Considerations for a Framework of Resilient Structural Design for Earthquakes

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Abstract

Building code seismic design requirements for structures were established primarily to protect occupants from injury and death. These seismic design requirements represent minimum standards that have been developed to protect the safety of the general public. Limiting earthquake damage or achieving post-earthquake functionality has historically not been a direct goal, but rather a secondary, hoped-for outcome that has had mixed results. An exception to this in current code is that the design of Risk Category IV structures also conceptually aims to limit damage and provide functionality, but it has not been definitively demonstrated whether current prescriptive requirements will meet this goal reliably.

The general public, for the most part, is unaware of the intent of the building code, and often expects a new code-compliant building to provide a higher level of earthquake performance than what is actually the goal of the code. Those who are aware of these limitations generally express a strong desire for greater earthquake resistance, at least to ensure post-earthquake habitability and often expecting post-earthquake functionality and limited repair cost (Davis and Porter, 2016). This paper presents a framework for resilient seismic design provisions that may be used to specify supplementary requirements and achieve better post-earthquake performance that aligns better with building owner and user expectations than the performance typically achieved by complying with the minimum building code design requirements. Various seismic performance goals and design methodologies are discussed for structural and non-structural components. Second-generation performance-based earthquake engineering techniques are described along with building characteristics that promote seismic resilience. Using the framework, one can address performance metrics expressed in terms of repair costs, life-safety impacts, and loss of function (also referred to as dollars, deaths, and downtime).

Introduction

This paper is written for audiences interested in structural engineering and the contribution that the design of the structure and components of a building can have in resilience of the built environment. The primary focus of the paper is on the lateral design of buildings subjected to the forces of a large earthquake. In the broader picture, the shock of an earthquake is only one of the many stressors to our buildings and our communities as a whole. Achieving resilience for our communities requires the combination of the individual performance of each building plus every other element of our community (such as lifelines and infrastructure to name a couple). In this paper references to "resilient design" or "resilience" means that the goal is for the building to have limited damage in an earthquake (or any design hazard), such that the repair costs and repair time are low, resulting in functionality that is either minimally affected or can be restored relatively quickly and economically. Another commonly used phrase is "immediate occupancy design" which also means high resilience to a design earthquake. This is in contrast to the typical building-code-based design approach, which focuses primarily on minimum requirements for safety (not controlling repair costs and repair time) which can lead to building designs that may be not functional or economically repairable after a strong earthquake.

This paper is also targeted at an audience that is interested in an analytical approach to resilient design rather than one based on empirical evidence or engineering judgment. This paper is also currently written in language tailored to structural engineers, but the content is also useful to other audiences such a building officials and municipal officials interested in resilient design for their jurisdiction. By an analytical approach, we mean one quantifies the expected performance and checks that the design meets goals in those terms.

This paper provides an overview of what needs to be accomplished for a building to be seismically resilient, how a design can be done using non-prescriptive design methods, and how prescriptive design methods could be calibrated to provide a resilient design. By prescriptive design, we mean design to meet requirements like those in the International Building Code and the International Residential Code, where most of the tests of compliance are binary, i.e., pass or no pass, without quantifying performance in terms of dollars, deaths, or downtime.

As the structural engineering profession now enters its 5th generation of modern earthquake engineering practice and 2nd generation of performance-based design, we are looking to go beyond the basic foundations of life-safety and collapse prevention as the default or minimum target for strong earthquakes. The five generations of modern earthquake engineering as identified by the milestones: 1) seismic design code language introduced in the 1927 UBC, 2) the SEAOC Blue Book in 1959, 3) load and resistance factor design and 4th edition Blue Book in 1974, 4) change to strength design and the 1997 UBC provisions. The first-generation performance-based seismic engineering being marked by the publication in 1995 of SEAOC Vision 2000.

Knowledge, methodologies and computing technology are now prevalent and accessible enough that the typical structural engineer can design for higher levels of earthquake performance. Implementation of above-code design is purely voluntary for most buildings, at least as of this writing, although that might change in the near future. Establishing improvements in minimum requirements and standards of practice will be necessary to consistently design new buildings for resilience on a systematic basis. This paper discusses such a framework for the implementation of resilient design requirements for earthquakes by individuals, institutions, and jurisdictions.

Define Quantitative Resilience Goals

Let the phrase "resilient design" mean design of buildings so that they can be economically returned to use quickly after an earthquake or other disaster for which they are designed. The definition of design goals for resilient design are generally framed in terms of amount of acceptable damage or loss of functionality in dollars and downtime relative to specific disaster scenarios or hazard probabilities.

The selection of appropriate earthquake performance goals for the design of new buildings and retrofit of existing ones is one of the most important aspects of a resilient design program. The technical community (i.e., scholars and practitioners) must clearly inform policymakers and other stakeholders about the risks and benefits of various design options, in relatively clear but nontechnical terms, meaning with little use of probabilities, mean recurrence intervals, and vaguely defined performance measures. Input from the community and property stakeholders must be obtained to craft goals that meet expectations. Actual selection of the goals are often made by those who have vested interest in protecting their assets, by building officials who represent the public's interests, and sometimes by city councils or other local elected officials (e.g., Mayoral Seismic Safety Task Force, 2015). The appropriate solution for each community, hazard, and building may vary. Examples of such programs may be found in Washington State "A Framework for Minimizing Loss and Improving Statewide Recovery after an Earthquake" (2012), and San Francisco Planning and Urban Research Association "The Resilient City" (2010).

Building-level performance metrics such as post-earthquake functionality, occupiability and repairability have been identified by committees in professional societies (e.g., SEAOC, 1996), in research (e.g. Burton et al., 2015), practice (e.g. Alfamuti et al., 2014) and advocacy groups (SPUR, 2012) as being directly appropriate for resilience-based design and assessment. Post-earthquake functionality implies that, following the earthquake, the building is accessible, safe to occupy (no major safety concerns) and the components and subsystems that are essential for functionality are not compromised. On the other hand, post-earthquake occupiability refers to the case where the building may not be fully functional, but the users can safely occupy it or "shelter-in-place." The goal of the repairability performance level is to avoid the need for technically or economically infeasible post-earthquake repairs.

In the manner of ASCE 41-13 (ASCE, 2013), building performance objectives can be defined by coupling the performance levels described earlier with specific hazard levels. Examples of such seismic hazard levels include 50% probability of exceedance in 30 years (43-year return period) and 50-year probabilities of exceedance ranging from 2% (2,475-year return period) to 50% (72-year return period). Table 1 shows a set of hypothetical resilience-based performance objectives, which are identified using alphabetical labels, pairing the aforementioned performance levels with ASCE 41-13 seismic hazard levels. Note that the collapse-prevention level, which is primarily related on life safety, is also included. The performance levels shown in Table 1 are all defined based on the immediate post-earthquake condition of the building. An alternative or complementary set of performance levels can be defined based in the time needed to restore building functionality or occupiability. Hypothetical examples of such recovery-based performance objectives are shown in Table 2.

Table 1 - Hypothetical resilience-based objectives

Seismic Hazard Level	**Building Remains Functional**	**Building is Occupiable (may not be fully functional)**	**Building is Repairable (may not be immediately occupiable)**	**Collapse Prevention (building may not be repairable)**
50%/50 years	A	B	C	D
20%/50 years	E	F	G	H
5%/50 years	I	J	K	L
2% in 50 years or MCE_R	M	N	O	P

Table 2 - Examples of recovery-based performance objectives for resilient design

Seismic Hazard Level	**Time to Restore Functionality**			**Time to Restore Occupiability**	
	Less than One Month	**One to Six Months**	**More than One Year**	**One to Six Months**	**More than One Year**
50%/50 years	A1	A2	A3	B1	B2
20%/50 years	E1	E2	E3	F1	F2
5%/50 years	I1	I2	I3	J1	J2
2% in 50 years or MCE_R	M1	M2	M3	N1	N2

Contemporary resilience-based design approaches (e.g. REDi, 2013; USRC, 2015) build on the previous thinking and then set specific targets for repair cost and repair time, so the building design can be tailored to the level of resilience desired. An example of such requirements, used by the U.S. Resiliency Council (2015) are shown in Table 3:

Table 3 - Example performance targets for building resilience

Level of Resilience	**Maximum Damage (% value)**	**Maximum Recovery Time**	**Safety**
Platinum	5%	5 days	Safe
Gold	10%	4 weeks	Safe
Silver	20%	6 months	Safe
Bronze	40%	1 year	Safe

Resilience Assessment Methods and Tools

Practicing engineers need tools and methods to evaluate structural designs to ensure that the desired resilience-based performance objective is achieved. The second-generation performance-based earthquake engineering framework, detailed in the FEMA P-58 guidelines (FEMA, 2012a), represents the current state of the art in assessing the seismic performance of buildings using the stakeholder driven metrics that are relevant to resilience. In the absence of a set prescriptive design guidelines for achieving resilience, the FEMA P-58 methodology can be used assess physical damage and losses and iteratively design the building to meet the stated resilience objective. Computer programs such the ATC Performance Assessment Calculation Tool (PACT) (FEMA, 2012b) and the Seismic Performance Prediction Program (SP3) (SP3, 2017) can be used to facilitate this process.

The FEMA P-58 methodology includes an explicit assessment of physical damage to both structural and non-structural components, which are then used to estimate direct economic losses, life-safety impacts, and measures of post-earthquake safety and repair time. An assessment of collapse risk using nonlinear structural response simulations (FEMA, 2009) or more a simplified approach is also integrated into the FEMA P-58 methodology and is especially important for estimating injury- and fatality-related losses. While not as well-grounded in theory as repair cost and the collapse limit state, the measures of post-earthquake functionality, post-earthquake safety, and repair time are also computed and can be used to address other, more-indirect earthquake consequences such as the cost of downtime.

The application of the FEMA P-58 methodology requires as assessment of the structural response (story drift ratios, floor accelerations and local deformations) due to earthquake shaking at a single or range of ground motion intensity levels. These demand parameters (DPs) are some of several important inputs to estimate damage and loss. The best estimate of these DPs can be obtained from nonlinear response history analyses (NRHA). However, because of the cost and complexity of NRHA, most buildings are currently designed using linear static or linear dynamic analysis. As such, there is a need to develop simple but accurate models (e.g., based on statistics) for estimating inelastic seismic demands. Such functionality has already appeared in software, and will likely appear in more as demand grows for design using second-generation performance-based earthquake engineering.

Conceptual Design Needs to Meet Resilience Goals

As detailed in an earlier section on resilience goals, there are several levels of resilient design, and the exact design requirements will depend on the level of resilience desired. Even so, the overall primary conceptual needs to make a building seismically resilient are as follows:

- Essentially no structural damage (i.e. no red tag and no damage that will inhibit building functionality).
- Residual drifts low enough to not cause red tag and not require repair.
- Peak transient drifts low enough to prevent damage to non-structural drift-sensitive components that would inhibit building functionality.
- Peak floor accelerations low enough to prevent damage to acceleration-sensitive components that would inhibit building functionality, or design of equipment anchorage to ensure that critical equipment functions after shaking.

The remainder of this section provides more conceptual detail on the specifics of controlling structural and non-structural damage, as well as thoughts on possible design restrictions and consideratons for resilient design.

Controlling Structural Damage

Controlling structural damage is critical to achieving resilient seismic design, since the performance of the structure has implications to the viability of other types of components (e.g., non-structural components and contents) and the functionality of the building as a whole. In the context of resilience-based design, each of the performance levels shown in Table 2 should be associated with a structural damage threshold, the exceedance of which indicates that the associated building level performance goal will not be achieved.

For post-earthquake functionality, the structural damage threshold should be defined such that (a) the residual load (gravity and seismic) carrying capacity is above an acceptable level and (b) the building functionality will not be affected by the necessary structural repair activities. On the other hand, for the post-earthquake occupiability performance level, minimizing the loss of load carrying capacity is the primary structural concern. In terms of structural performance, achieving post-earthquake repairability means avoiding large permanent deformations as permanent lateral drifts or settlement can lead to loss of use or even require demolition. While not explicitly mentioned for any of the three performance levels, minimizing economic losses should be an overall building performance goal since the ability to absorb those losses has a direct impact on the ability to recover in a timely manner.

Most structural damage caused by earthquake occurs because members are overloaded and experience inelastic deformation, which manifests in part as large relative lateral displacements between floor levels. In a sense, limiting story drift demands and local deformations is key to controlling structural damage. For conventional seismic lateral force resisting systems, this means designing for an appropriate drift limit, which, depending on the performance objective, may be less than the limits set by the code. Limiting story drift and deformation demands in conventional seismic systems is generally achieved by increasing the strength and stiffness. Where cost-effective, high-performance seismic protection systems such as base isolators, dampers and rocking systems can also be implemented to control both structural and non-structural damage. For both conventional and protective systems, the relationship between structural design parameters and the inelastic displacement and deformation demands cannot be accurately estimated using linear elastic analysis. As such, there is a need for simplified models, tools, and prescriptive methods for linking structural design parameters to response demands or more directly to building-level performance objectives.

For most lateral force resisting systems, earthquake demands are expected to overstress and yield portions of the material in a controlled ductile manner consistent with a specific design intent. In order to form a resilient system, yielded portions of the structure must be reusable, repairable or replaceable and returned to service. For some systems there is limited data on what levels of demand are acceptable for reuse, and there is not always a strong consensus on what degree of post-earthquake demand states are “repairable” or how effective various repairs may be in future events. It is a complex subject that needs more study to facilitate improvements in resilient design practice.

Attention must be made to how the foundation system and underlying soils will respond to various levels of earthquake demands. The overall resilience of a structural design is sometimes affected or limited by the performance of the foundations. When attempting to increase lateral strength or stiffness of the superstructure, care must be taken to provide a compatible foundation for the selected design approach to perform as anticipated.

Restrictions on Systems

Every structural lateral force resisting system has the potential for poor performance in an earthquake when improperly designed or constructed. In general, building codes implement reasonable precautions to avoid serious risk of local or global collapse. For the next generation of construction to be resilient against damage additional controls must be implemented that restrict or discourage the use of lateral systems and building layouts that are known to be easily damaged at service level earthquake shaking, or significantly damaged or impractical to repair after a design-level earthquake. Such restrictions should be based on past performance and laboratory testing data.

As a case in point, unreinforced masonry buildings are easily damaged in service-level earthquakes and extremely hazardous in design-level earthquakes. These structures are entirely prohibited in new construction because of their past poor performance. In a similar manner, building codes, jurisdictions or owners may restrict specific systems, features, materials, or configurations that are expected to be excessively damaged in an earthquake. Indeed, this has long been the approach of the modern building code for life-safety items. Prescribing specific restrictions will not catch all the various scenarios that lead to damage in earthquakes, especially for newer materials and arrangements in the recently developed systems that have not yet been strongly shaken. For this reason, care should be given to supplementing specific restrictions with minimum performance goals.

A review of the appropriateness of building code "R-factors" may need to be performed for improved resilience, especially for low ductility "ordinary" lateral systems and systems which historically are relatively easily damaged in earthquakes. A possible approach to improving seismic resilience may be to limit the maximum R-factor used in design unless specific systems are used or design measures are implemented. For a general overview of relative expected performance of standard lateral systems see "SEAONC's Earthquake Performance Rating System: Translating ASCE 31-03" (SEAONC, 2012).

For all structures, designs that rely on resisting earthquake forces by dissipating seismic energy within load-bearing structural members is in some situations contrary to what is appropriate for resilience. Extensive damage to primary beams, columns and bearing walls are a key reason for red- or yellow-tagging a building, resulting in loss of use until mitigated. For such lateral systems, redundancy of the vertical load path (i.e. non-bearing shear wall systems) may be an approach that lessens the impact of earthquake damage on restoration to at least partial functionality. Resilient designs should however consider using lateral systems which dissipate energy in non-bearing members which are easily inspected and repaired after an earthquake, and whose damage does not compromise the ongoing functionality of the building.

Buildings that must perform the best in an earthquake will understandably have the most restrictions. Some jurisdictions may mandate that buildings such as hospitals and emergency operations centers must use seismic energy dissipation/control devices, such as Chile where all public hospitals are required to be base isolated. The proper use of base isolators, dampers, and similar features has been well proven to provide good seismic performance.

Restrictions on Configurations

It is a fundamental tenet of seismic design that regularly configured structures with well-balanced arrangements of mass, strength and stiffness perform much better and more predictably than irregularly shaped ones. The building code includes special analysis and detailing requirements for common irregularities in order to provide consistent levels of seismic safety and avoid early risk of collapse. Studies such as the Applied Technology Council ATC-123 series are ongoing on how various irregularities are hazardous or damaging and what may be done to improve seismic design methods. Performance-based design methods can often overcome most, but not all, irregularities with sufficient engineering and analysis to achieve resilience goals.

While it can be done (sometimes at great expense), buildings with irregularities will be outperformed regular structures in an earthquake and are fundamentally less resilient. In this particular aspect, the Architect and Owner will play a strong role as their decisions on layout and finishes will directly impact the maximum performance that can be designed into a building. Continued outreach and education for Architects and Owners who are committed to seismic resilience will play a key part in complete implementation. Of particular note is that regular structures make more efficient use of material, cost less, and take less time to construct; which often allows for more freedom of architectural expression in nonstructural components and the use of higher-end materials in the finish work. The combined effect of higher seismic resilience and superior aesthetics will consequently generate higher value for both the owner and the community.

Controlling Non-Structural Damage

Controlling non-structural damage is relevant to the performance levels of post-earthquake functionality and occupiability. A key first step in establishing the associated damage thresholds is classifying each type of component based on (a) sensitivity to acceleration or drift demands (or both) and (b) their level of importance to each performance level. For example, whereas the presence of functional cladding is critical to achieving both performance levels, a building can remain occupiable without the functionality of certain electrical equipment. Once the components have been classified, damage thresholds can be defined for each category. It is worth noting that this type of component classification and triggering damage levels is incorporated as part of the FEMA P-58 methodology.

Damage to non-structural components can be caused by floor accelerations and story drifts. Non-structural components that are attached to two or more floor levels (e.g. cladding, glazing and partitions) are mostly affected by the latter and those that are anchored to a single floor or wall (e.g. ceiling grids, pipes, floor-mounted equipment, wall-mounted shelving) are acceleration sensitive. As noted earlier, drift demands can be controlled by adjusting the stiffness and strength of conventional lateral force resisting systems and other design parameters that are specific to seismic protective systems (e.g., initial post-tensioning force in self-centering systems). However, large stiffness can also aggravate acceleration and damage to acceleration-sensitive components. An iterative design approach can be used to balance story drift and acceleration demands based on the target performance objective. Alternatively, protective systems can also be employed for non-structural components. Examples of such techniques include employing floor isolation systems and seismic snubbers for critical equipment, flexible connections in utility lines, and enhanced partitions and cladding elements with high drift capacities.

The term “non-structural” officially refers to “non-loadbearing” materials, but leads to a misconception that their detailing and attachment to the structure do not require engineering. In order to achieve higher seismic performance goals, such items require experienced designers to perform explicit design and detailing, as well as special inspections to confirm proper installation. This is the standard of practice for most hospitals, schools, and critical facilities. For normal buildings to achieve resilience, similar efforts are required and must be enforced. A requirement that all ceiling, partition and cladding connection details be stamped and signed by a licensed engineer for buildings in a resiliency program is one such example that may be implemented, among many options.

Design for damage control of components is an important part of resilient design. It is often impractical or uneconomical to hold every component to very high performance standards for normal buildings. When implementing such a program, components should be identified whose damage poses an outsized risk for loss of functionality of the building (such as fire sprinklers and exit stairs), and special efforts assigned where real benefits will occur. Such provisions may need to recognize that not every component is critical to permit continued minimum functionality, and even among a type of component some may be damaged while a subset are designed for higher performance. For instance, not every elevator in a building needs to be in running condition immediately after an earthquake but a certain minimum should remain operable.

Limitations Based on Earthquake Hazards

Current U.S. building codes for new normal-use buildings are predominately written with the goal of providing a specified low probability of collapse during the design life of the building (generally 50 years). To achieve that goal, the code calibrates design-level shaking so that, if the design satisfies strength requirements and deformation limits at that level of shaking, it will provide the desired degree of long-term risk. But assuring collapse prevention during the design life of the building does directly address repair costs, occupiability, or repairability. These latter resilience measures can be strongly affected by frequent small and medium-sized earthquakes, such that damage is likely to occur and compound within the design life of a structure.

For resilient design, an important question is ask is whether 50 years is a realistic economic life for a specific project or building type or site. Certain uses or building types should by reviewed for their expected longevity within a region, community or site, and the appropriate design shaking calibrated to that economic life. Failure to recognize longer lifespans may increase the adverse impact of damage when an earthquake occurs, resulting in lower effective resilience.

For sites with frequent small or moderate earthquakes relative to the building economic life, control of damage to minimal or repairable levels is required to achieve resilience. The implementation of performance-based targets having minimal or limited damage in such events is appropriate. This is commonly referred to as a “service level” earthquake, which if often taken as having a probability on the order of 50% in 50 years (approximately a 74 year mean recurrence interval) and is reasonably expected to occur within the lifespan of the building. For buildings with a longer economic life or more critical functionality, the service level earthquake should be increased commensurately, such as to a 50% in 100 year probability or 20% in 50 year probability for example. Where improved resilience is desired a "functional level" earthquake may be considered with a probability on the order of 10% in 50 years (stronger than a service level event) or as appropriate to the use and importance (Kircher, 2012). For sites dominated by specific faults, scenario event(s), such as a given earthquake magnitude occurring at a prescribed distance from a site, may be used to define a specific hazard that a community plans to be resilient for, and is often easier to explain to the public.

Each site has other non-shaking earthquake hazards that must be reviewed and designed for where they occur. Most jurisdictions require liquefaction, landslide, surface fault rupture potential and tsunami to be addressed where they are shown on official maps. Where major hazards such as these occur, it is more challenging to design a building to avoid damage or loss of use, and the resulting actual performance may be difficult to reliably predict. Regions such as these should not be expected to be resilient unless significant study and effort is expended to understand the issues and a corresponding degree of engineering effort performed to address them.

It is well known that in an earthquake, buildings which resonate dynamically with the soil it is founded on will experience longer and stronger shaking, more damage and in some cases collapse. Site vibrational dynamics are a well-studied phenomenon, with detailed analysis models of faulting regions and extensive field equipment arrays measuring real time data (SCEC, 2017). Unfortunately most building codes do not currently require engineers to design explicitly for such effects. Those that do (such as Caltrans, 2013) provide site amplification effects for deep geologic basins, and/or require the geotechnical engineer to indicate the predominant characteristic dynamic period(s) of the soil in order that the structural engineer may avoid dynamic resonance in the structure. Flexible and taller buildings tend to be problematic on softer soils, and this is a relatively easy issue to design for if the problem is known early in the planning phase.

Sites that are located near major faults can see earthquake forces amplified dramatically due to directional pulses and other effects. This phenomenon has less experiential data available and most building codes do not address it explicitly in normal design methods. In such regions additional engineering may be needed to improve the resilience of affected structures, such as stronger connections to foundations, seismic damping systems, and additional ductility for anticipated overstresses. Jurisdictions should consider zoning areas to avoid important or hazardous uses in such regions unless special engineering is performed.

For very important buildings and critical facilities, the best approach is to avoid significant hazards as much as practical. Additional study is often prudent into other hazards such as less-active fault zones not published in official maps, dam inundation zones, dynamic settlement concerns, etc. If certain hazards have return periods greater than the maximum considered, facilities whose failure would affect the surrounding region must be designed to fail safely should such a rare event occur in order to maintain resilience of the community.

Consideration of Externalities

Complete resilience of a building requires that access to the site be maintained, utility services be available in at least minimally functional states, and that no hazardous conditions exist in the surrounding area. Such items that are not in control by the designers and property owners are referred to as "external conditions" or "externalities." These should be considered and planned for as far as practical in the design of important structures, such as providing emergency water and power on-site, and providing multiple access points for redundancy for example. But many things are beyond the control of individuals, and the responsibility then shifts to the community and jurisdictions who must develop studies and plans for restoring damaged utilities, upgrading critical lifelines, enforcing retrofit requirements in older economic zones, etc., in order to enable resilient design of individual buildings to be effective.

Overview of Prescriptive and Non-Prescriptive Approaches to Resilient Design

Direct Quantitative Resilience-Based Design Approach

There are approaches in the building code with the goal of making the building "better," such as by enforcing more stringent strength, stiffness and detailing requirements for a higher Risk Category. These requirements were put in place only in the latest generation of earthquake codes and it has not yet been demonstrated that they actually deliver the desired resilience consistently and reliably.

If a quantitative resilient design approach is desired, there are currently no prescriptive design requirements, to the authors' knowledge, that have been quantitatively shown to deliver a resilient building (although some of us are engaged in the necessary research as of this writing, and others may be as well, the topic being particularly timely). In the absence of prescriptive design requirement for resilience, a resilience analysis can be conducted to demonstrate that the building meets the following goals for damage and recovery time after an earthquake. The common approach for this is to use the FEMA P-58 analysis method (FEMA, 2012) to estimate the repair cost and repair time of the building, and then can be used to iteratively design the building to meet stated resilience goals. The FEMA P-58 approach is complete and accounts for all of the important components of resilience – ground motion hazard, structural response (accounting for many though not all uncertainties), assessment of damage to building components (with uncertainties), identification of which component damage inhibits functionality, and assessment of repair cost and repair time to building components and resulting repair time for the full building (with uncertainties), and consideration of the effects of residual drifts. At least one method adds fault-tree analysis to estimate the probabilistic time required to restore functionality (Porter and Ramer, 2012). Resilience assessment could also be subject to random peer review to ensure quality control (such as that offered by the U.S. Resiliency Council).

Table 4 - Example of Resilient Design using FEMA P-58

Design Changes	Mean Loss at 10% in 50yr	Mean Loss at 2% in 50yr	Median REDi Functional Recovery at 10% in 50yr
Baseline	17%	43%	37 days
Self-Centering Frame (No Residual Drift)	11%	27%	32 days
Cladding Detailed for No Damage	7%	17%	29 days
Slab-Column Connections Detailed for No Damage	4%	11%	27 days
Lateral Frame Connections Detailed for No Damage	2%	5%	27 days
Elevators Detailed for No Damage	2%	5%	4 days

This FEMA P-58 assessment method can be used directly for resilient design, but could also be used for studies to calibrate prescriptive methods for resilient design, as outlined in the next sections. The results shown in Table 4 outline an example resilient design process that could be used based on FEMA P-58 analysis. For this example, we use a baseline new 12-story reinforced concrete special moment frame office occupancy building designed for a site in Los Angeles, based on current building code requirements. This design example shows the incremental resilient design process where the following steps are used. This is an illustrative example and many approaches can be used to achieve the same resilience target. This example shows that approximate Platinum-level performance is achieved.

- A self-centering precast hybrid moment frame system is used to remove issues with residual drifts.
- The cladding is detailed to have low likelihood of damage.
- The slab column connections are designed to have no damage (lower shears, etc.).
- The lateral frames are further detailed to have no damage that requires repair.
- The elevators are designed to have no damage.

Prescriptive Design Approach

Another possible approach to resilient design would be to create prescriptive design requirement that can be used, much like current code requirements, in order to design the building to be resilient. As mentioned in the last section, to the knowledge of the authors, no set of prescriptive requirements currently exist which have been either quantitatively or experientially shown to deliver a resilient and operational building after a large earthquake.

Even so, such prescriptive requirements could be created in the near-future, through the use of the new FEMA P-58 assessment method, such as the example studies shown in this section. Table 5 shows a simple illustrative table of what some final prescriptive requirements might look like once such a study was completed (*Important: These are not proposed requirements; such a study still would need to be completed*). The components of these requirements are:

- Reduced drift limits to protect drift-sensitive components.
- Limitations on the R factor, to provide additional strength to the structure, and to limit structural damage. Note that this would limit the R factor used in the strength design but this does not suggest that low-ductility systems can be used for high-seismic areas. Building code requirements on structural systems (e.g. the need to use special systems in high-seismic areas) should be maintained because this is needed for ensuring acceptable safety and predictability of performance if a larger than design level event occurs.
- Limitations on the Rp factor, to provide additional strength to non-structural anchorages, which are acceleration-sensitive. An alternative to this would be to reduce floor acceleration demands.
- Non-structural detailing based on a higher Risk Category, to partially protect equipment functionality. Note that this partially overlaps with the other requirements and an alternative to this would be to reduce floor acceleration demands. Note also that most equipment must remain functional, so additional pre-qualification requirements may be needed to confidently deliver such functionality.

Table 5 - Example Prescriptive Requirements for Resilient Design

Level of Resilience	Drift Limit	Maximum R Factor	Maximum Rp Factor	Risk Category for Nonstructural
Platinum	1.0%	3.0	2.0	IV
Gold	1.25%	5.0	4.0	IV
Silver	1.75%	n/a	n/a	III
Bronze	2.0%	n/a	n/a	II

Example of Calibration of Prescriptive Design Requirements using a Large Set of Quantitative Resilience Assessments

As mentioned in the previous section, to meet the need for a prescriptive method for resilient design, based on quantitative estimates of resilience, the FEMA P-58 analysis method can be used to create such prescriptive design requirements. To convey this concept, this section contains an initial pilot study looking at possible prescriptive design requirements; such a study would need to be substantially expanded in scope to develop final recommendations for prescriptive design. Until such a study is done, we suggest that resilient design be done using the FEMA P-58 analysis method directly.

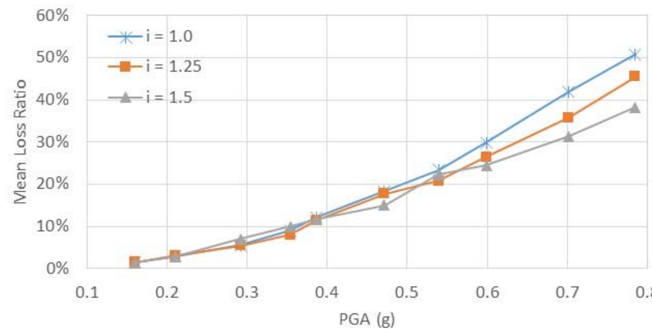
For these sample studies, we used the same baseline 12-story reinforced concrete special moment frame building used in the previous example; we then modified this building design to see the effects of varying design requirements. For this example site the 10% in 50 year motion has 0.47g peak ground acceleration and 2% in 50 year motion has 0.77g peak ground acceleration.

Effects of Increased Strength on Repair Cost and Time

For the first step in this study, Figure 1 shows the effects that increased building strength (I_e > 1.0) has on repair cost for a 10% in 50 year and 2% in 50 year earthquake. In this study, the building is fully redesigned for each strength target, a nonlinear model is created, and response-history analysis is used for computing structural responses. The results table shows the effects on the mean loss ratio (the repair cost as a fraction of replacement cost) and the recovery time (where recovery time is computed in accordance with REDi, 2013 and excludes impeding factors). For this example mid-rise RC SMF building, increased strength without increase in stiffness has little effect on repair cost for the 10% in 50 year motion. It has modest beneficial impacts on repair cost in the 2% in 50 year motion.

This result makes sense because strength is mostly about safety and not repair cost; greater strength reduces collapse risk and the risk of life-threatening damage that can lead to red- and yellow tagging. As many as 60 buildings are red- or yellow tagged for every collapse, so strength increases can greatly reduce the risk of these other important performance measures (Porter, 2015). Also, greater stiffness often accompanies increased strength.

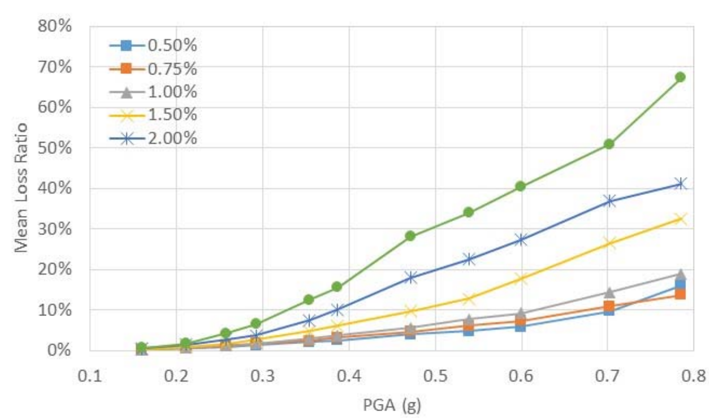
Figure 1 - Effects of More Strength on Repair Cost (Ie > 1.0)



Effects of Increased Stiffness on Repair Cost and Time

The next study looks at the effects of design drift requirements. Results are provided in Figure 2. Note that the baseline building differs slightly in this example because the simplified structural response method (FEMA, 2012) and the building stiffness is modified to meet design drift targets. This shows that the changes to design drift limits have clearly measurable and beneficial impacts on repair cost and slight impact on repair time. Note that reducing drifts is especially important for this building example (office occupancy) because the majority of building components are drift-sensitive with only a small number of acceleration-sensitive components. If this same study were done for a medical occupancy with many acceleration-sensitive components, the results would likely differ because the increased stiffness also increases the floor acceleration demands.

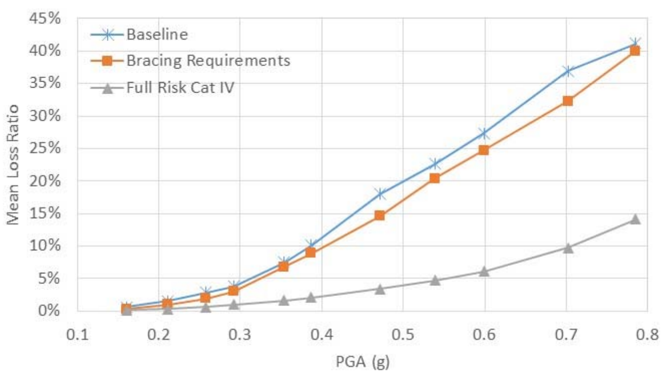
Figure 2 - Effects of Reducing Drift on Repair Cost



Effects of Risk Category IV Requirements on Repair Cost

The next study looks at the effects of the components of Risk Category IV requirements and how they affect repair cost; these results are provided in Figure 3. This shows that the bracing requirements have some effect on repair cost, but the primary benefit comes from the reduced drift limits of 1%.

Figure 3 - Effects of Risk Category IV on Repair Cost



If quantitative and reliable prescriptive requirements are desirable for resilient design, the authors suggest that this pilot study be extended, and that such a study be used to develop final quantitative requirements for prescriptive resilient design, especially to manage repair cost and repair time in addition to safety.

Impact of Ductility and Stiffness on Predictability of Seismic Response

Many building codes primarily focus on the strength, redundancy and regularity of the lateral system and connections with a secondary emphasis on ductility and lateral stiffness. Thus far this approach has served relatively well for life safety, but the results for seismic resilience have been observed to vary greatly after strong earthquakes. Implementing design measures intended to improve resilience must consider the effects of uncertainty in seismic response and focus on methods which will reliably provide the desired performance goals.

Buildings that are engineered to be very strong, but with relatively low ductility (i.e. ordinary systems) often perform unpredictably when earthquake demands exceed what they are designed to resist. Excessive ductility demands above what a low ductility structure can resist will increase collapse risk, especially with long duration events. Standard linear elastic analyses and design methods do not show this risk, however it is a phenomenon that is readily apparent with nonlinear time history analyses. Higher ductility demands result in better predictability in seismic performance based on review of actual building damage data, research on constant ductility spectra and inelastic displacement ratios (Chopra, 2017; Miranda, 2000). The unpredictability of seismic response for a structure with a lateral ductility demand of 2 is nearly the same as for elastic response, which is a ductility demand of 1 or less. Ductility demands of 4 and higher exhibit a much narrower, more predictable response. For seismic resilience it is important to avoid decreasing ductility even if strength increased, especially where earthquakes stronger than a design event are possible. It can therefore be beneficial for the lateral ductility of a building be evaluated explicitly to demonstrate that reliable performance is likely to occur.

Unpredictability of seismic response is higher for shorter period structures (short/stiff buildings), and lower at longer periods (tall/flexible buildings) on non-soft soil sites. The primary factor behind this phenomenon is in how the energy content of earthquakes is generally distributed more in the high frequency range, often exciting short period buildings with short-lived accelerations which peak well above design level forces. Short/stiff buildings thus have an increased likelihood of experiencing potentially high overstresses above what they were designed for. Tall/flexible buildings so long as they are not in resonance with the ground motion tend to have more predictable responses. Such seismic performance behaviors and the effects of site-specific response must be accounted for in any design approach to mitigate damage and improve resilience.

Increasing the lateral stiffness in buildings that have standard nonstructural finish materials and components will generally reduce the expected earthquake damage, so long as their connections are strong enough to resist the forces. Buildings that are more flexible require special detailing considerations to avoid drift induced damage to brittle or rigid finishes and components. Seismically resilient designs must account for these effects.

Building strength, ductility and stiffness each play an important role in the design of seismically resilient structures, and must be balanced with the specific conditions for each project in order to more confidently aim to achieve resilience.

Design Reviews

It is envisioned that verification of seismically resilient designs will follow the customary approach of building official review and/or peer review. While the engineering analysis and design requirements that are being implemented for resilient seismic design are more advanced than they were a generation ago, the changes that will occur in the quality control and plan check process are expected to be relatively minor. Once requirements and procedures are established by a jurisdiction it is straightforward exercise to review and validate the designs of individual projects. Review of additional prescriptive requirements will take a modest amount of additional plan check effort. Checking a performance based design can take more effort, and such designs are often delegated to peer reviews. With the adoption of ASCE 41 into the International Existing Building Code however, many jurisdictions are becoming experienced and accustomed to reviewing some performance based design project submittals.

Quality Assurance During Construction

The expectation that a building will perform well during an earthquake is highly dependent upon the quality of the materials and workmanship in connecting the various building components together. Lack of quality during construction typically leads to completed buildings underperforming when exposed to natural hazards such as earthquakes and windstorms.

Controlling quality is difficult during construction, as the contractor's task is to complete the building in the least amount of time, at the least cost for the building owner. The mindset needs to be adjusted during the construction phase, to allow a little additional time to allow for quality construction.

The onus regarding quality assurance on the jobsite is generally left up to the contractor. The building code requires special inspections, which in the Southern California market are typically performed by third party deputy inspectors licensed by the jurisdiction.

In the years following the 1994 Northridge Earthquake, structural observation by the structural engineering design firm has become mandatory. Due to cost considerations and design offices being busy, this structural observation is often limited, which leads to a reduction in quality.

While it has not been traditional for the structural engineer to be part of regular construction meetings, there can be advantages. The structural engineer can bring the construction team up to speed as construction progresses, reminding them of the difficulties they may encounter and the need to spend more time preparing for the construction of individual building components.

Given the importance of quality assurance, especially when claiming a high reliability for resilience it follows that there must be a quantifiable way to ensure quality assurance. Therefore, it follows that for higher levels of resilience, there should be special inspections to ensure the corresponding level or resilience. This inspection would be supplementary and would focus on key design and construction characteristics of which the building relies on to achieve the given level of resilience.

Table 6 provides suggested requirements for special resilience inspection.

Table 6 - Example Prescriptive Requirements for Quality Assurance for Resilient Design

Level of Resilience	Resiliency Special Inspection
Platinum	Required
Gold	Required
Silver	Suggested
Bronze	Suggested

Ongoing Maintenance, Inspections and Assessment

All buildings require periodic maintenance in order to avoid deterioration that can compromise the integrity of materials. Periodic inspection of the structure and architectural components is necessary to watch for signs of distress which may require repairs in order to sustain a building's functionality. Buildings that have existing deterioration when an earthquake strikes may perform very poorly if critical elements are already compromised and then subsequently overloaded. Generally such buildings can be expected to perform worse than when it was new, depending on the degree to which it was maintained.

In order to achieve a continuing expectation of resilient performance, the building must be properly maintained and repairs made when necessary. Many jurisdictions mandate building official inspections when the property is sold or during major renovations. The timing of these inspections is very unpredictable and scope of review does not usually encompass structural condition or expected seismic performance.

For the typical building, seismic assessments occur rarely, if at all. Major property owners will generally perform structural and seismic assessments at least every 10 or 20 years in order to fully understand the risks in their portfolio of buildings and be able to predict and plan for the consequences of various disaster scenarios. The riskiest buildings are usually addressed by retrofit or other maintenance with these costs planned and incorporated into financial plans and annual budgets.

Jurisdictions are becoming increasingly able to economically collect and process data in such a way that similar risk vs. reward decisions can be made across communities. Many are implementing required structural and seismic assessments for buildings that have exceeded their original design life. When significant deterioration is found repairs would be required, and when exceptionally poor seismic performance is anticipated retrofit or restrictions in use implemented.

Mandating that structural checkups occur on a regular period and that repairs or retrofits be made when appropriate is an economically feasible and reliable method to improve community resilience.

Of important note, availability of complete, accurate and legible building drawings are critically necessary to be able to inspect and evaluate existing buildings. The costs and time associated with surveying and detailing as-built conditions for buildings without such documentation can be extraordinary, and the uncertainties inherent will obstruct engineers and code officials from being efficient when dealing with such buildings. In order to enact a complete resilience plan, jurisdictions will need to maintain detailed building records and perhaps require filing of as-built construction documents for specific types of structures.

Those performing the assessments must be able to maintain independence from property owners in order to avoid undue influence over the results, and should be performed by either the jurisdiction itself or by private firms verified through the use of peer reviews or certification programs such as USRC.

In order to provide a quantifiable requirement to ensure the condition of the building is consistent with current resilience goals a structural condition assessment should be provided at a reasonable frequency. A Platinum level resilient building may need to be re-evaluated when significant changes are made to the building codes, which may be a period of less than 10 years. Each passing code cycle also represents a greater understanding of building performance as more knowledge is gained from research and observed performance of buildings during major earthquakes. The changes to codes can at times be drastic such as after the San Fernando and Northridge earthquakes where many lessons were learned as these events exposed design or construction flaws that were previously unaccounted for. The resilience of the building must be able to be correspondingly adjusted when new knowledge becomes available.

Table 7 - Example Prescriptive Requirements for the Minimum Frequency for a Structural Condition Assessment

Level of Resilience	Minimum Frequency of Structural Condition Assessments
Platinum	3 years
Gold	6 years
Silver	9 years
Bronze	n/a

As advocated for previously in this paper, it follows that FEMA P-58 be the basis of such a structural condition assessment. Table 7 provides a suggested minimum frequency of which such an assessment should be performed.

Facilitating Repairs and Reoccupancy

Getting repair materials and builders into a damaged community is challenging, and even the most basic of repairs will take more time and money than before the event. Jurisdictions should plan with material producers, building supply and home goods chains and work out how to provide emergency support and utilities to facilitate rapid delivery and disbursement of critical repair materials to affected areas. Large corporations and national “big-box” store chains have experienced natural disasters before and often have plans in place for such events.

Lessons learned from similar events should be studied. One such lesson is the expectation that an influx of substandard building materials and a shortage of skilled labor is likely to occur when market demands spike following a disaster. Implementing resilience based seismic design and retrofit requirements will lessen the quantity of damage, and consequently the amount of materials and labor required by a community to rebuild.

Another lesson is in how jurisdictions will need to expand their manpower rapidly to process repair permits and expedite inspections for reoccupancy. The primary way to plan ahead for such disasters is to implement a “back to business” program, permitting private practitioners to act on behalf of a jurisdiction according to preapproved plans for inspecting and repairing important buildings.

Back to Business Program

After a natural disaster, such as an earthquake, the local community needs to be able to recover quickly in order to remain economically viable. A critical element of this recovery is being able to re-occupy the majority of the community buildings either immediately or very shortly after the natural hazard occurs. When say 20% or more of the building stock is declared uninhabitable, it slows the economic engine of the community down to a trickle as the community attempts to rebuild itself from all of the damage. Even if less than 20% of the building stock is rendered uninhabitable, this will still have a dramatic impact on the local economy. Recovery can take years, even decades, depending upon the amount of damage, and the number of people who find themselves relocating to other regions in order to secure new jobs, to replace the ones they previously had, that have disappeared because of the disaster.

A building owner disaster preparedness model that has been developed during the last decade is the "Back to Business" model, and goes by different names in different regions. In this model, the building owner hires a structural engineer, on retainer, to be on call for physically reviewing their building shortly after the earthquake, often within 48 hours or less, to review for structural damage. The engineer inspects the structure for damage and has the authority to post its status to allow the building to be re-occupied sooner than later.

The preparedness model requires acceptance and coordination with the local jurisdiction-building department. The building department, the structural engineer, and building owner all have duties that need to be performed on an annual basis in order for the program to be successful.

Role of the Structural Engineer:

The structural engineer reviews the building structural plans, walks the building to understand what the building is, and estimates the building's performance during a natural disaster. Understanding the building's expected performance during an event allows the structural engineer to identify the potential vulnerable areas of the building and prepare a damage priority list for review of the building after the event. This information can also provide the building owner with an opportunity to do some retrofitting in advance of the event to reduce vulnerabilities.

The structural engineer reviews the building and other coordination details (contacts, access arrangements, etc.) on an annual basis with the building owner to find out if there have been any structural modifications to the building, and updates their preparedness plan as required.

After an event, the structural engineer, as authorized in the agreement between the owner and City will access the building and perform a post-earthquake structural inspection and will post a status per the local jurisdiction's procedures. Typically, the status is conveyed by the posting of notices based on ATC-20's green (inspected), yellow (restricted use), and red (unsafe) placard system. All structural repair sketches are to be submitted to the building department for approval prior to beginning structural repairs.

Role of the Building Department:

The building department conducts an annual review with the structural engineer to go over any changes that have occurred to the building, and be introduced to the structural engineer that will be inspecting and posting that particular building and for that particular year. The building owner pays the building department an annual fee to allow his approved structural engineer to inspect and post the building after the event. The building department agrees that as soon as the City authorities declare a local emergency, the designated structural engineer is pre-authorized to inspect and post that particular building. The building department requires submission of all structural repair sketches for approval prior to beginning any repair work.

Role of the Building Owner:

The building owner agrees to pay the annual fee to the building department for the privilege of having the "Back to Business" program by a certain renewal date. The owner also makes sure the annual review by the building department occurs, and to let the city know if there are any changes in staffing of who the reviewing structural engineer is for that building for that given year.

The Benefit:

By having this program in place, it provides the building owner with a knowledgeable structural engineer, who understands their building and can address the building's re-occupancy immediately, and get the owners building up and running again as soon as feasible. This also frees up the building department inspectors following the disaster to look at other buildings, knowing those buildings in the Back to Business program are being thoroughly reviewed, more so than the normal building rapid damage assessment process utilized after a natural disaster. The public remains protected, as all construction work is still approved and permitted by the jurisdiction in advance of any repair work.

The main differences by having the "Back to Business" is the building repair schedule is greatly accelerated after the event, Building Department staff can be better utilized to access other potential damaged buildings, and the economy can recover more quickly as more people have a chance of economically remaining in their homes and still having a place to work.

Improving the Back to Business Model:

The resilience of the community directly correlates with the time required before buildings can be re-occupied after an event. The next step in further reducing the wait time, after the event occurs, is to allow the structural engineer approved to post the building safety status (Red, Yellow, Green placards) to also issue repair sketches, as required, that can be implemented immediately to begin repair of the building, prior to submission to the building department for approval. The improved scenario for such a program includes;

A. The building owner signs a recorded affidavit with the building department allowing the building owner to proceed with making the structural repairs at their own risk after the event. This is based on the assumption that any structural repair sketches prepared by the building owner's structural engineer (previously approved by the building department as part of the Back to Business Model) will be acceptable to the building department without requiring any changes or additional work.

B. If the building department determines the submitted structural repair details that have been installed are insufficient, then the owner understands that it is at their cost to remove and replace any portion of the retrofit that is not approved.

C. To assure the public remains protected; all other standard building department design and construction requirements remain in effect, such as providing deputy inspection for all work where deputy inspection is required. The building department will still inspect and sign-off on all repair construction prior to allowing it to be covered up. Therefore, while the building may look like it is still undergoing construction repairs with the repaired framing members being left temporarily exposed for a while; the building owner may be able to re-occupy the building sooner; assuming clearance by the fire department can be obtained.

Early Adoption of Latest Standards

Recommended seismic design practices are updated continually, and often the adopted building code language is six to ten years out-of-date from current research. Some jurisdictions are able to amend the requirements to adopt critical life-safety changes in a timely manner. Similar efforts would be prudent for updating requirements which are known to improve seismic performance in a meaningful way.

Designers and building officials seeking to provide improved seismic performance based on the latest research and earthquake reconnaissance findings are advised to keep up with the latest NEHRP "Recommended Seismic Provisions" (FEMA 2015), updates to seismic design standards (ASCE 7, AISC 341, etc.) and the recommendations given in the NEHRP Seismic Design Technical Briefs series available at http://www.nehrp.gov/library/techbriefs.htm.

Requirements for Existing Buildings

Requirements for existing buildings are arguably the most critical component of community resilience. Many existing buildings have known deficiencies that represent a significant collapse potential and therefore fall well below current minimum performance objectives.

With this in mind, local jurisdictions have provided mandatory ordinances to address the most severe of these deficiencies. Recent examples of this are the City of Los Angeles's mandatory Non-Ductile Concrete (NDC) and Soft, Weak, or Open-Front (SWOF) wall line ordinances. These ordinances are good examples on approaches to improving the performance of existing buildings. The NDC ordinance requires a holistic retrofit approach to achieve a minimum structural performance objective for existing buildings. The SWOF ordinance on the other hand is a deficiency only approach that targets a specific critical deficiency in a localized portion of the building and requires mitigation of the deficiency, but not necessarily elimination. These two ordinances are expected to drastically improve the resilience of Los Angeles as they address structural deficiencies known to pose a collapse risk. For more information about Los Angeles's ordinances, the reader is referred to the NDC Design Guide (SEAOSC Seismology Committee, 2016) and the SWOF Design Guide (SEAOSC Existing Buildings Committee, 2016). This is a great first step towards building resilience as the most dangerous deficiencies are addressed. Local jurisdictions must continue to address these critical deficiencies that pose a significant safety hazard. While public policy has been useful in moving towards resilience, more must be done.

It is important that there be a uniform standard for resilience whether the building is existing or new. An objective standard should be created to compare buildings built in different eras. All new buildings will be existing buildings once constructed and therefore will need an objective evaluation procedure to measure resilience at that time. Therefore, concepts and quantifiable measures outlined in this paper that largely focus on a framework for new buildings should also apply to existing buildings. In the case of resilience quality assurance inspection, for buildings already constructed clearly this cannot be implemented. However, it can be implemented for the retrofit of such structures to meet given resilience objectives. Also, the design of new structural systems or strengthening of existing structural systems can be done with consideration to a targeted level of resilience.

Sustainability Benefits

Seismically resilient design goes hand-in-hand with sustainable design practices. Designing structures for more redundancy, strength, ductility, etc., may result in a modest initial increase in material use and carbon footprint, however this is more than offset by reduced repairs due to damage reduction in a strong earthquake, and potentially increased useful lifespan of the structure. A sustainability study on concrete frame buildings by Welsh-Huggins & Liel (2011) shows that embodied carbon content does not follow a linear relationship between design base shear and material volumes (meaning a 25% increase in strength may only embody 10% more carbon content for example), and weaker structures damaged in high-level seismic events require more material volume for repair than stronger structures, resulting in a larger net carbon emission output. The complete lifecycle costs (both environmental and actual) of a building must account for the risk of damage and repair, or collapse and early replacement due to earthquake hazards in high seismic regions in order to fully compare the benefits of design decisions and performance goals when constructing new buildings. Similarly, retrofit of existing seismically hazardous not only promotes community resilience, but is also a sustainable design practice (Wei et al., 2015).

Concluding Remarks

The focus on resilient structural design for earthquakes is the natural progression for the next-generation improvement in the field of modern earthquake engineering. Performance-based methodologies have matured and are moving into mainstream use as our analysis software and technical knowledge have grown to meet the challenge. While the fundamentals of seismic design and earthquake dynamics have not changed, the engineering tools we are able to bring to bear on these problems are continually becoming more rigorous and powerful. Previous methodologies should be expected to remain in place as a baseline practice and are not being replaced, merely supplemented. The importance of seismic safety will always be a primary focus of earthquake engineering, however this problem is arguably satisfactorily in large part with respect to new construction. This allows us to push for a state of practice that routinely designs for additional earthquake risks such as damage control, loss of function, sustainability, and thus continue to improve our built environment and communities for generations to come.

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