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New Developments in Resilience-Based Seismic Design and Enhanced Building-Specific Risk Assessment in the U.S.

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Abstract

Over the past many decades, building codes in the United States (and similarly in numerous other countries) have continually sought to improve the protection of life safety in the event of an earthquake. With the focus on life safety, the other aspects of seismic performance, such as direct economic losses and building repair times, have gone largely unconsidered. This has resulted in U.S. earthquakes causing fairly low numbers of fatalities but having very large economic costs, both in terms of direct economic losses and the long societal recovery time (e.g. 1994 Northridge). Similar trends can be seen in other recent earthquakes in developed countries around the world (e.g. Christchurch, New Zealand). In the U.S., the current building design approach and infrastructure, do not provide societal resilience in the event of a large earthquake in a populated region.

The engineering community has turned a focus to resilience-based design and enhanced seismic risk assessment, with the goal of better understanding economic losses due to earthquakes (both direct loss and loss due to building closure). The FEMA P-58 Methodology (which was released in 2012) now provides an analysis method that gives unprecedented building-specific information about building resilience for earthquakes, providing information for all three resilience dimensions (safety, repair cost, and repair time). With the introduction of this new technology, an emerging viewpoint is that such beyond-safety considerations should be included in the design of a least some classes of structures. This paper discusses the emerging trend of resilience-based design in the U.S., including recent policy decisions, and examples of formative seismically resilient building projects.

Keywords: Seismic loss assessment; FEMA P-58; Resilient design

1. Introduction

The United States Congress declared, in the National Earthquake Hazards Reduction Program Reauthorization Act of 2004, that all 50 States are “vulnerable to the hazards of earthquakes”, though a fraction among them are exposed to much higher hazard. Every American is a stake holder in the resilience of the country’s building stock and while modern buildings are well designed to meet code requirements, a large disconnect exists between the public perception that buildings will be functional or repairable following an earthquake and the reality that the main intent of the building code is to protect life-safety. Based on experience from earthquakes in the United States, modern buildings tend to fulfill their designed purpose of protecting the lives and safety of occupants in most seismic events. However this performance leaves much to be desired in terms of direct economic loss and downtime. From the U.S. Federal Government down to individual municipalities and engineers, the interest in seismically resilient design seems to be gaining momentum.

The fundamental question is what the goals of building design are (and what they should be). Building design (e.g. ASCE 7) almost always focuses on the goal of safety and rarely if at all directly considers the other aspects of building performance (repair cost and repair time). Similarly, assessments of existing buildings (e.g. by ASCE 41) also focus on safety only and do not typically consider the other aspects of performance. Though one can argue that some aspects of these design and assessment approaches consider beyond-safety criteria (e.g. importance factors, immediate occupancy limit states, etc.), they are approximate at best.

Interest in the topic of resilient design has grown, from the federal level, down to the local level, but the fundamental technology to support resilient design has not been available. With the development of the FEMA P-58 Methodology in the U.S., and its release in 2012, the technology is now available to complete a building-specific seismic risk assessment that quantifies three dimensions of performance (safety, repair cost, and repair time). Giving unprecedented information about building performance and enabling resilience-based seismic design in a way that was never before possible.

This paper explores the current trend of resilient seismic design in the U.S. and how the introduction of the FEMA P-58 Methodology can support the implementation of resilient design approaches being applied in practice.

2. State of Resilient Design in the United States

The development of building code has tended to lag behind lessons learned from highly damaging earthquakes. The Uniform Building Code (UBC) was the first code to apply any seismic design provisions. They were initially implemented within its appendix in 1927 in response to the 1925 Santa Barbara Earthquake. However these provisions were not shifted into the body of the code until 1961 [1]. The concept of “performance-based” design was put forward in the 1970s following the San Fernando Earthquake in which significant damage and collapse was observed in several hospitals. The concept of “performance-based” design provisions were first implemented into code indirectly through occupancy importance factors in the 1976 UBC [2]. However, “performance-based” design has focused on the safety dimension of building performance and has not typically included consideration of building repair costs or repair time.

In contrast to “performance-based” design, “resilience-based” design is an emerging approach of designing a building directly considering three dimensions of resilience (safety, repair cost, and repair time). The two design concepts are similar, the building design in either case is based on demonstrating adequate performance using some quantitative analysis method, the difference comes in the performance objectives. We are excited about this concept of resilience-based design and its emerging use in the U.S. structural engineering practice.

2.1 U.S. White House Executive Order

On February 2, 2016 the United States President issued an Executive Order: *Establishing a Federal Earthquake Risk Management Standard*. This Order states that it is the "policy of the United States to strengthen the security and resilience of the Nation against earthquakes, to promote public safety, economic strength, and national security". It requires that all executive departments and agencies strive for resilience in their new and existing buildings. The performance goals for government buildings are outlined not only to protect life-safety, but also to support "essential functions" following an earthquake. To achieve resilient seismic design, agencies are directed towards the seismic provisions in the International Building Code or similar sources for new design. Buildings existing prior to the Order are required to use the Standards of Seismic Safety for Existing Federally Owned and Leased Buildings. The Order further acknowledges that to attain resilience, measures beyond code requirement may be necessary and suggests agencies should aim to exceed the code requirements [3].

2.2 The United States Resiliency Council

The United States Resiliency Council (USRC) was born out of the Structural Engineers Association of Northern California (SEAONC) Building Rating Committee and officially launched as a non-profit organization in November 2015. The overall goal of the USRC is to improve the resilience of the United States building stock and how it effects society. This goal is addressed through the implementation of a rating system to capture the performance of buildings in seismic events (in the future this rating system will consider other natural disasters as well) and to inform the public on these risks. The rating system assigns a one to five star resiliency rating based upon three kinds of loss: 1) human casualties 2) building downtime 3) direct economic loss.

Sixty-four Founding Members from a range of industries including engineering and architectural companies and technical organizations signed on to support and lead the USRC as they seek to perform a similar function in resilient design as the United States Green Building Council did for sustainable design [4]. As this paper is being written, the USRC is accepting applications from Professional Engineers to facilitate official building ratings and the first analyses to support ratings are underway.

2.3 Resilience by Design, Los Angeles, California, U.S.

In Los Angeles California, the current condition of the existing building stock and the recoverability of the urban environment after an earthquake have become a major concern to the public. A program called *Resilience by Design* was released by the Los Angeles Mayors Office in 2014 with the goal of defending the lives, economy and recovery of the residence of Southern California following an earthquake [1]. The document identifies three main areas capable of causing extensive losses in an earthquake: the building stock, water systems, and communications systems.

The document notes that, "building codes are not retroactive". In an effort to protect life-safety in pre 1980s structures non-ductile reinforced concrete frame buildings and soft-first-story buildings were singled out for retrofit. These structures have had higher probability of collapse in past earthquakes. To prevent future deaths, Los Angeles set a requirement to retrofit these buildings for life safety. In October 2015 the recommendation that non-ductile frames and soft-story buildings be retrofit became mandatory based on a unanimously passed ordinance [5].

Reaching beyond the baseline goal of life safety, the time to rebuild and recover not only building stock but the local economy, population and culture following natural disasters was noted as unacceptably long (possibly on the order of decades). Further the cost of considering resilient design before an earthquake has been shown to be a fraction of the cost to clean-up after an earthquake. To this end voluntary participation in the United States Resiliency Council Rating System for building resilience was recommended to encourage resilient design and inform the public on the level of risk associated with particular buildings. It was further recommended that buildings owned by the city be rated using the USRC Building Rating System.

3. Demand for Resilient Design

The extensive economic losses and long recovery time following seismic events in the United States, Japan, New Zealand, and Chile have provided strong evidence that only addressing life-safety component in building design does not give the complete picture of seismic risk (The Northridge earthquake in 1994 caused an estimated $13-20B USD in losses). The best way to significantly reduce these losses is to change our expectations of how buildings should perform jointly with how we design buildings for specific performance. FEMA and many engineering professionals regard performances-based design as one of the best tools to achieve a better understanding of damage and loss following seismic events.

Modern code treatment of performance based engineering is split between two documents, ASCE 7 for new design and ASCE 41 for existing structures. The American Society of Civil Engineers (ASCE) first published ASCE 7 – Minimum Design Loads for Buildings and Other Structures in 1988. However it was not until ASCE 7-10 that building performance was considered through the inclusion of the Risk Category based on building occupancy. The American Society of Civil Engineers (ASCE) published the ASCE 31 in 2003 and ASCE/SEI 41 in 2006 standards which have since been collected into a single document ASCE 41-13 – Seismic Evaluation and Retrofit of Existing Buildings. This standard defines qualitative performance levels (Immediate Occupancy, Damage Control, Life Safety, Limited Safety, Collapse Prevention) [7].

Though ASCE 7 and ASCE 41 indirectly set building performance objectives through the risk category and qualitative performance levels respectively, they do not provide metrics that facilitate decision making in the building design process. Further there is not clear correlation between performance levels in new and existing buildings designed or evaluated/retrofitted using the two different methods. ASCE 7 and 41 alone are incomplete tools in discovering the full picture of seismic risk.

Along with the need for the correct tools to analyze and assess seismic risk, the need for a specific level of performance must be understood by a whole host of stake holders and decision makers. Metrics that make sense to engineers designing buildings (e.g. 2% interstory drift limit at a design level event) are not useful to building owners or inhabitance. Nor does the requirement “I want my factory to regain operation within 3 days of an earthquake.” translate neatly into a section of building code. To be successful at selecting and designing for less damage and loss following an earthquake, all of the stakeholders (engineers, architects, insurers, owners, inhabitance, ...) must be able to speak the same language in terms of necessary building performance. These needs demand a robust method capable of realistically estimating monetary, downtime, and human losses for individual buildings.

Several methods of analyzing building performance have been proposed and adopted over the years, each method differing in rigor, source, applicability, and results metrics. The Thiel Zsutty Method, ATC-13, and HAZUS are all able to estimate the risk of building classes in differing seismic areas, but none are able to quantify and capture building specific parameters of seismic risk, and therefore are not refined and powerful enough to aid the progression of resilient based design.

In order to incorporate a full picture of resiliency into the design process, we as engineers need a method for assessing seismic risk and resilience that is mathematically rigorous and statistically expansive. We need a method that is founded on real observations and experimentations. We need a method that is able to capture the effects that building specific details have on risk and resilience. We need a method that allows us to communicate building performance to other stake holders.

4. FEMA P-58 Seismic Performance Assessment of Buildings

The FEMA P-58 Method was developed by ATC under the funding and direction of FEMA and published in 2012 [11]. It is based on laboratory testing and intended for the rigorous analysis of individual structures at any site. It employs Monte Carlo Simulation to directly consider seismic demands, structural components, non-structural components, and occupancy as probabilistic variables. The results are provided in terms of casualties, direct economic loss and repair time. Though other methods for loss analysis have sprung up over the past 30 years or so, none but the FEMA P-58 Methodology were intended to analyze single structure responses at the necessary level of detail. The FEMA P-58 Methodology was created to respond to the need for clearer loss estimation; balancing rigorous analysis with efficient implementation.

4.1 The FEMA P-58 Method

The P-58 Methodology resulted initially from the FEMA 349 Action Plan for Performance Based Seismic Design created by PEER in 2000. The FEMA Action Plan sought to fulfill one of FEMA's fundamental goals, "prevention, or mitigation, of this country's losses from natural hazards." through performance based design criteria that would enable the nations engineers to select levels of performance beyond life-safety for critical buildings. ATC was brought on board and the goals for the ATC-58-1 Project were laid out as follows: build a framework that considers limitations and uncertainty in predicting earthquake hazard, define performance levels which facilitate decision-making, build a procedure to estimate the performance of new and existing buildings, and update and expand the assessment of the seismic performance of structural and non-structural building components. In 2012 the first phase of P-58 was complete and a methodology along with supporting documentation was made available.

The P-58 Method is rooted in the performance based earthquake engineering framework constructed by the Pacific Earthquake Engineering Research Center (PEER). The PEER framework employs the total probability theorem to obtain probabilistic losses. The P-58 Methodology adapts to simplify the determination of losses by employing Monte Carlo Simulation and varying demands, building component strengths, occupancy, consequences, and other factors based on defined probabilistic distributions. Figure 1 below provides a simplified procedure for the P-58 method.

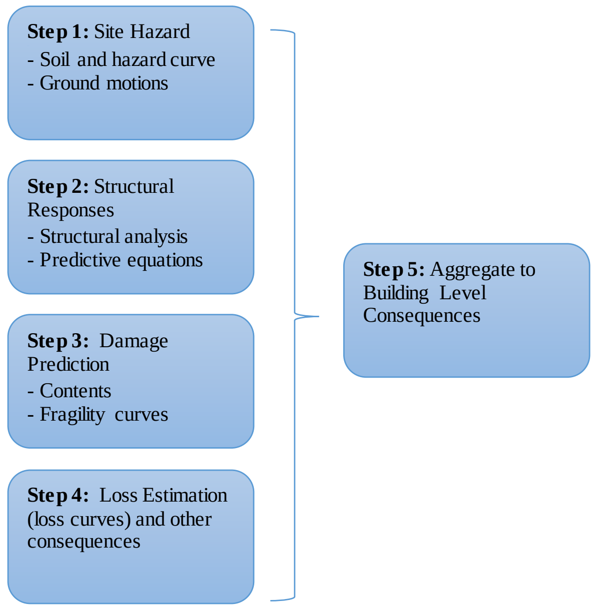

Fig. 1 - FEMA P-58 Analysis Overview

The methodology may be employed to assess the expected losses in existing buildings, inform design on new buildings or inform the retrofit of existing buildings. The expected losses are presented in terms of casualties, repair cost, repair time, and unsafe placarding. Several types of analysis are available through P-58: intensity-based, scenario-based, and time-based.

4.2 The Benefits of FEMA P-58 Providing Detailed Building-Specific Information

The advantages of the P-58 Method are many. The method is designed to provide accurate results for individual buildings, enabling the method to support single structure and grouped structure analysis. The methodology is objective and rigorous, built on data and research rather than expert opinion. This rigor enables identifiable cause and effect relationships detailed enough to inform the building design process. The results are reported in metrics that allow clear performance requirements to be set and decision making amongst varied stakeholders. With P-58, engineers are able to fully incorporate resilient design parameters into their design process without losing modeling accuracy and statistical significance.

4.3 The FEMA P-58 Method Present and Future

The desire to evaluate building performance, design buildings beyond code required resiliency and implement the FEMA P-58 Methodology specifically are gaining traction in the United States. The support for the method comes from different directions. The United States Resiliency Council (USRC) has selected the method for its rating system, Los Angeles has recommended USRC Ratings (and thus the FEMA P-58 Method) through its Resilience by Design document, and demand for the method is spreading amongst building owners and local municipalities interested in higher performance for their critical buildings.

4.4 Continuing Development of the FEMA P-58 Method

A follow-up effort on the part of ATC under the direction of FEMA began in 2012 and will conclude in the fall of 2017. The directive for this effort is to refine the published FEMA P-58 Methodology and to expand the methodology. Expected updates to the fragility database and repair time calculations are under development. One exciting direction for expansion is into the sustainability realm. Work is underway to expand the methodology to provide environmental impact in the form of CO_2 emissions, energy usage and solid waste creation [2].

Looking further into the future this Methodology has the capability to spread into fields outside of engineering. The results provided plainly in casualties, repair time and direct economic loss make the methodology accessible to the gamut of stake holders; from investors to insurers and beyond.

4.5 Research-Design-Industry Link

As previously mentioned, the FEMA P-58 Method is unique in that it is built upon real test data. Laboratory tests of structural and non-structural components were used in the creation of the fragility functions defining building components in the FEMA P-58 database. The ability to create component fragilities based on sound component testing creates a new link between researchers and component producers to effect resilient design. As more researchers and component producers provide the data for a wider fragility database, the FEMA P-58 Methodology will be strengthened and the process for resilient design fortified by the broader array of fragility components.

4.6 Recent Application of FEMA P-58 in U.S. Structural Engineering Practice

An early example of resilient design through the FEMA P-58 Methodology is the new Long Beach City Hall Building. The City of Long Beach required in the RFP that building be designed for the following recovery in the event of a Design Level Earthquake: Functional Recovery within 30 days, Re-occupancy within 7 days, experiencing little to no casualties, and less than 5% loss relative to the building replacement value. Nabih Youssef and Associates Structural Engineers accepted the challenge to design to these strict requirements. The FEMA P-58 and REDi Methodologies were used to inform the design of the 11 story reinforced concrete structure and to evaluate the performance of the design under the acceptance criteria set by the City of Long Beach. The final design was selected through iterations of loss analyses resulting in a system of reinforced concrete shear walls and concrete columns supporting post tensioned concrete slabs. [12]

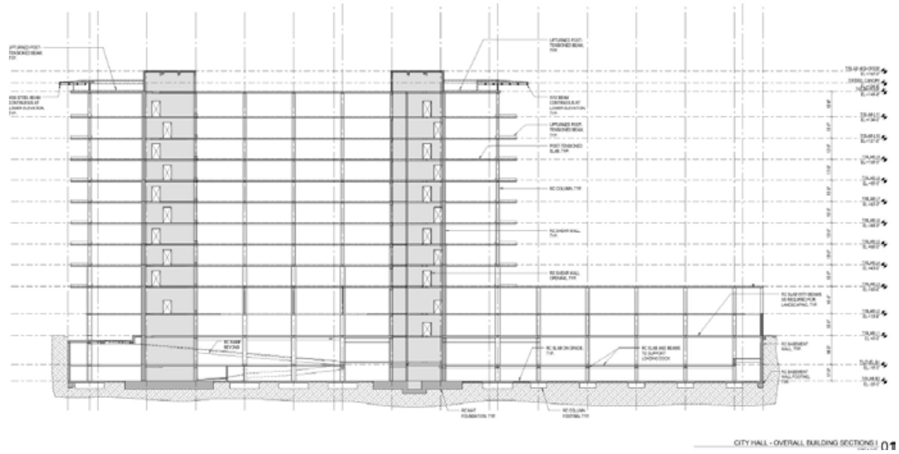

Fig. 2 Long Beach City Hall Building Elevation (courtesy of NYASE)

5. Conclusion

This paper has reviewed the emerging trend of resilience-based design in the U.S., where a building can be designed to meet performance objectives in terms of safety, repair cost, and repair time (which is in contrast to the concept of performance-based design, which just looks at safety considerations). There are substantial efforts underway in the U.S. to advance resilience-based design, and the introduction of the FEMA P-58 Methodology provides the technical underpinnings for delivering on this new type of design approach. We look forward to seeing how this develops in the future.

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