynamic analyses, where each ground motion pair is scaled until the collapse point is reached (10% drift is exceeded). The 48 pairs of ground motions are scaled such that their geometric mean match the target intensity. As noted earlier, two analysis cases are used for each record pair by switching the orthogonal direction of the ground motions. Figure 8 shows the collapse fragility curves obtained from Incremental Dynamic Analysis including the effect of spectral shape (*SSF*) and modeling uncertainty (*MU*). The median collapse capacity for Buildings 2A and 2B are 0.6 g and

0.5 g respectively and the record-to-record variation is approximately 0.45 for both buildings. The probability of collapse at the *MCE* spectral acceleration (0.20 g) is 0.0073 and 0.021 for Buildings 2A and 2B respectively. Figure 9 shows the collapse fragility curves from *IDAs* overlaid with those obtained using the FEMA 154 checklist. It shows that the *IDA* collapse results are conservative compared to the FEMA 154 results. For example, the median collapse capacity of Building 2A obtained from the FEMA 154 checklist approach is almost twice that (1.35g) computed from the *IDAs*. It should be noted that the relative difference in the collapse performance of the two buildings is not captured by the FEMA 154 checklist. Using the *IDA* approach, there is a 20% difference in the median collapse capacity of Buildings 2A and 2B. The difference is only 2% when the FEMA 154 checklist is used.



(a)



(b)

Figure 8 Collapse fragility curves from incremental dynamic analysis including the effects of spectral shape factor (SSF) and modeling uncertainty (MU) for (a) Building 2A and (b) Building 2B

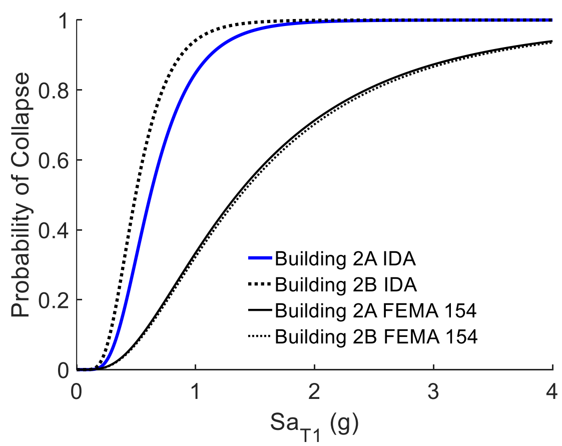


Figure 9 Collapse fragility curves from incremental dynamic analysis (including *SSF* and *MU*) and FEMA 154 checklist for Buildings 2A and 2B

2.3 Building components

The normative quantities of structural and non-structural components are defied in FEMA P-58. The fragility curves are assumed to take on a lognormal distribution. Story drift ratio (SDR), peak floor acceleration (PFA), coupling beam rotation (CBR) and wall chord rotation (WCR) are the four demand parameters that are considered for two buildings. The fragility parameters for structural components and non-structural components are summarized in Tables 1 and 2 respectively.

Table 1 Components Fragility of Building 2A and Building 2B

Structural Component												
Fragility ID	Fragility Name	Fragility Quantity	Fragility Location	Fragility Direction	Demand Parameter	Damage State					
						DS1		DS2		DS3	
						Median	Dispersion	Median	Dispersion	Median	Dispersion
B1041.013a	MF with SMF-conforming beam and column flexural and confinement reinforcement but weak joints , Conc Col & Bm = 36" x 36", Beam one side	4	All Stories	Direction 1	SDR	0.02	0.4	0.025	0.3	0.04	0.3
B1041.013a	MF with SMF-conforming beam and column flexural and confinement reinforcement but weak joints , Conc Col & Bm = 36" x 36", Beam one side	4	All Stories	Direction 2	SDR	0.02	0.4	0.025	0.3	0.04	0.3
B1041.013b	MF with SMF-conforming beam and column flexural and confinement reinforcement but weak joints , Conc Col & Bm = 36" x 36", Beam both sides	4	All Stories	Direction 1	SDR	0.02	0.4	0.025	0.3	0.04	0.3
B1041.013b	MF with SMF-conforming beam and column flexural and confinement reinforcement but weak joints , Conc Col & Bm = 36" x 36", Beam both sides	4	All Stories	Direction 2	SDR	0.02	0.4	0.025	0.3	0.04	0.3

Structural Component											
B1049.031	Post-tensioned concrete flat slabs- columns with shear reinforcing 0	24	All Stories	Direction1+2	SDR	0.028	0.5	0.04	0.5		
B1044.101	Slender Concrete Wall, 18" thick, 12' high, 15' long	0.74	All Stories	Direction 2	WCR1	0.0084	0.5	0.012	0.45	0.019	0.5
B1044.101	Slender Concrete Wall, 18" thick, 12' high, 15' long	0.74	All Stories	Direction 2	WCR1	0.0084	0.5	0.012	0.45	0.019	0.5
B1044.101	Slender Concrete Wall, 18" thick, 12' high, 15' long	0.74	All Stories	Direction 2	WCR1	0.0084	0.5	0.012	0.45	0.019	0.5
B1044.101	Slender Concrete Wall, 18" thick, 12' high, 15' long	1.11	All Stories	Direction 2	WCR2	0.0084	0.5	0.012	0.45	0.019	0.5
B1044.101	Slender Concrete Wall, 18" thick, 12' high, 15' long	0.74	All Stories	Direction 2	WCR3	0.0084	0.5	0.012	0.45	0.019	0.5
B1044.103	Slender Concrete Wall, 18" thick, 12' high, 30' long	2.06	All Stories	Direction 1	WCR4	0.0084	0.5	0.012	0.45	0.019	0.5
B1044.101	Slender Concrete Wall, 18" thick, 12' high, 15' long	0.74	All Stories	Direction 2	WCR6	0.0084	0.5	0.012	0.45	0.019	0.5
B1044.101	Slender Concrete Wall, 18" thick, 12' high, 15' long	1.11	All Stories	Direction 2	WCR7	0.0084	0.5	0.012	0.45	0.019	0.5
B1044.101	Slender Concrete Wall, 18" thick, 12' high, 15' long	0.74	All Stories	Direction 2	WCR8	0.0084	0.5	0.012	0.45	0.019	0.5
B1044.103	Slender Concrete Wall, 18" thick, 12' high, 30' long	2.06	All Stories	Direction 1	WCR9	0.0084	0.5	0.012	0.45	0.019	0.5

Structural Component											
B1051.021b	Concrete link beam, diagonally reinforced, aspect ratio between 2.0 and 4.0, beam > 24" wide and depth < 30"	1	1-20 Stories	Direction 2	CBR1	0.0203	0.39	0.0394	0.35	0.0602	1
B1051.021b	Concrete link beam, diagonally reinforced, aspect ratio between 2.0 and 4.0, beam > 24" wide and depth < 30"	1	1-20 Stories	Direction 2	CBR2	0.0203	0.39	0.0394	0.35	0.0602	1
B1051.021a	Concrete link beam, diagonally reinforced, aspect ratio between 1.0 and 2.0, beam > 24" wide and depth < 30"	1	1-20 Stories	Direction 1	CBR3	0.0179	0.38	0.0352	0.44	0.0543	0.95
B1051.021b	Concrete link beam, diagonally reinforced, aspect ratio between 2.0 and 4.0, beam > 24" wide and depth < 30"	1	1-20 Stories	Direction 2	CBR4	0.0203	0.39	0.0394	0.35	0.0602	1
B1051.021b	Concrete link beam, diagonally reinforced, aspect ratio between 2.0 and 4.0, beam > 24" wide and depth < 30"	1	1-20 Stories	Direction 2	CBR5	0.0203	0.39	0.0394	0.35	0.0602	1
B1051.021a	Concrete link beam, diagonally reinforced, aspect ratio between 1.0 and 2.0, beam > 24" wide and depth < 30"	1	1-20 Stories	Direction 1	CBR6	0.0179	0.38	0.0352	0.44	0.0543	0.95

Structural Component											
B1051.011b	Concrete link beam, diagonally reinforced, apsect ratio between 2.0 and 4.0, beam > 16" wide and depth < 30"	1	21-42 Stories	Direction 2	CBR1	0.0203	0.39	0.0394	0.35	0.0602	1
B1051.011a	Concrete link beam, diagonally reinforced, apsect ratio between 1.0 and 2.0, beam > 16" wide and depth < 30"	1	21-42 Stories	Direction 1	CBR3	0.0179	0.38	0.0352	0.44	0.0543	0.95
B1051.011b	Concrete link beam, diagonally reinforced, apsect ratio between 2.0 and 4.0, beam > 16" wide and depth < 30"	1	21-42 Stories	Direction 2	CBR4	0.0203	0.39	0.0394	0.35	0.0602	1
B1051.011b	Concrete link beam, diagonally reinforced, apsect ratio between 2.0 and 4.0, beam > 16" wide and depth < 30"	1	21-42 Stories	Direction 2	CBR5	0.0203	0.39	0.0394	0.35	0.0602	1
B1051.011a	Concrete link beam, diagonally reinforced, apsect ratio between 1.0 and 2.0, beam > 16" wide and depth < 30"	1	21-42 Stories	Direction 1	CBR6	0.0179	0.38	0.0352	0.44	0.0543	0.95

Table 2 Non-component Fragility of Building 2A and Building 2B

Non-structural Component											
Fragility ID	Fragility Name	Fragility Quantity	Fragility Location	Fragility Direction	Demand Parameter	Damage State					
						DS1		DS2		DS3	
						Median	Dispersion	Median	Dispersion	Median	Dispersion
B2022.002	Curtain Walls - Generic Midrise Stick-Built Curtain wall, Config: Insulating Glass Units (dual pane), Lamination: Unknown, Glass Type: Unknown, Details: Aspect ratio = 6:5, Other details Unknown	120	All Stories	Direction 1	SDR	0.021	0.45	0.024	0.45		
B2022.002	Curtain Walls - Generic Midrise Stick-Built Curtain wall, Config: Insulating Glass Units (dual pane), Lamination: Unknown, Glass Type: Unknown, Details: Aspect ratio = 6:5, Other details Unknown	120	All Stories	Direction 2	SDR	0.021	0.45	0.024	0.45		
B3011.011	Concrete tile roof, tiles secured and compliant with UBC94	36.979	Roof	Non-direction	PFA	1.1	0.4	1.4	0.4		
C1011.001a	Wall Partition, Type: Gypsum with metal studs, Full Height, Fixed Below, Fixed Above	8	All Stories	Direction 1	SDR	0.0021	0.6	0.0071	0.45	0.012	0.45

Non-structural Component											
C1011.001a	Wall Partition, Type: Gypsum with metal studs, Full Height, Fixed Below, Fixed Above	8	All Stories	Direction 2	SDR	0.0021	0.6	0.0071	0.45	0.012	0.45
C3021.001a	Generic Floor Covering - Flooding of floor caused by failure of pipe - Office - Dry	2500	42 Floors	Non-direction	PFA	0.75	0.4	0.95	0.4		
C3032.003a	Suspended Ceiling, SDC D,E (Ip=1.0), Area (A): A < 250, Vert & Lat support	12	42 Floors	Non-direction	PFA	1	0.4	1.8	0.4	2.4	0.4
C3032.003b	Suspended Ceiling, SDC D,E (Ip=1.0), Area (A): 250 < A < 1000, Vert & Lat support	13	42 Floors	Non-direction	PFA	0.7	0.4	1.15	0.4	1.8	0.4
C3032.003d	Suspended Ceiling, SDC D,E (Ip=1.0), Area (A): A > 2500, Vert & Lat support	0.25	42 Floors	Non-direction	PFA	0.35	0.4	0.55	0.4	0.8	0.4
D1014.011	Traction Elevator - Applies to most California Installations 1976 or later, most western states installations 1982 or later and most other U.S installations 1998 or later.	17	Ground Only	Non-direction	PFA	0.39	0.45				
D2021.013a	Cold Water Piping (dia > 2.5 inches), SDC D,E,F, PIPING FRAGILITY	1.5	42 Floors	Non-direction	PFA	2.25	0.5	4.1	0.5		

Non-structural Component										
D2021.013b	Cold Water Piping (dia > 2.5 inches), SDC D,E,F, PIPING FRAGILITY	1.5	42 Floors	Non-direction	PFA	1.5	0.5	2.25	0.5	
D2022.013a	Hot Water Piping - Small Diameter Threaded Steel - (2.5 inches in diameter or less), SDC D, E, or F, PIPING FRAGILITY	5	42 Floors	Non-direction	PFA	0.55	0.5	1.1	0.5	
D2022.013b	Hot Water Piping - Small Diameter Threaded Steel - (2.5 inches in diameter or less), SDC D, E, or F, BRACING FRAGILITY	5	42 Floors	Non-direction	PFA	2.25	0.5			
D2022.023a	Hot Water Piping - Large Diameter Welded Steel - (greater than 2.5 inches in diameter), SDC D, E, or F, PIPING FRAGILITY	1	42 Floors	Non-direction	PFA	2.25	0.5	4.1	0.5	
D2022.023b	Hot Water Piping - Large Diameter Welded Steel - (greater than 2.5 inches in diameter), SDC D, E, or F, BRACING FRAGILITY	1	42 Floors	Non-direction	PFA	1.5	0.5	2.25	0.5	
D2031.023a	Sanitary Waste Piping - Cast Iron w/bell and spigot couplings, SDC D,E,F, PIPING FRAGILITY	2.5	42 Floors	Non-direction	PFA	3	0.5			

Non-structural Component										
D2031.023b	Sanitary Waste Piping - Cast Iron w/bell and spigot couplings, SDC D,E,F, BRACING FRAGILITY	2.5	42 Floors	Non-direction	PFA	2.25	0.5			
D3031.013h	Chiller - Capacity: 350 to <750 Ton - Equipment that is either hard anchored or is vibration isolated with seismic snubbers/restraints - Equipment fragility only	1	42 Floors	Non-direction	PFA	0.72	0.2			
D3041.011c	HVAC Galvanized Sheet Metal Ducting less than 6 sq. ft in cross sectional area, SDC D, E, or F	1	42 Floors	Non-direction	PFA	1.5	0.4	2.25	0.4	
D4011.023a	Fire Sprinkler Water Piping - Horizontal Mains and Branches - Old Style Vitaulic - Thin Wall Steel - Poorly designed bracing, SDC D, E, or F , PIPING FRAGILITY	2.542	42 Floors	Non-direction	PFA	1.5	0.4	2.6	0.4	
D4011.063a	Fire Sprinkler Drop Standard Threaded Steel - Dropping into braced lay-in tile HARD ceiling - 6 ft. long drop maximum, SDC D, E, or F	1.387	42 Floors	Non-direction	PFA	0.55	0.4	1.3	0.4	

3. FEMA P-58 Based Rating Methodology

3.1 Rating Acceptance Criteria

The USRC rating serves as a tool to communicate the results of an engineering-based building evaluation to the relevant stakeholders of that building. Star ratings are provided for three separate dimensions: safety, damage and recovery.

The safety rating is described in terms of the potential for earthquake-related injuries, loss of life and the ability to evacuate the building following a seismic event. Five stars, which is the highest rating, is assigned in cases where the level of damage is unlikely to cause injuries or prevent timely evacuation. The lowest rating, which is one star, is assigned in cases where there is a high likelihood of collapse and loss of life within or around the building. When serious injuries are unlikely, loss of life is unlikely or loss of life possible in isolated locations, four, three and two stars are assigned respectively.

The damage rating is assigned based on the estimated cost of repairing earthquake-related damage. This cost is defined relative to the replacement cost of the building and includes structural, architectural mechanical, electrical and plumbing components. Content damage is not considered in estimating the repair cost. Five (minimal damage), four (moderate damage), three (significant damage) and two (substantial damage) star ratings are given in cases where the repair cost is less than

5%, 10%, 20% and 40% of the replacement cost respectively. One star (severe damage) is assigned in cases where the repair cost exceeds 40% of the replacement cost.

The recovery rating is assessed based on the time it takes the owner to regain use of the building for its primary intended function. It includes the time needed to perform repairs, mitigate safety hazards and impediments to re-entry and use. The time to address disruptive conditions that originate away from the building site, is not considered. Five, four, three two and one-star rating is assigned in cases where the delay in restoring basic functionality is days, days to weeks, weeks to months, months to a year and more than one year, respectively.

The rating systems relies on existing tools, techniques and professional norms for performing the engineering evaluation. Currently, the ASCE 41-13 and the FEMA-P58 performance assessment methodologies can be used to establish building ratings. The rating is developed assuming the building is subjected to ground shaking at its site corresponding to a hazard level of 10% probability of exceedance in 50 years.

3.2 Overview of FEMA P-58 Methodology

The FEMA-P58 guidelines (Volumes 1, 2 and 3) form the basis of the second-generation of PBEE. Key features of the methodology include (1) robust techniques for accounting for and communicating uncertainty to stakeholders, (2) the use of quantitative measures of performance that are relevant to new and existing buildings, (3) explicit assessment of physical damage to structural and non-structural components and (4) an assessment of performance based on global parameters. Performance measures considered in FEMA P58 include the probable number of casualties, the expected cost of repairing or replacing a damaged building, the time needed to restore the building to its pre-earthquake condition and the likelihood of unsafe placarding. The assessment of the probable number of casualties is enabled by an explicit and quantitative evaluation of collapse safety using the methodology outlined in the FEMA P695 (FEMA, 2009) guidelines. Performance functions are used to link the ground shaking intensity to exceeding some level loss (causalities, economic etc.). Three alternative types of assessments have been enabled, which vary based on the treatment of seismic hazard. Intensity-Based assessments are used to evaluate the probable performance measure conditioned on the occurrence of a specific shaking intensity. Scenario-based assessments calculate the probable performance of a building subjected to an earthquake scenario defined by a specific magnitude event occurring at a specific location relative to the site. In time-based assessments, mean seismic hazard curves are used to defined ground shaking hazard, which is used to compute the mean annual frequency of a particular consequence (e.g. collapse, losses exceeding a particular level etc.).

3.3 FEMA P-58 Criteria for USRC Seismic Rating

The description for each USRC rating level within the three dimensions is linked to a specific

FEMA P58 criterion. Recall that the USRC safety rating criteria is based on the likelihood injuries and blocking of evacuation routes. The associated FEMA P58 rating criteria is based on the computed probability of fatal and non-fatal injuries considering both collapse and non-collapse falling hazards and egress routes being intact for the 475 event. The definition of each star under each rating dimension is shown in the Table 4.

For the damage rating, the repair-cost thresholds for the FEMA P58 criteria, which are described as a percentage of the building replacement cost, are the same as the USRC rating criteria. The FEMA P58 criteria for the recovery ratings are based on the median recovery time. For the five, four, three and two-star ratings, the corresponding median recovery times after a 475-year event are 5 days, 4 weeks, 6 months and one year respectively. A one-star rating is assigned if the median recovery time is more than one year.

Table 3 The USRC Rating Criterion

Safety		
Rating	Expected Safety Performance	USRC Thresholds
5 Stars	Expected performance results in conditions unlikely to cause injuries or to keep people from exiting the building.	The requirements shall be met for 4-star. The likelihood of a building occupant being fatality injured, considering both building collapse and other non-collapse falling hazards, is less than 0.00003 for a 475-year event. Egress routes are expected to be intact for a 475-year event, with the building meeting the specific requirements listed here.

4 Stars	Expected performance results in conditions that are unlikely to cause serious injuries.	The likelihood of a building occupant being fatality injured, considering both building collapse and other non-collapse falling hazards, is less than 0.0001 for a 475-year event. The likelihood of a building occupant being injured, considering both building collapse and other non-collapse falling hazards, is less than 0.02 for a 475-year event.
3 Stars	Expected performance results in conditions that are unlikely to cause loss of life.	The likelihood of a building occupant being fatally injured, considering both building collapse and other non-collapse falling hazards, is less than 0.0004 for a 475-year event.
2 Stars	Expected performance results in partial collapse or falling objects which have a potential to cause loss of life at some locations within or around the building.	The likelihood of a building occupant being fatally injured, considering only building collapse, is less than 0.004 for a 475-year event. Fatalities due to falling hazards are not considered
1 Stars	Expected performance results in building collapse which has a high potential for deaths of people who are in or around the building.	The building was evaluated but did not meet the 2-star rating criteria.
Repair Cost		
Rating	Expected Repair Cost	USRC Thresholds
5 Stars	Repair Cost likely less than 5% of building replacement cost.	The mean repair cost in a 475-year event is less than 5% of building replacement cost.
4 Stars	Repair Cost likely less than 10% of building replacement cost.	The mean repair cost in a 475-year event is less than 10% of building replacement cost.
3 Stars	Repair Cost likely less than 20% of building replacement cost.	The mean repair cost in a 475-year event is less than 20% of building replacement cost.
2 Stars	Repair Cost likely less than 40% of building replacement cost.	The mean repair cost in a 475-year event is less than 40% of building replacement cost.
1 Stars	Repair Cost likely greater than 40% of building replacement cost.	The mean repair cost in a 475-year event is greater than or equal to 40% of building replacement cost.
Time to Regain Basic Function		
Rating	Expected Time to Regain Basic Function	USRC Thresholds

5 Stars	The expected performance will likely result in people being able to quickly re-enter and resume use of the building from immediately to a few days, excluding external factors.	The median recovery time after a 475-year event is less than five days.
4 Stars	The expected performance may result in delay of minimum operational use for days to weeks, excluding external factors.	The median recovery time after a 475-year event is less than four weeks.
3 Stars	The expected performance may result in delay of minimum operational use for weeks to months, excluding external factors.	The median recovery time after a 475-year event is less than six months.
2 Stars	Expected performance may result in delay of minimum operational use for months to a year.	The median recovery time after a 475-year event is less than one year
1 Stars	Expected performance may result in delay of minimum operational use for at least one year or more.	The median recovery time after a 475-year event is greater than or equal to one year.

An estimate of the collapse capacity of the building is needed to compute the repair cost and time and the probability of fatal and non-fatal collapse-injuries, all of which are included in the FEMA P58 rating criteria. The USRC rating requires the use of the FEMA 154 approach to estimating the building's collapse capacity in lieu of other methods such as incremental dynamic analyses. The FEMA 154 approach begins by using the checklists to compute the resultant "score" $(S\,value)$ for the building. Given the $S\,value$, the probability of collapse occurring and affecting an occupant at a specific location within the building conditioned the risk-targeted maximum considered earthquake (MCE_R) ground motion is computed.

$$P["Collapse"|MCE_R] = 10^{-S} \tag{1}$$

Where $P["Collapse"|MCE_R]$ is the probability of total or partial collapse times the ratio of the area of the building affected by collapse. The collapse area ratio, which is provided in Table 1 of Appendix E of the USRC implementation manual, is needed to convert the "collapse" probability from equation 1 to the collapse probability used in the FEMA P58 methodology. The dispersion or log-standard deviation of the collapse capacity is obtained from Table 2 of Appendix E of the USRC implementation manual.

The FEMA 154 checklist does not provide score values Risk Category III and IV and base isolated structures. The score values for buildings falling in these three categories are provided on page 6 of Appendix E of the USRC implementation manual. In cases where a building is partially retrofitted, checklist deficiencies addressed by "comprehensive building retrofit" can be ignored. A full basic score increase can be used if the retrofit meets the performance objectives at or above 75% of the new code. In cases where it can be demonstrated that specific checklist items do not affect the building performance or are explicitly addressed during the building design, these items can be removed from the checklist. Engineering judgement can be used to modify the collapse fragility curves based on building properties not considered in the FEMA 154 checklist. For building 2B, S is equal to 2.6 when utilizing the FEMA 158 checklist and the $P["Collapse"|MCE_R] = 0.251\%$. Since in this case the building is concrete system, the default collapse area ratio is equal to 1. From Table 8-1 of FEMA 155, we can get lognormal standard deviations of the collapse fragility, β, is equal to 0.7. Using the iteration method, the $P[" \ Collapse"|DBE]$is 3.5543E-4 for building 2A and 3.5639E-4 for building 2B. The figure 10 shows the collapse probability distribution of two models. Table 3 shows the collapse parameter for building 2A and building 2B.

The MCER hazard level is converted to the 10% in 50-year hazard level using the USRC rating conversion factor of 1.5. However, it is noted that this conversion factor does not include near-fault and transition zone regions that are deterministically capped. Conversion factors for these conditions are likely to be less than 1.5 and buildings located at building sites with these characteristics will be required to meet a higher FEMA 154 score in our to achieve a particular safety rating.

The fatality-rate thresholds used in the safety rating are based on the fatality-rates computed at the 10% in 50-year hazard level using the (FEMA 154), collapse area ratio and the default collapse capacity dispersion and fatality rate for each building type. The computed fatality-rates are summarized in Table 4 of Appendix E of the USRC implementation manual. The thresholds are based on the average values for all building types. The allowable fatality-rate for safety ratings corresponding to three stars and higher is increased by a factor of two account for falling-hazard fatalities.

The injury-rate threshold for the four-star safety rating is based on a benchmark study by Cook et al. (2015). This threshold was set such that the building used in the study required additional anchorage above code-requirements to meet the four-star threshold of 0.02.

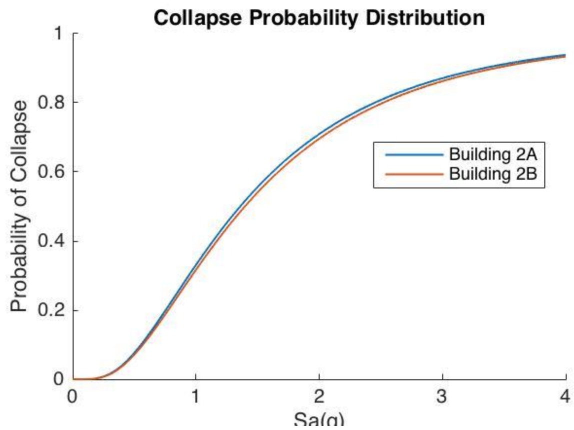


Figure 10 Collapse Distribution for building 2A and building 2B calculated by FEMA 154 approach

Table 4 Collapse Parameters for 2A and 2B

Building Type	P[Collapse|MCE]	P[Collapse|DBE]	Mean Mu	Collapse Variability Beta	Sa_{MCE}	Sa_{DBE}
Building 2A	0.00251	3.5543E-04	0.3069695	0.7	0.1907	0.1271
Building 2B	0.00251	3.5639E-04	0.334382687	0.7	0.1960	0.1307

3.4 REDi Methodology for Recovery Rating

The USRC Rating system uses REDi Methodology to estimate the recovery time. This rating is based on the recovery time needed for building to regain its function under the influence of impending factors such as the time to have the building inspected, obtain financing etc. The REDi Methodology creates a repair sequence to estimate repair time under different recovery levels: re-occupancy, functional recovery and full recovery. Meanwhile, it separates types of damage into “repair classes”. For USRC recovery rating, the functional recovery level is supposed to be considered, which means we should pay attention to the repair class 2 (Non-structural damage which does not pose a risk to life-safety) and 3 (Heavy structural or non-structural damage which poses a risk to life-safety) components. The recovery time is consisted of two parts: time due to repair and time due to delay. From the FEMA P-58 database, the time consequence of components in each damage states has been defined. Repair time of the building is relative to the types of the building components and the repair classes associated with the level of earthquake damage. However, we also need to account for the influence of floor repair sequence, labor allocation for each floor and maximum number of works.

The time from the earthquake to the start of repairs (lead time) is determined by a set of impeding factors. This time is probabilistically described using a lognormal distribution. Five impeding factors are considered: inspection, engineering mobilization & review/re-design, financing, contractor mobilization and permitting. For tall buildings, the time due to delay contributes to majority of the recovery time. For the USRC rating, the worst situation has been considered. The lead time is defined based on the sequence of the impeding factors. Path 1 is from inspection to financing, path 2 starts from inspection to engineering mobilization & review and ends in permitting, path 3 starts from inspection to contractor mobilization and ends in long-lead time components. The critical delay path governs the lead time. Table 4 shows the impeding factors considered in this study.

Table 5 Impeding factors and details of Building 2A & 2B

Impeding Factor	Details	θ	β

Inspection	Non-Essential Facility	5 days	0.54
Engineering Mobilization & Review/Re-Design	No Engineer on Contract, Max RC=3	12 weeks	0.4
Financing	Private Loans	15 weeks	0.68
Contractor Mobilization	≥20 Stories, no GC on Contract, Max RC=3	40 weeks	0.31
Permitting	All Facilities, Max RC=3	8 weeks	0.32

4. Summary of USRC Rating Results

A *USRC* seismic rating assessment is performed for the two building cases using the FEMA P58 approach. Intensity-Based analyses are performed at the *DBE* and *MCE* hazard levels. Only the *DBE* level assessment was used for the *USRC* rating. *REDi* recovery times are computed which includes repair times and lead time. A comparative *ASCE-31/ASCE-41* rating was not performed. The construction cost for Buildings 2A and 2B are $149 million and $174 million respectively and multi-unit residential occupancy type was assumed. The effect of residual drifts on the expected losses and repair time is considered.

A summary of the results of the rating is shown in Table 5. Both buildings received 5 and 2 stars for the safety and repair dimensions respectively. However, Building 2A got 4 stars for damage while 2B got 5 stars. The mean repair cost (normalized by the replacement cost) at the 475-year event is 5.57% for Building 2A and 4.01% for Building 2B. Figure 11 shows the disaggregation of losses at the *DBE & MCE* event for the two buildings. For both buildings, the partition wall dominated the losses accounting for 37% of the total repair cost. For the safety dimension, the total probability of injuries for Building 2A (0.00639) is about 80% higher than that of Building 2B (0.003506). The median *REDi* functional downtime is 352 days for Building 2A and 363 days for Building 2B. For both buildings, the impeding factors account for more than 60% of the recovery time. This can be observed in Figure 12 which shows that the *REDi* functional recovery time without impeding factors is only 71 days and 81 days for Buildings 2A and 2B respectively. This suggests that the main impediments to a higher star rating for both buildings are the impeding factors. What's more, minimizing the lead time (per REDi) can at best achieve a 3-star rating.

Table 6 Summary of USRC Rating for (a) Building 2A and (b) Building 2B

(a)

Building 2A		
Rating Dimension	**Rating**	**Rating Description**
Safety	5 Stars	Total Probability of Injuries: 0.006303 Total Probability of Fatalities: 1.8E-5
Damage	4 Stars	Mean Repair Cost at 475 year event: 5.57%
Repair	2 Stars	Median REDi Functional Down Time at 475 Year Event (including impedance factors): 352 Days

(b)

Building 2B		
Rating Dimension	**Rating**	**Rating Description**
Safety	5 Stars	Total Probability of Injuries:0.003653 Total Probability of Fatalities: 2.2E-5
Damage	5 Stars	Mean Repair Cost at 475 year event: 4.01%
Repair	2 Stars	Median REDi Functional Down Time at 475 Year Event (including impedance factors): 362 Days

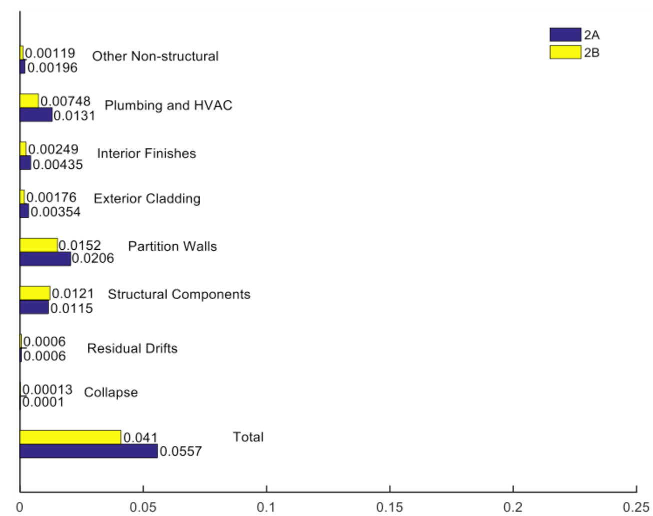
The results of the FEMA P58 assessment at the *MCE* hazard level are also summarized in Figures 11 and 12. It is interesting to observe that, at the *MCE* hazard level, the total losses in Building 2B is 16% higher than Building 2A compared to the *DBE* case where it was about quarter as much. The reason being that, unlike at the *DBE* level, there is a measurable contribution from residual drifts which is significantly higher in Building 2B (as observed in Figure

4). At the *MCE* level, residual drifts account for 42% of the total losses in Building 2B compared to 4% for Building 2A. For both Building 2A and Building 2B under DBE level, the partition walls contribute most to the total loss. However, the loss associated with building structural components increases significantly between the DBE level to MCE level due to a substantial increase in the story drift ratio. As a result, building structural components contribute more than partition walls to the total loss at the MCE level. The residual drifts also affect the *REDi* functional recovery time (shown in Figure 12 b) at the *MCE* level, which is computed to be 392 days for Building 2A and 452 days for Building 2B without the effect of impeding factors.

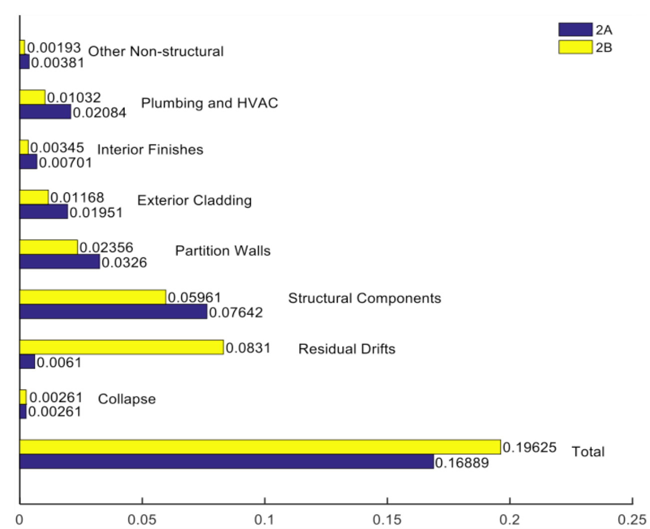
For the drift, the thesis's result is generally consistent with the TBI report. For example, at the MCE hazard level, the median peak drift in the X-Direction is 1.4% in Building 2B compared to 1.6% in Building 2A. In the Z-Direction, the MCE level median peak drift demand is 1.4% and 1.1% in Buildings 2A and 2B respectively. You can see in my thesis the drifts are approximately 18% less for the PBD model compared to the code-base design.

The TBI study did not incorporate the effect of excessive residual drifts (which may result in demolition) on the earthquake-induced losses and explicit collapse analyses were not performed. Instead, the MCE maximum story drift ratio is used as a proxy for collapse and demolition (TBI PEER Report Page 113, 6.6.8). In my thesis, residual drifts are considered as a crucial part of rating as required by the USRC Rating procedure in cases where any of the star ratings is greater than 3.

At the MCE hazard level, the median peak residual drift in the X-Direction is 0.27% in Building 2B and 0.09% in Building 2A (the result of the reduced core wall boundary reinforcement in Building 2B). Under the moderate shaking intensity corresponding to the DBE level, the influence of residual drift on earthquake-induced losses is not significant. However, at the MCE level, residual drifts account for 42% of the total losses in Building 2B compared to 4% for Building 2A. Hence, at the MCE level, the loss performance of Building 2B is greater than Building 2A.

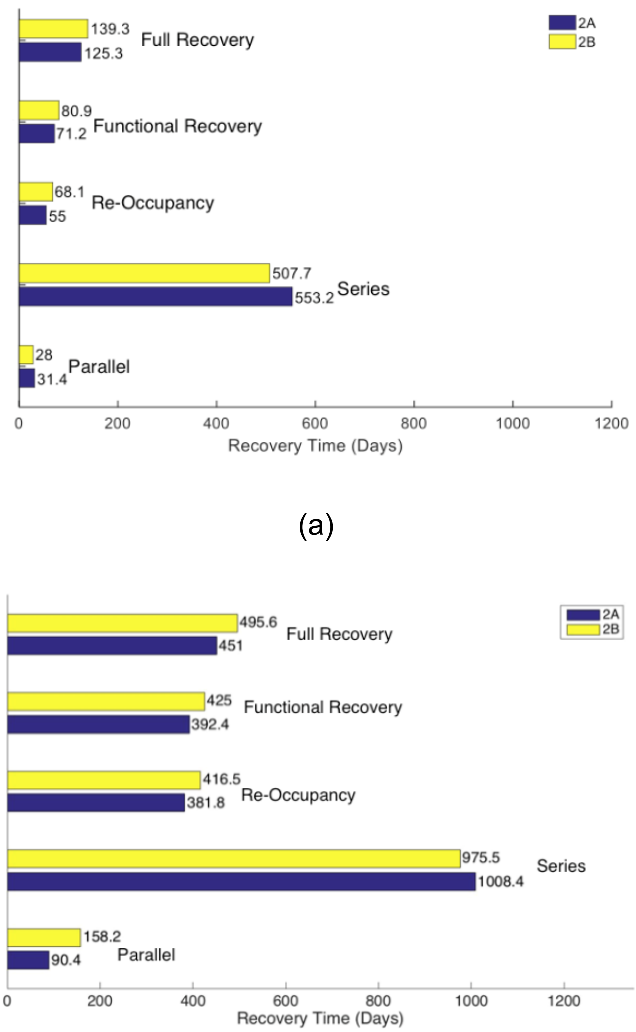


(a)



(b)

Figure 11 Disaggregation of losses at the (a) DBE and (b) MCE hazard level for Building 2A & Building 2B using FEMA 154 collapse performance and residual drifts considered (USRC Rating Methodology)



(a)

(b)

Figure 12 Comparing recovery times at the (a) DBE and (b) MCE hazard level for Building 2A & Building 2B using FEMA 154 collapse performance and residual drift considered

5. Sensitivity of Building Performance to EDP Levels

As noted in Section 4, the partition walls and building structural components are the highest contributors to the economic losses. What's more, both are controlled by the story drift ratio. Figure 13 shows the effect of artificially scaling EDPs on the economic losses for Building 2B under the DBE level. The horizontal axis is the scale factor applied to the EDPs and the vertical axis is the resulting change in economic losses (relative to DBE level EDPs and losses). The objective here is to gain an understanding of which EDPs should be targeted for reducing economic losses. Figure 13 shows that reducing the story drift ratio is the best way to decrease the economic losses (damage). Scaling peak floor acceleration has a big influence between 0.9 and 0.7 for the normalized loss, after which, the influence of scaling peak floor acceleration seems to be limited. Scaling core wall rotation does not make any difference because the demands are already very small at the DBE level.

Figure 14 shows the effect of artificially scaling EDPs on the recovery time for Building 2B under the DBE level. Scaling coupling beam rotation contributes most to reducing recovery time. The reason is that, although the drift sensitive partition walls and slab-column dominate the loss, coupling beams has the strongest influence on the lead time as well as the direct repair time.

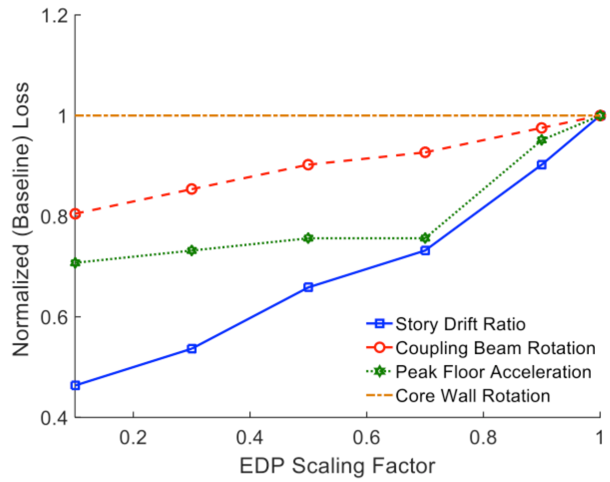


Figure 13 Sensitivity of losses to component damage for Building 2B at DBE level using FEMA 154 collapse performance and residual drifts not considered

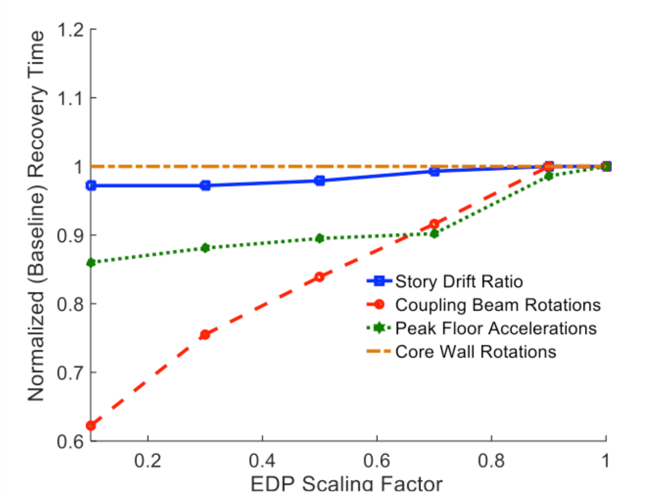


Figure 14 Sensitivity of recovery time to component damage for Building 2B at DBE level using FEMA 154 collapse performance and residual drifts not considered

6. ASCE 31/41 Based Rating Methodology

This study also applied a methodology to translate the ASCE 31 seismic evaluation into a three-part USRC rating. ASCE 31 has 3 tiers: tier 1-screening phase, tier 2-evaluation phase (full building or deficiency only), tier 3-detailed evaluation. Tiers 1&2 are used in this study. ASCE 31 tier 1&2 also divided the evaluation of a building into 3 dimensions: safety, repair cost and recovery. Because the ASCE 31 checklist does not support the dual system, the worst case of special moment frame and shear wall ASCE 31 rating is used to develop the dual system rating. The checklist shown in the Appendix forms the basis of the rating.

The ASCE 31 based rating is 5 stars, 3 stars and 2 stars for safety, repair cost and recovery respectively for both building 2A and building 2B. Although building 2A and building 2B meet all the requirements to achieve 5 stars in the ASCE 31 safety dimension, the evaluation of the repair cost dimension of two buildings seem to be conservative. The reason is that there is a limit placed on structural/nonstructural repair cost sub-rating which is a function of ASCE 31 building type and overall safety rating. So the ASCE 31 repair cost rating for building 2A and building 2B are both 3 stars. The 2-star recovery rating is due to the consideration of the size adjustments, public use adjustments and contents adjustments.

As noted earlier, the ASCE 31 rating methodology is quite conservative in repair cost and recovery dimensions. As a result, building 2B can only get 3 stars on ASCE 31 repair cost rating but 5 stars in the FEMA-P58 damage rating. However, in the recovery dimension, the rating results of two methodology are same. Because the ASCE 31 recovery rating does not take consider the number building stories, it treats building 2A and building 2B as two low-rise buildings and gives them a conservative recovery rating. In other words, using the ASCE 31 checklist to rate buildings does not properly address variations in building height.

7. Summary and Conclusion

The *USRC* seismic rating procedure is applied to two variations of a 42-story concrete building with a core wall and special moment frame lateral system. The buildings were developed as part of the *PEER TBI* project. One variation was designed using the prescriptive requirements of the *IBC* 2006 and the other using the *LATBSDC* guidelines. Three-dimensional structural models of the two variants were constructed in *OpenSees* and nonlinear response history analyses were performed using bi-directional inertial loading including *IDAs* to collapse. The intensity-based analyses were performed at the *DBE* and *MCE* hazard levels.

SP3 was used to perform the *USRC* Seismic Rating assessment based on the FEMA P58 methodology. User-defined *EDPs* were incorporated into the assessment using the results from the nonlinear response history analyses. Story drift demands were used to assess the extent of damage to the moment frame elements and other deformation-controlled structural and non-structural components. Chord rotations were used to assess the damage to the core wall and coupling beams. Floor accelerations were used to simulate damage to acceleration-controlled components such as ceilings and mechanical, electrical and plumbing equipment. Residual drifts were used to account for the effect of demolition on the mean repair costs and recovery time. Collapse fragility curves were developed using the *IDA* results however, the FEMA 154 checklist-based collapse capacity was used in the *USRC* rating assessment.

The two buildings achieved the same *USRC* rating: five and two stars for the safety and recovery dimensions, respectively. For the damage dimension, building 2B received a 5-star rating while 2A received a 4-star rating. The *USRC* rating is performed at the *DBE* hazard level. The mean repair costs for the code-based and performance-based designs are, 5.57% and 4.01% of the replacement cost respectively. At this intensity level, the repair cost for both buildings is dominated by damage to the partition wall, which accounts for about 37% of the losses. For both building cases, impeding factors account for more than 75% of the *REDi* functional recovery time. The results from the nonlinear response history analyses show that the residual drifts are significantly higher in the performance-based design case. This is likely the result of using less boundary element reinforcement in the performance-based design case. In fact, at the *MCE* hazard level, residual drifts dominate the losses for the performance-based design case and the mean repair cost is about 16% higher than the code-based design case. For Building 2B, losses are most sensitive to story drift demands and recovery is most sensitive to coupling beam rotations.

Although this research was carefully prepared, there are still limitations and shortcomings. First, the effect of axial demands on column strength and rotation capacity was not considered during the analysis. Moreover, the need to epoxy inject wall shear cracks was not considered, which could affect the difference in repair costs between Buildings 2A and 2B. Lastly, the cost and earthquake damage to the foundation was not considered.

Appendix

ASCE 31/41 Rating		
ASCE 31/41 Building Type	C1-Concrete Moment Frames (for shear wall the checklist is almost same)	
Designed Performance Level	Immediate Occupancy	
Level of Seismicity	High	
Eligibility		
Topic	Question	Answer
Site Visit	Was a site visit conducted in accordance with ASCE 31 Section 2.3?	Yes
Investigation	Was document review and visual and/or destructive investigation performed as required by ASCE Section 2.2?	Yes
Condition Assessment	Were existing components investigated for significant deterioration, damage, or defects, in general conformance with ASCE 30 sections 4.3.3 and 4.7.2, with structural capacities adjusted accordingly?	Yes
Tier 2 Requirements	If a full-building analysis was required by ASCE Table 3-3, was such an analysis performed? If no such analysis was required, enter NA.	Yes
Safety		
Structural		
Question		Answer
Is the seismic force resisting system benchmarked for life safety but not immediate occupancy, in accordance with ASCE 31 Table 3-1 and Section 3.2?		Yes

Is the seismic force resisting system benchmarked for immediate occupancy using FEMA 310 (but not CBC), in accordance with ASCE 31 Table 3-1 and Section 3.2?			Yes
Geologic Site Hazards and Foundations			
Question			Answer
Is the building site and nearby topography sloped or otherwise graded such that lateral spreading would be likely to lead to structural collapse?			No
Geologic			
Section	Item	Min. Compliance Rating	Answer
Geologic Site Hazards	Liquefaction	3 stars	Compliant
Geologic Site Hazards	Slope Failure	2 stars	Compliant
Geologic Site Hazards	Surface Fault Rupture	2 stars	Compliant
Capacity of Foundations	Pole Foundations	2 stars	Compliant
Capacity of Foundations	Overturning	3 stars	Compliant
Capacity of Foundations	Ties Between Foundation Elements	3 stars	Compliant
Capacity of Foundations	Deep Foundations	5 stars	Compliant
Capacity of Foundations	Sloping Sites	5 stars	Compliant
Non-Structural			
Section	Item	Min. Compliance Rating	Answer
Partitions	Unreinforced Masonry	3 stars	Compliant
Ceiling Systems	Support	4 stars	Compliant
Light Fixtures	Emergency Lighting	4 stars	Compliant
Cladding and Glazing	Cladding Anchors	3 stars	Compliant
Cladding and Glazing	Cladding Isolation	3 stars	Compliant
Cladding and Glazing	Multi-Story Panels	3 stars	Compliant
Cladding and Glazing	Bearing Connections	3 stars	Compliant
Cladding and Glazing	Inserts	3 stars	Compliant
Cladding and Glazing	Panel Connections	3 stars	Compliant

Masonry Veneer	Shelf Angles (LS)	3 stars	Compliant
Masonry Veneer	Shelf Angles (IO)	4 stars	Compliant
Masonry Veneer	Ties	3 stars	Compliant
Masonry Veneer	Weakened Planes	3 stars	Compliant
Appendages	URM Parapets	3 stars	Compliant
Appendages	Canopies	3 stars	Compliant
Chimneys	URM Chimneys	3 stars	Compliant
Stairs	URM Walls	3 stars	Compliant
Stairs	Stair Details	3 stars	Compliant
Contents	Tall Narrow Contents	3 stars	Compliant
Mechanical and Electrical Equipment	Emergency Power	3 stars	Compliant
Mechanical and Electrical Equipment	Hazardous Material Equipment	3 stars	Compliant
Mechanical and Electrical Equipment	Attached Equipment	3 stars	Compliant
Piping	Fire Suppression Piping	3 stars	Compliant
Piping	Flexible Couplings	2 stars	Compliant
Hazardous Materials	Toxic Substances	3 stars	Compliant
Partitions	Drift	4 stars	Compliant
Partitions	Structural Separation	5 stars	Compliant
Partitions	Tops	5 stars	Compliant
Ceiling Systems	Edges	5 stars	Compliant
Ceiling Systems	Seismic Joint	5 stars	Compliant
Light Fixtures	Pendant Supports	5 stars	Compliant
Light Fixtures	Lens Covers	5 stars	Compliant
Cladding and Glazing	Glazing Restraint	4 stars	Compliant

Masonry Veneer	Mortar	4 stars	Compliant
Metal Stud Back Up Systems	Stud Tracks	4 stars	Compliant
Metal Stud Back Up Systems	Openings	5 stars	Compliant
Concrete Block and Masonry Back-Up-Systems	Anchorage	4 stars	Compliant
Concrete Block and Masonry Back-Up-Systems	URM Back-Up	4 stars	Compliant
Contents	File Cabinets	4 stars	Compliant
Contents	Access Floors	5 stars	Compliant
Contents	Equipment on Access Floors	4 stars	Compliant
Mechanical and Electrical Equipment	Heavy Equipment	4 stars	Compliant
Mechanical and Electrical Equipment	Electrical Equipment	5 stars	Compliant
Mechanical and Electrical Equipment	Doors	5 stars	Compliant
Piping	Fluid and Gas Piping	5 stars	Compliant
Piping	Shut-Off Valves	5 stars	Compliant
Piping	C-Clamps	5 stars	Compliant
Ducts	Duct Bracing	5 stars	Compliant
Ducts	Duct Support	5 stars	Compliant
Hazardous Materials	Gas Cylinders	2 stars	Compliant
Hazardous Materials	Hazardous Materials	3 stars	Compliant
Elevators	Support System	5 stars	Compliant

Elevators	Seismic Switch	5 stars	Compliant
Elevators	Shaft Walls	5 stars	Compliant
Elevators	Retainer Guards	5 stars	Compliant
Elevators	Retainer Plate	5 stars	Compliant
Elevators	Counterweight Rails	5 stars	Compliant
Elevators	Brackets	5 stars	Compliant
Elevators	Spreader Bracket	5 stars	Compliant
Elevators	Go-Slow Elevators	5 stars	Compliant
Repair cost			
Since ASCE 31 does not address repair cost, the EPRS repair cost rating is intentionally conservative. For more accurate results consider using the P-58 methodology.			
Functional Recovery			
Since ASCE 31 does not address recovery time, the EPRS functional recovery rating is intentionally conservative. For more accurate results consider using the P-58 methodology.			
Non-structural			
Section	Item	Min. Compliance Rating	Answer
Partitions	Unreinforced Masonry	4 stars	Compliant
Ceiling Systems	Support	4 stars	Compliant
Light Fixtures	Emergency Lighting	3 stars	Compliant
Cladding and Glazing	Cladding Anchors	4 stars	Compliant
Cladding and Glazing	Cladding Isolation	4 stars	Compliant
Cladding and Glazing	Multi-Story Panels	4 stars	Compliant
Cladding and Glazing	Bearing Connections	4 stars	Compliant
Cladding and Glazing	Inserts	4 stars	Compliant
Cladding and Glazing	Panel Connections	4 stars	Compliant
Masonry Veneer	Shelf Angles (LS)	4 stars	Compliant
Masonry Veneer	Weakened Planes	4 stars	Compliant

Appendages	URM Parapets	4 stars	Compliant
Appendages	Canopies	4 stars	Compliant
Chimneys	URM Chimneys	4 stars	Compliant
Stairs	URM Walls	4 stars	Compliant
Stairs	Stair Details	3 stars	Compliant
Contents	Tall Narrow Contents	5 stars	Compliant
Mechanical and Electrical Equipment	Emergency Power	3 stars	Compliant
Mechanical and Electrical Equipment	Hazardous Material Equipment	3 stars	Compliant
Mechanical and Electrical Equipment	Attached Equipment	3 stars	Compliant
Piping	Fire Suppression Piping	2 stars	Compliant
Piping	Flexible Couplings	2 stars	Compliant
Hazardous Materials	Toxic Substances	2 stars	Compliant
Ceiling Systems	Lay-In-Tiles	5 stars	Compliant
Ceiling Systems	Integrated Ceilings	5 stars	Compliant
Ceiling Systems	Suspended Lath and Plaster	4 stars	Compliant
Light Fixtures	Independent Support	3 stars	Compliant
Cladding and Glazing	Overhead Glazing	4 stars	Compliant
Appendages	Concrete Parapets	4 stars	Compliant
Appendages	Appendages (LS)	4 stars	Compliant
Appendages	Appendages (IO)	4 stars	Compliant
Chimneys	Anchorage	4 stars	Compliant
Mechanical and Electrical Equipment	Vibration Isolators	3 stars	Compliant
Ducts	Stair and Smoke Ducts	3 stars	Compliant

Partitions	Drift	4 stars	Compliant
Partitions	Structural Separation	5 stars	Compliant
Partitions	Tops	4 stars	Compliant
Ceiling Systems	Edges	5 stars	Compliant
Ceiling Systems	Seismic Joint	5 stars	Compliant
Light Fixtures	Pendant Supports	3 stars	Compliant
Light Fixtures	Lens Covers	5 stars	Compliant
Cladding and Glazing	Glazing Restraint	4 stars	Compliant
Masonry Veneer	Mortar	4 stars	Compliant
Metal Stud Back Up Systems	Stud Tracks	4 stars	Compliant
Metal Stud Back Up Systems	Openings	4 stars	Compliant
Concrete Block and Masonry Back-Up-Systems	Anchorage	4 stars	Compliant
Concrete Block and Masonry Back-Up-Systems	URM Back-Up	4 stars	Compliant
Contents	File Cabinets	5 stars	Compliant
Contents	Cabinet Doors and Drawers	5 stars	Compliant
Contents	Access Floors	3 stars	Compliant
Contents	Equipment on Access Floors	3 stars	Compliant
Mechanical and Electrical Equipment	Heavy Equipment	5 stars	Compliant
Mechanical and Electrical Equipment	Electrical Equipment	3 stars	Compliant

Mechanical and Electrical Equipment	Doors	3 stars	Compliant
Piping	Fluid and Gas Piping (hazmat)	2 stars	Compliant
Piping	Fluid and Gas Piping (non hazmat)	3 stars	Compliant
Piping	Shut-Off Valves	2 stars	Compliant
Piping	C-Clamps	4 stars	Compliant
Ducts	Duct Bracing	3 stars	Compliant
Ducts	Duct Support	3 stars	Compliant
Hazardous Materials	Gas Cylinders	2 stars	Compliant
Hazardous Materials	Hazardous Materials	2 stars	Compliant
Elevators	Support System	3 stars	Compliant
Elevators	Seismic Switch	3 stars	Compliant
Elevators	Shaft Walls	3 stars	Compliant
Elevators	Retainer Guards	3 stars	Compliant
Elevators	Retainer Plate	3 stars	Compliant
Elevators	Counterweight Rails	3 stars	Compliant
Elevators	Brackets	3 stars	Compliant
Elevators	Spreader Bracket	3 stars	Compliant
Elevators	Go-Slow Elevators	3 stars	Compliant
Answer the following questions for all 5 Stars star nonstructural recovery time deficiencies			
Question			Answer

Size Adjustment: Are any of the deficiencies extensive throughout the building, or is the building large enough that the functional recovery time for that item would probably exceed the time implied by the initial sub-rating?				Yes
Public Use Adjustment: Do any of the building's occupancies or functions of interest involve public access or accommodation, so that the functional recovery time for any of the deficiencies must consider issues of habitability?				Yes
Contents Adjustment: Would any of the deficiencies (or expected damage to other contents items not considered explicitly by ASCE 31) have a disproportionate impact on functional recovery time due to specialized use or occupancy, or performance requirements of the building?				Yes
Rating Summary				
	Structural	Geologic/Foundation	Non-Structural	Overall Rating
Safety	5 Stars	5 Stars	5 Stars	5 Stars
Repair	3 Stars	5 Stars	3 Stars	3 Stars
Functional Recovery	5 Stars	5 Stars	2 Stars	2 Stars

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