Initially published: November 14, 2019

Revision 1: January 13, 2020

Earthquake Resilience and Functional Recovery of Buildings in the United States: Problem Statement and Technical Solutions

Marios Panagiotou, PhD, PE

Senior Consultant at Nabih Youssef Associates

Founder of the Online School of Earthquake Resilient Design

mpanagiotou@nyase.com mp@school-of-earthquake-resilient-design.com

Introduction

This paper presents insights of the Online School of Earthquake Resilient Design[25] on the recent efforts and plans in the United States for enhancing the resilience and functional recovery of individual buildings, urban regions, and communities in the event of an earthquake. These actions were initiated because of Public Law 115-307 (NEHRP Reauthorization Act of 2018),[34] discussed below, and legislation efforts in California (Assembly Bill 393).[4]

Why Functional Earthquake Recovery and Resilient Design

The modern code-minimum seismic design of most structures, worldwide, is aimed at ensuring life safety and a low probability of collapse under the design earthquake (about 475-year return period or 10% in 50 years probability of exceedance). Such structures are prone to significant post-earthquake damage, downtime, costly repairs, or demolition. The potential for moderate-to-severe damage increases significantly when located at sites near major faults. Post-earthquake loss of the functionality of large numbers of structures has profound socioeconomic effects, including business interruption and displacement of thousands of people at several scales: local communities, cities, broader regions, and nations.

The field of earthquake and structural engineering is now a mature field. Decades of analytical and experimental research has resulted in sophisticated design methods and technologies that allow construction of cost-effective buildings (and the retrofit of existing buildings) that can sustain strong ground shaking and recover their functionality in reasonable time after a major earthquake without requiring cost-prohibitive repairs, excessive downtime, or demolition. That said, implementation of the latest scientific advancement to enhance the seismic resilience of communities is a complex task, involving, major socioeconomic interrelations among stakeholders of different technical backgrounds and interests. Key questions that emerge are as follows:

1. What earthquake scenarios best describe the cumulative (over a period of future time) damage of urban regions in the United States? How important is the consideration of near-fault scenarios, and how should the seismic hazard and ground motions be defined in these scenarios?
2. What are the objectives for communities in the process of developing strategies to achieve resilience under different earthquake scenarios at different future times (e.g., twenty and forty years from now)? How will population growth and the ever-changing built environment affect these objectives?
3. What should be the main seismic design (and retrofit) strategies for enhanced earthquake resilience of new and existing buildings?
4. Compared to current seismic design and construction practices, what is the incremental cost for achieving enhanced seismic resilience of local communities, cities, and broader regions?
5. Will these incremental costs decrease over time with standardization and widespread use of enhanced seismic design strategies and construction?
6. How will the incremental costs associated with enhanced earthquake resilience affect community members?
7. How will the rate of replacing existing seismically vulnerable buildings affect earthquake resilience objectives for the retrofit of buildings and new designs?

Recent Legislation and Efforts in the United States

Legislation for enhancing the earthquake resilience of urban regions of United States is ongoing, including: (1) Public Law No:115-307[34] and legislation efforts (California Assembly Bill 393 Building codes: earthquake safety: functional recovery standard).[4] Public Law 115-307 requires the National Institute for Standards and Technology (NIST) and the Federal Emergency Management Agency (FEMA) to convene a joint committee of experts to assess and recommend options for improving seismic safety standards for functional recovery. By 30 June 2020, this committee will *assess and recommend options for improving the built environment and critical infrastructure to reflect performance goals stated in terms of post-earthquake re-occupancy and functional recovery time*. California Assembly Bill 393[4] envisioned that by 30 June 2021 a functional recovery working group, assembled by the California Building Standards Commission, *will consider whether a "functional recovery" standard is warranted and, if it is warranted, investigate the practical means of implementing it.*

In July 2019, ICC and Calbo hosted a roundtable to address the development of a nationally applicable approach to new buildings that remain functional at some point after an earthquake. Discussion participants represented NIST, FEMA, ASCE, EERI, SEAOC, ATC, and more. SEAOC and EERI have initiated efforts that include the formation of distinct functional recovery working groups. EERI published a White Paper,[10] which describes a *Conceptual Framework for functional recovery* that builds on research and practice in four areas: *Definitional*, *Policy*, *Technical*, and *Implementation*.

The cities of Los Angeles, San Francisco, and Seattle have described their needs, plans, and programs for enhancing their earthquake resilience.[14, 37, 38] Ideas, discussions and proposals on the earthquake resilience of cities track back a decade. [39-42]

Learning from Earthquakes

Most devastating earthquakes (excluding tsunami) in history have been shallow earthquakes with the fault rupture close to densely populated regions.[36] Although subduction zone megathrust earthquakes can be destructive, this paper focuses only on shallow earthquakes near densely populated areas. Such earthquakes are documented back thousands of years, starting with the 115 magnitude 7.5 (M7.5) Antioch and 525 M7 Antioch earthquakes (250,000+ deaths in each of them). The earthquake with the largest number of fatalities is the 1556 M8 Shaanxi China earthquake (800,000+ deaths), while earthquakes with tens of thousands of fatalities continue to occur in this century, including the 2008 M8 Sichuan, China, earthquake (85,000+ deaths) and the 2010 M7 Haiti earthquake (150,000+ deaths).

Japan is one of the most seismically active countries in the world. In the 19th century, it experienced seven earthquakes, with fatalities between 1000–3000. [49] The 1923 M8 great Kanto earthquake resulted in 140,000+ deaths. With this history, the 1995 M6.9 Kobe, Japan, earthquake was a milestone for earthquake engineering practice and research. The fault rupture passed through a major urban region of a country that had been at the forefront of earthquake engineering practice, research, and development. There were over 6,000 fatalities and 150,000+ buildings were destroyed. [20] The financial losses were the largest ever reported in an earthquake: $200+ billion.

The United States is not immune to destructive earthquakes. The earthquake with most fatalities in in the United States is the 1906 M7.9 San Francisco, California, earthquake (700–3000 deaths), which destroyed the city of San Francisco. [47] California has been subjected to several damaging earthquakes after the iconic 1906 earthquake. The 1989 M6.9 Loma Prieta (63 deaths,

$6 billion damage) and 1994 magnitude 6.7 Northridge earthquakes (57 deaths, $20 billion damage, $49 billion economic loss) resulted in the largest number of fatalities and financial losses in the last thirty years. [8,9,18,19] The fault rupture for both these earthquakes was not near to many medium-rise or high-rise buildings. In the Loma Prieta earthquake, most of the fault rupture occurred under the forest of Nisene Marks State Park, and urban areas near the fault rupture were largely populated by one- and two-story houses and buildings (e.g., the city of Los Gatos). For the Northridge earthquake, most of the fault rupture was directly under an urban area with mostly one- and two-story housing stock and buildings (e.g., Northridge, San Fernando, Sylmar, and Pacoima). This was the first earthquake to occur in California after the 1933 Long Beach earthquake with the fault rupture so close to an urban area.

Other shallow earthquakes that have occurred at the end of the 20th century and resulted in significant damages are the 1999 M7.6 Chi-Chi, Taiwan, the 1999 M7.6 Izmit, Turkey, and the 1999 M7.2 Duzce, Turkey, earthquakes. The Chi-Chi earthquake provided a wealth of ground-motion data, including ground motions with the largest ground velocities and displacements ever recorded.

The 2011 Christchurch, New Zealand, M6.3 earthquake (185 deaths, $40 billion damage and losses) had a significant impact on earthquake engineering practice and research. The fault rupture in this earthquake was about at about 5 km distance from Christchurch downtown. While only two multi-story buildings collapsed in this earthquake, 70% of the medium and high-rise buildings in downtown Christchurch (population 377,000) were demolished after the earthquake because of foundation, structural, or non-structural damage. Among the demolished buildings were 36 buildings with between 10 and 21 stories; six of them built after 2000. [50] The importance of this poor seismic performance of a significant portion of its building stock in an earthquake with a relatively moderate magnitude has special weight because New Zealand is one of the most developed countries in earthquake structural engineering practice, both academically and professionally.

In shallow earthquakes, the intensity and destructiveness of ground motion is usually largest at sites close to the fault rupture, called "near-fault sites" and the corresponding motions as "near-fault ground motions." The destructiveness of near-fault ground motions depends on several physical parameters: the magnitude and fault-rupture process, the location of the site with respect to the fault-rupture, the soil profiles between the fault plane and the recording site, and the local soil profile at the recording site. According to ASCE 7-16,[1] a site is classified as "near fault" if it is within 15 km of a known active fault capable of producing a M7 or larger earthquake, or if it is within 10 km of a fault capable of producing a M6 or larger earthquake.

With increasing population and the rise of megacities, larger numbers of people will live and work close to major known or unknown faults. The characteristics of near-fault earthquake ground motions and their interrelation with the structural characteristics determines the seismic performance and damage sustained by urban regions and their functional recovery time. The relationship between damage and earthquake distance can be highly nonlinear: five earthquakes at M6.5, 25 km away from five different cities might result in much smaller cumulative damage than a M6.5 earthquake 5 km away from one of these cities. From a broader community resilience point of view, the probability of experiencing a near-fault earthquake in an urban center increases as the urban landscape grows.

Seismic Design Spectra of Western United States

The western part of the United States includes many shallow faults located near urban regions that can result in devastating near-fault earthquakes. The USGS has published a catalog of earthquake scenarios for the entire U.S.[45,46] When compared to the ASCE 7-16 mapped seismic design spectra of some major cities along the West Coast (Los Angeles, San Francisco, Seattle, and San Diego), the city of Los Angeles has the strongest spectrum; San Francisco, Seattle, and San Diego are about 15%, 25%, and 25% smaller, respectively (for site class D). All these cities are extremely vulnerable to near-fault earthquake scenarios.

Today, there are more than 300 near-fault ground motions recorded in fifty earthquakes (worldwide), ranging in magnitude from 6.0 to 7.9. [31] The response spectra of many of these ground motions significantly exceed even the MCE-level event demands for downtown Los Angeles (the strongest design spectrum among the largest West Coast cities).[15,26] Figure 1 compares the envelope spectra of some of the strongest ground motions recorded in six different earthquakes with the MCE spectrum in downtown Los Angeles. The comparison indicates that for near-fault earthquake events of magnitude ranging between 6.2 and 6.9, the strongest ground motions result is spectral demands that match or even exceed significantly the MCE spectral demands of Los Angeles for periods up to 3.5 s. For earthquake magnitude larger than 7.0, the strongest near-fault ground motions match the MCE demands in the 0 s to 3 s period range while significantly exceed the MCE demands for periods longer than 4 s.

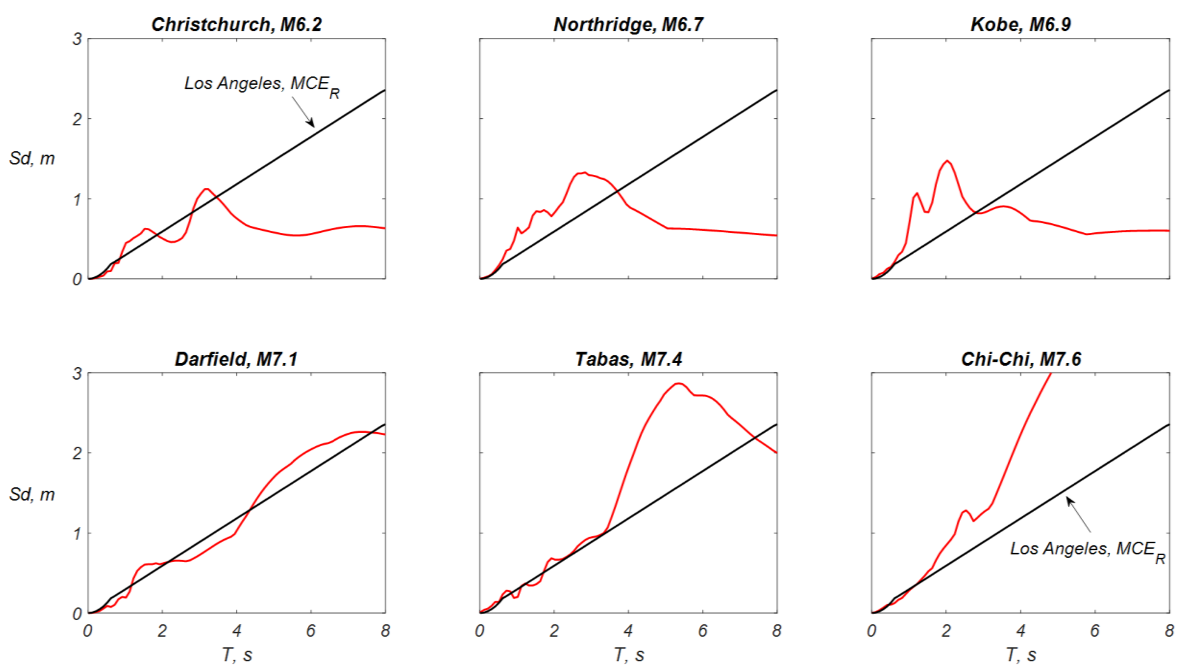

Figure 1. *Comparison of envelope displacement response spectra of some of the strongest ground motions recorded at near-fault sites in six earthquakes versus MCE mapped ASCE 7-16 spectrum of downtown Los Angeles (Site Class D).* [26]

Seismic Design of Buildings in the United States

Most buildings in the United States are designed to satisfy the minimum requirements of ASCE 7. The seismic requirements of ASCE 7 aim at ensuring life safety for the design earthquake and a low probability of collapse for the MCE_R. Code-prescriptive seismic designs of concrete[3] and steel buildings are based on the notion of ductile behavior, which corresponds to structural and non-structural damage in order to reduce seismic design forces and construction cost. Code-prescriptive designs use the results of equivalent elastic analysis, which for large classes of common buildings result in significant underestimation of design forces and displacements.[26, 27-29,33, 44]

Another less common class of buildings follows performance-based-seismic-design (PBSD) requirements. PBSD is used for buildings that exceed specific limit heights or buildings that use alternative materials and/or structural systems not covered by prescriptive code requirements. This class of buildings includes reinforced-concrete wall buildings taller than 240 ft. Performance-based seismic design has also been used to achieve enhanced seismic performance of buildings. For example, the new Long Beach Civic Center was designed to achieve functional re-occupancy and limit repair costs for the design earthquake. [48] Within the generic framework of PBSD, seismic performance objectives are selected individually for each building, and enhanced analysis and design procedures are used until the design criteria are met. Existing PBSD frameworks such as FEMA P58[5] allow for the quantification of the seismic performance and damage after an earthquake, including losses due to required repairs and downtime.

Groups like the LATBSDC and TBI have developed PBSD guidelines for tall buildings.[13,43] One of the main differences of PBSD compared with prescriptive code designs is that PBSD uses nonlinear dynamic analysis, which eliminates the underestimation of seismic demands of the code prescriptive analysis methods facilitating also capacity-based design. [30] The main objective of PBSD guidelines is to prevent collapse for the MCE-level event. Collapse prevention describes a performance level associated with significant and extensive damage, which translates to poor functional recovery.

Another distinct class of buildings and structures are those that incorporate base isolation, which is a mature seismic design technology. In the United States, base isolation is used primarily for essential buildings, some historic buildings and structures, and special or complex structures. Base isolation reduces significantly both structural and non-structural damage (both at DE and MCE hazard levels) and compared to both code-prescriptive and PBSD designs of fixed-base buildings, enhances the functional recovery. Seismic isolation in the United States is not commonly used for residential or office buildings. This is in contrast with Japan where base isolation is used extensively and is now being incorporated into high-rise buildings. [6,7,16,17] As of the end of 2011, there were over 170 isolated high-rise buildings in Japan of height ranging between 60 and 175 m. [6] Seismic isolation of buildings in Japan experienced a huge increase after the 1995 Kobe earthquake. Seismically base-isolated high-rise buildings have been also constructed in Chile.[12]

Future code provisions and functional recovery standards must eliminate the major differences between code prescriptive and PBSD approaches in terms of seismic analysis and design methods. For example, when a code-minimum analysis underestimates significantly design shear forces and story drifts of a building, it results in a false impression regarding the seismic performance and the functional recovery status of the building. [26]

U.S. Frameworks for Community Earthquake Resilience

All recent guides and frameworks for community resilience that have been developed in the United States and described herein were prepared in a generic manner to address all prevailing hazards (earthquakes, wind, fire, inundation, human-caused, etc.). In 2016, NIST published a two-volume-guide on *Community Resilience Planning for Buildings and Infrastructure Systems.* [21,22] This guide supported the *National Preparedness Goal* developed by FEMA[11] in response to a *Presidential Policy Directive*. [32] This guide is a six-step planning process that will enable communities to improve their resilience in a cost-efficient manner. The guide addresses different hazards including earthquakes. The six steps include the: (1) formation of a planning team; (2) understanding the social dimensions and built environment and their interdependencies; (3) determine objectives; (4) develop a plan; (5) prepare and approve a plan; (6) implementing the plan.

The guide defines three hazard levels (Routine, Design, and Extreme) and four performance level definitions for building clusters: (A) *Safe and Operational*; (B) *Safe and Usable During Repair*; (C) *Safe and not usable*; and (D) *Unsafe*. Three functionality levels are defined for building clusters: 30%, 60%, and 90% functional, respectively. The different sizes of the affected areas defined as follows: *Localized*, *Community*, and *Regional*, and are based on the notion that a region includes multiple communities. The guide characterizes the Built Environment as five distinct sectors: *Buildings, Transportation, Energy, Communications, Water, and Wastewater*, which includes their complex dependencies and their link to the *Social Dimensions*. Examples of performance goals are presented and evaluated in three phases: Short-Term (days), Intermediate (Months), and Long-Term (Months).

NIST published, in 2016, a report on *Critical Assessment of Lifeline System Performance: Understanding Societal Needs in Disaster Recovery*. [23] A report on *Research Needs to Support Immediate Occupancy Building Performance Objectives Following Natural Hazard Events* was published by NIST in 2018; [24] it was developed in response to a mandate from U.S. Congress to NIST. The report is organized around four areas: building design, community considerations, economic and social considerations, and acceptance and adoption.

In 2019, the American Society of Civil Engineering published a book titled *Resilience-Based Performance*, which focused on the complex interaction and interdependencies of the economic, social, cultural, and other types of community development within the built environment. [35] The book considers the *physical, functional, geospatial, and informational interdependencies within the built environment.* Its main objective is to create a roadmap for the next generation of resilience-based performance standards and guidelines. As part of the conceptual framework described in this book, Community-Level Resilience Goals are determined before the determination of the Performance Objectives for Vital Community Functions. The main steps of the framework include descriptions of performance objectives and targets for Building Clusters and Individual buildings, respectively. ASCE 41 [2] is used in this framework as a partial analogy and guide. Three types of assessment are described: event-based, scenario-based, and time-based. This framework involves characterization of the community in terms of structure, functions, and supporting infrastructure, including building clusters and lifelines. Metrics of performance and resilience in this framework build on definitions included in the NIST guide.

Technical Solutions for Earthquake Functional Recovery of Buildings and their Bounds

Improving the earthquake resilience at the community level considering the complex interdependencies of the different sectors of the built environment and socio-economic dimensions, requires first to describe the possible technical solutions and their bounds for individual buildings.

This paper describes four main seismic design strategies for both new and existing buildings to reduce post-earthquake structural and nonstructural damage to improve their seismic performance, functional recovery, and resilience. They are: (i) increase of stiffness and strength combined with capacity design; (ii) energy-dissipation (hysteretic and/or viscous) enhancement of fixed-base buildings using dampers; (iii) use of low-damage controlled rocking components; and (iv) seismic (shear) isolation using bearing and damping devices. [26] The feasibility, efficiency, and incremental cost of these strategies depends on the characteristics of the building (height, geometry, etc.) and the performance objectives in terms of repair costs and downtimes at specific seismic hazard levels.

The building response parameter that best relates to overall structural and displacement-sensitive non-structural damage of a building system is the interstory drift ratio (Θ_{int}). For the evaluation of the force-sensitive non-structural damage, floor accelerations are used. The seismic performance evaluation of buildings depends on an evaluation of the performance of interior partitions. Most partitions are significantly damaged when the Θ_{int} is roughly equal to 1% and it is the limit that separates distinct performance levels such as immediate occupancy versus being deemed safe and usable during repairs.

An increase of stiffness and strength is the most traditional strategy to enhance the seismic resistance of a building, with specific limitations and bounds. This method is associated with an increase of design forces and floor accelerations, resulting in larger structural members (i.e., superstructure and foundations) and more expensive anchorage of acceleration-sensitive non-structural elements. This method may become inefficient as the level of seismic hazard increases, and the post-event performance objectives include immediate occupancy. For example, designing a 10-story fixed-base building for safe and usable during repairs when subject to an MCE-level event at a site of high seismic hazard (e.g., downtown Los Angeles) may be much more expensive (if even feasible) than a corresponding base-isolation design.

Using dampers in fixed-base buildings, is an advanced seismic design strategy that can be used, in a cost-efficient manner, to control seismic response and performance at high seismic hazard levels and satisfy architectural requirements.

Buildings that incorporate low-damage rocking components (e.g., post-tensioned rocking concrete walls or post-tensioned rocking steel frames) have increased deformation capacity and concurrently enhanced re-centering capabilities, thus reducing significantly structural damage and residual deformations. The drawback of rocking systems is that for high seismic hazard, significant damage of displacement-sensitive non-structural elements may occur, unless their stiffness and strength increase to correspond to an increase in the size of structural members, increasing costs and unaesthetic architecturally.

By this point, seismic (shear) isolation is a mature seismic design strategy and technology, resulting in cost-efficient buildings built with the expectation of excellent functional recovery even when subjected to extreme seismic hazard, including near-fault earthquake scenarios. Seismic isolation of buildings has been used worldwide, including low-, medium- and high-rise buildings and near-fault sites. Contrary to the other three seismic design/retrofit strategies discussed here, this is the only method that, for most buildings, is cost efficient to build when the objective is to control damage for the MCE at sites of very high seismic hazard; isolation technology reduces forces and interstory drifts enhancing post-earthquake functionality. Seismic base shear isolation is the most effective method for reducing significantly higher-modes response that dominates story shear forces and floor acceleration demands. For most buildings, base isolation may be the most cost efficient and feasible strategy that achieves prompt functional recovery, even when subjected to an MCE-level event near a major fault.

Summary and Suggestions for Ongoing and Future Efforts

Recent legislation in the United States has resulted in the initiation of efforts and discussions among communities to enhance the earthquake resilience of the built environment. At the national level, by 30 June 2020, ongoing efforts will *assess and recommend options for improving the built environment and critical infrastructure to reflect performance goals stated in terms of post-earthquake re-occupancy and functional recovery time*. Ongoing legislation efforts in the State of California envision the development of a functional (earthquake) recovery standard for future adoption by the California Building Standards Commission.

The resilience frameworks provide a generic basis for assessing the socioeconomic dimensions a community will have to address in the event of an earthquake. These frameworks map out the complex interdependencies of the built environment and infrastructure. Future resilience assessments and the development of the functional earthquake recovery standards should include the latest technology available to enhance the earthquake resilience of individual buildings at different seismic hazard levels, including realistic earthquake scenarios or time-based seismic hazard assessments. The quantification of incremental costs for achieving specific levels of functional recovery of several types of buildings is another aspect to consider in developing functional recovery standards. Such seismic performance and incremental cost comparisons of different design strategies exist for specific cases.

For individual buildings and building clusters, a realistic earthquake resilience assessment is highly dependent on the effective description of seismic hazard that best represents these future earthquake events. Defining the threat level and extent of expected damage for different sizes of community (from local to regional) is necessary. History has shown repeatedly that shallow earthquakes near densely populated areas have the greatest loss of life and damage. Thus, a realistic realization and description of the possible shallow earthquake scenarios near major urban regions of U.S. is an essential step.

With recent advances in earthquake structural engineering research and the development of earthquake-resilient technology, cost-efficient buildings that can sustain most of the strongest and most destructive near-fault ground motions ever recorded can now be built. Limitations as to the level of functional recovery that can be achieved for different types of buildings located in highly seismic regions will continue to exist but is important that the seismic risk be clearly described and quantified.

References

1. ASCE 7, 2016. *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* [ASCE/SEI 7-16]. American Society of Civil Engineers, Reston, Virginia.
2. ASCE 41, 2017. *Seismic Evaluation and Retrofit of Existing Buildings* [ASCE/SEI 41-17]. American Society of Civil Engineers, Reston, Virginia.
3. ACI-318. (2019). Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-19). Farmington Hills, MI: American Concrete Institute.
4. Assembly Bill 393, 2019. “Building codes: earthquake safety: Functional Recovery Standard” California Legislature – 2019-20 Regular Session. Introduced by Assembly Member Nazarian, February 6; Amended in Senate, May 29, 2019. Link
5. ATC, 2012. *Seismic Performance Assessment of Buildings* [FEMA P-58]. Federal Emergency Management Agency.
6. Becker TC, Yamamoto S., Hamaguchi H., Higashino M., Nakashima M. (2014). Application of isolation to high-rise buildings: a Japanese design case study through a US design code lens, Earthquake Spectra 31 (3), 1451-1470.
7. Calugaru, V., and Panagiotou, M. (2014) “Seismic Response of 20-story Base-isolated and Fixed-base RC Structural Wall Buildings at a Near-fault Site,” *Earthquake Engineering and Structural Dynamics*, Vol. 43, Issue 6, pp. 927-948. Link
8. EERI, reports on 1989 Loma Prieta Earthquake. Link
9. EERI reports on 1994 Northridge Earthquake. Link
10. EERI, 2019. Functional Recovery: A Conceptual Framework. Link

11. Federal Emergency Management Agency (FEMA 2015a) National Preparedness Goal, Federal Emergency Management Agency (FEMA), Washington, DC. Link

12. Lagos R., Boroschek R., Retamales R., Lafontaine M. (2014). Seismic Isolation of the Nunoa Capital Building, The Tallest Base Isolated Residential Building in the Americas, Tenth U.S. National Conference on Earthquake Engineering.

13. LATBSDC (2019). An Alternative Procedure for Seismic Analysis and Design Of Tall Buildings Located In The Los Angeles Region. Link

14. Los Angeles, City. (2018). Resilient Los Angeles. Link

15. Lu, Y., and Panagiotou, M. (2014). "Characterization and Representation of Near-fault Ground Motions Using Cumulative Pulse Extraction with Wavelet Analysis," *Bulletin of the Seismological Society of America*, 104:410-426. Link

16. Lu. Y., and Panagiotou M. (2015). "Earthquake Damage Resistant Tall Buildings at Near Fault Regions Using Base Isolation and Rocking Core Walls," Structures Congress, Portland, Oregon.

17. Nakagawa K., Shimazaki D., Yoshida S., Okada K. (2015). Application of Seismic Isolation Systems in High-Rise Buildings, Council on Tall Buildings and Urban Habitat Journal. Issue II.

18. NIST SP 778 (1990). Performance of Structures During the Loma Prieta Earthquake of October 17, 1989. Link

19. NIST SP 862 (1994). 1994 Northridge Earthquake: Performance of Structures, Lifelines and Fire. Link

20. NIST, 1996. January 17, 1995 Hyogoken-Nanbu (Kobe) Earthquake: Performance of Structures, Lifelines, and Fire Protection Systems (NIST SP 901). Link

21. NIST SP1190 (2016). *Community Resilience Planning Guide for Buildings and Infrastructure Systems – Volume I.* U.S. Department of Commerce, National Institute of Standards and Technology.

22. NIST SP1190 (2016). *Community Resilience Planning Guide for Buildings and Infrastructure Systems –Volume II.* U.S. Department of Commerce, National Institute of Standards and Technology.

23. NIST (2016). "Critical Assessment of Lifeline System Performance: Understanding Societal Needs in Disaster Recovery," NIST GCR 16-917-39, Prepared by Applied Technology Council for the National Institute of Standards and Technology, Gaithersburg, MD. Link

24. NIST SP 1224. (2018). *Research Needs to Support Immediate Occupancy Building Performance Objective Following Natural Hazards Events.* U.S. Department of Commerce, National Institute of Standards and Technology.

25. Online School of Earthquake Resilient Design. Los Angeles, California.

26. Online Course on Earthquake Resilient Buildings, Online School of Earthquake Resilient Design, Los Angeles, CA.

27. Panagiotou, M., Restrepo, J.I. (2011). "A Displacement-Based Method of Analysis for Regular Reinforced Concrete Wall Buildings: Application to a Full-Scale 7-Story Building Slice Tested at UC San Diego." *ASCE Journal of Structural Engineering*, Vol. 137, No. 6. **2012 Alfred Noble Prize**. Link

28. Panagiotou, M., Restrepo, J.I., and Conte J.P. (2011). "Shake Table Test of a 7-Story Full Scale Reinforced Concrete Wall Building Slice, Phase I: Rectangular Wall." *ASCE Journal of Struct. Engineering*, Vol. 137, No. 6. Link

29. Panagiotou M, (2017), "Seismic Response of Medium-rise and Tall RC Core-Wall Buildings at Near-fault Regions and Simplified Calculation of Design Demands," Proceeding of Annual Conference of Los Angeles Tall Buildings Seismic Design Council. Link

30. Paulay T, Priestley MJN. Seismic Design of Reinforced Concrete and Masonry Buildings. John Wiley & Sons, Inc., Hoboken, NJ. 1992.

31. PEER ground motion database NGA WEST2. Berkeley, California. Link

32. PPD-8 (2011) Presidential Policy Directive, PPD-8 – National Preparedness, The White House, March 30, 2011, Link

33. Priestley MJN, Calvi GM, Kowalsky MJ. Displacement Based Seismic Design of Structures. IUSS Press, Pavia, Italy. 2007.

34. Public Law No: 115-307, Senate Bill 1768, 2018. "National Earthquake Hazards Reduction Program Reauthorization Act of 2018." 115th Congress. Link

35. Risk and Resilience Measurement Committee, 2019. *Resilience-Based Performance: Next Generation Guidelines for Buildings and Lifeline Standards.* American Society of Civil Engineers.

36. Ritchie H. (2018). What were the world's deadliest earthquakes. Our World in Data. Link

37. San Francisco, City and County of, 2016. *Resilient San Francisco*. City and County of San Francisco, April 2016. Link

38. Seattle, City (2018). Seattle Future City: Resilience Roadmap. Link

39. SPUR. (2009a). "The Resilient City: Defining what San Francisco needs from its seismic mitigation policies." Link

40. SPUR, (2009b). "The Dilemma of Existing Buildings: Private Property, Public Risk." Link

41. SPUR, 2009c. "Building it Right the First Time: Improving the Seismic Performance of New Buildings." Link

42. SPUR, 2012. "Safe Enough to Stay." Link

43. Tall Buildings Initiative (2017). Guidelines for Performance-Based Seismic Design of Tall Buildings," Version 2.03. Link

44. Visnjic, T., Panagiotou, M., and Moehle J.P. (2015). "Seismic Response of 20-Story Reinforced Concrete Special Moment Resisting Frame Buildings Designed with Current Code Provisions," *Earthquake Spectra*, Vol. 31, No. 2. Link

45. USGS, Earthquake Scenarios Catalog. Link

46. USGS, Earthquake Scenario Map (BSSC 2014).

47. USGS, Casualties and Damage After the 1906 San Francisco Earthquake. Link

48. Youssef N., Sarkisian M., Hata O., Long E., Krebs A., Ibbi A., and Hazelton C. (2016). Designing for Resiliency: Long Beach Civic Center – A Case Study, Annual Conference of LATBSDC. Link

49. Wikipedia, List of Earthquakes in Japan. Link
50. Wikipedia, Christchurch's Tallest Buildings. Link

Acronyms and Abbreviations

ACI	American Concrete Institute
AISC	American Institute of Steel Construction
ASCE	American Society of Civil Engineers
ATC	Applied Technology Council
CALBO	California Buildings Officials
Caltrans	California Department of Transportation
CBC	California Building Code
EERI	Earthquake Engineering Research Institute
ICC	International Code Council
FEMA	Federal Emergency Management Agency
LATBSDC	Los Angeles Tall Buildings Structural Design Council
MCE	Maximum Considered Earthquake
MCE_R	Risk-targeted Maximum Considered Earthquake
NEHRP	National Earthquake Hazards Reduction Program
NIST	National Institute of Standards and Technology
PBSD	Performance-based Seismic Design
PEER	Pacific Earthquake Engineering Research Center
SEAOC	Structural Engineers Association of California
TBI	Tall Buildings Initiative
USGS	United States Geological Survey