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RESILIENT SEISMIC DESIGN FOR FUNCTIONAL RECOVERY USING PRESCRIPTIVE AND NON-PRESCRIPTIVE DESIGN METHODS

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Abstract

This paper looks at a wide range of buildings high-seismic zones of the United States, seeking to answer two primary questions – (a) what building repair times are we expecting for a new code-compliant design of the building, and (b) how could we design the building to recover more quickly (looking at both prescriptive code approaches and other direct resilient design approaches). FEMA P-58 analysis is used to evaluate the building performance and the primary conclusions are:

- Current code-compliant buildings do not deliver building function after a design level earthquake. This is because building function is not a goal of the current US building code. The building functional recovery time for design level shaking ranges from six months to two years.
- General changes to prescriptive building code "nobs" in the US building code (e.g. Ie = 1.5, Ip = 1.5, and Risk Category IV) are shown to result in improved performance but do not result in short functional recovery times that may be desired. Note that these nobs could be "turned up more" to achieve acceptably low functional recovery times, but this would increase design requirements on all components (many of which are not preventing building function) so a more targeted approach may be desirable.
- More direct and targeted resilient design can be used to improve the specific components that are impeding function of the building. This can be done to both (a) achieve the desired time to regain function, and (b) avoid overdesigning components that do not need it.

This paper then proposes a next step of using this FEMA P-58 analysis process to calibrate building design requirements that can be shown to deliver acceptably short functional recovery times for new buildings.

Keywords: FEMA P-58, resilient design, functional recovery, resilient design standard, repair costs, downtime

1. Intended Audience

This paper is written as a technical document targeted at two primary audiences – (a) those considering how to change building codes to meet a Functional Recovery design objective (rather the design objective being "safe but disposable"), and (b) Structural Engineers interested in how to design buildings to be resilient and meet Functional Recovery goals (which they can do now, with existing analytical tools, even before a possible building code change to require it). Although this paper is written toward an engineering audience, this paper can also be used by government officials and policy-makers interested in Functional Recovery design; specifically, examples are provided to show expected downtimes of new buildings and how buildings can be designed to meet Functional Recovery goals.

2. Introduction and Motivation

In recent years, in the United States, it has become more widely known that the design objective of our building codes (e.g. ASCE 2016) is for buildings to be safe, but not necessarily to be functional or even repairable after an earthquake. Many have begun referring to code-compliant buildings as "safe but disposal." Several efforts are underway to consider design requirements that are also focused on building reparability and functionality, and the new terminology often being used is "design for Functional Recovery". These include efforts by the State of California [1], the federal government (through the recent National Earthquake Hazards Program, NEHRP, reauthorization and direction to NIST/FEMA to look into functional recovery standards), and efforts by local governments such as San Francisco [2].

In parallel with this new awareness of what the building code is providing (and not providing), analytical methods have now been developed to the point that engineers are able to analytically estimate building damage and function through a building-specific engineering analysis. This was not possible 10 years ago. These supporting research efforts have occurred over the past couple decades [3] and have coalesced with the 2012 release of the FEMA P-58 risk analysis method [4] and complementary extensions for repair times and downtimes [5, 6]. Enabling software tools are also now available to support these engineering analyses (SP3 2019, PACT software available from ATC). Many in the Structural Engineering profession have been adopting and vetting the FEMA P-58 and REDi technologies starting in 2014, with most large California Structural Engineering firms now utilizing this new technology. This new technology has already been electively used to design recent buildings to be resilient, with limited building closure time and limited repair costs after the earthquake [7, 8].

The above two recent developments (societal interest and new engineering technology) have created a remarkable situation and opportunity. Structural Engineers now have the technology to predict building damage and functionality, and they can use that information to iteratively design buildings to be better (e.g. building functionality within weeks). Many levels of government are now making it clear that they desire post-earthquake functionality and smoother recovery for their communities, rather than only safe (but disposable) buildings. This societal need, coupled with new technology available to Structural Engineers, puts our society in a good place to improve our building design practices and create more resilient buildings and communities. This paper focuses on how such resilient design can be achieved, both electively for individual building projects (which can start now and has already started), and through possible building code updates to change future design of all buildings (which will require a consensus development process to be completed to determine the building code changes).

3. Current and Recent Research

There has been a great deal of recent work focused on both resilient design of individual buildings, as well as possible building code requirements focused on resiliency (post-earthquake functionality). This paper does not present a complete literature review of recent work, but one recent study is mentioned here because this paper extends that study. This is the study by the Applied Technology Council that looked at performance expectations for new tall buildings in San Francisco and some possible measures that San Francisco could take to reduce the closure times expected even for new buildings [2]; Kakoty [9] provides a shorter conference paper summarizing the ATC-119 study. This current paper extends some of the ATC-119 studies to look further at performance expectations for new buildings, and ways that buildings could be intentionally designed to be more resilient.

4. Methods Used in This Paper for Building-Specific Seismic Risk Assessment

The following sections present example buildings, showing their current performance expectations in terms of building closure time and repair costs. The building-specific analyses completed for these examples include running a FEMA P-58 risk analysis [4] and a Resilient Design Initiative (REDi) building downtime analysis [5]. These example analyses were run using the "Level 0" analysis functionality of the *SP3-RiskModel* [10], which uses many databases and auto-population engines to make the analyses quick and to support such upfront design studies. This automation-enabled level of analysis provides information regarding code performance expectations and how a building will relatively improve as the design requirements are improved, but a more detailed FEMA P-58 analysis run by a licensed engineer would be required to make any conclusions about the performance of any specific building.

Each of the risk assessments in this paper are run for both the "design level" and the "rare event", which are the 475-year and 2475-year return period earthquake motions. These levels are often similar to, but are not the same as, the design and maximum-considered ground motion levels used in building codes.

5. Example: Performance Estimates for a 40-Story Steel Frame Building

This section provides one example resilient design process for a single sample building, and Appendix A provides several additional example cases for readers who want to dig a bit deeper into the details.

5.1 Overview of Requirements for a Resilient Design

There are several levels of resilient design, and the exact design requirements will depend on the level of resilience desired, but the primary needs for a seismic resilient building 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 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 anchorages and equipment being specifically designed to remain functional under the imposed floor accelerations.

Contemporary resilience-based design approaches (e.g. REDi 2013and USRC 2015) also 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 as follows:

Table 1 - 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

5.2 Overview of Example Building

The example building is a 40-story pre-Northridge 1975 steel moment frame in San Francisco. Though this building is much like many pre-Northridge moment frames in San Francisco [11], so as to not make a statement about any one actual building, this is a fictitious building placed on Fremont Street and is a commercial office occupancy. This section presents the performance of the original 1975 building, shows how the performance would change if the building was built by current code, and then shows how this example building code be made to be more resilient by using improved seismic design requirements.

5.3 Expected Downtime and Repair Costs for Original Building and Code-Conforming Designs

This full section on Example #1 is focused on showing what one could do to make this example tall building in San Francisco to be more resilient. The first step is to show the performance difference between the original building and an equivalent new code-compliant building; this is not to advocate that all older buildings be replaced with newer buildings, but is simply to show the comparison to see how much better the new buildings perform (and how they don't perform drastically better when it comes to building closure times).

First, we can check the effect on building collapse safety using the FEMA 154 screening method [12], which shows that the probability of complete collapse reduces by an order of magnitude, from 2% to 0.2% for the Maximum Considered Earthquake motion (MCE_R); this shows a large improvement in safety, as would be expected. Figure 1a then shows the repair costs, which reduce from 15% to 5% (factor of three) for the Design Level earthquake; the repair costs for the larger Rare Event earthquake do go down for the newer building but not as much, because both buildings will be heavily damage at the high level of ground motion. Both the collapse safety and repair costs reduce as expected between the older and new building variants, but the effects on functional recovery time are much less; Figure 1b shows that the functional recovery time for the Rare Event does go down substantially (which is intuitive), but the functional recovery time for the Design Level earthquake only reduces slightly, from slightly over one year to slightly under one year (which is counter-intuitive to most). This small reduction from the Design Level comes from the fact that new code-compliant buildings are designed to be safe but are not designed to limit damage ("safe but disposable"), so the original and new building variants are both expected to be non-functional after the earthquake and are expected to require a substantial amount of time to repair (and both include a very similar multi-month wait time before repairs will even be able to start).

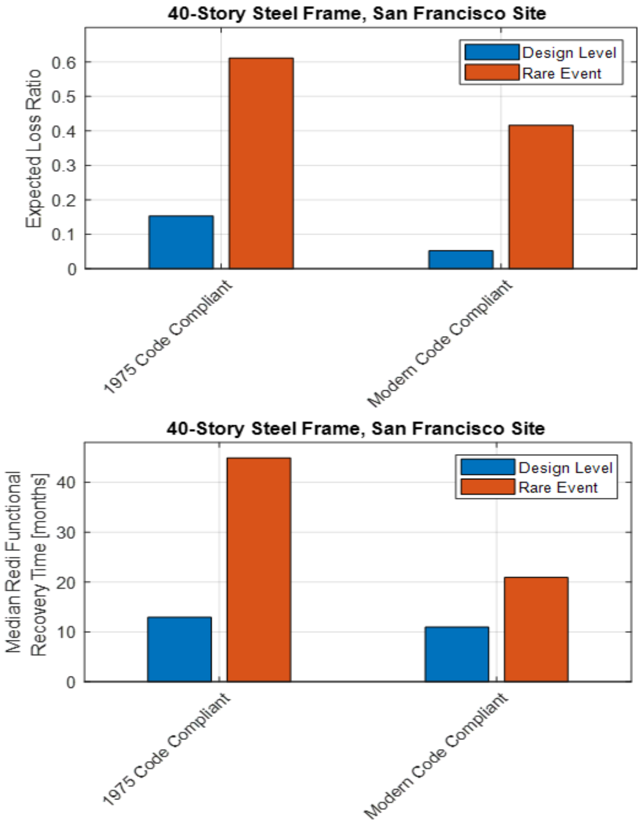

Figure 1. Expected performance for 1975 and new building variants of a 40-story steel frame building, including (a) repair costs and (b) functional recovery time

5.4 Sources of Downtime for New Code-Compliant Design

The next step in this example is to look at how building design could be improved in order to reduce the functional recovery time of the building. Using the FEMA P-58 and REDi analysis methods for the new code-compliant building subjected to the Design Level earthquake, it can be shown that the following specific building components are what is driving the building closure (along with approximate percentages for how often these are trigged in the Design Level earthquake). It is noted that the triggering percentages are approximate and should only be used to decide which components need better design to make the building resilient (e.g. we can't say that the elevator closes the building 42.6% of the time).

- Structural damage
    - Primary system (50-75%)
    - Gravity system (10-20%)
- HVAC:
    - Cooling tower and air handling (80-100%)
    - Chiller (40-50%)
- Electrical – motor control, distribution (80-100%)
- Elevators (40-50%)
- Partitions (30-40%)
- Building envelope (glazing) (10-20%)

In order to design the building to be resilient and to regain function in an acceptable amount of time after the earthquake, the above issues must be addressed in the design. This could be done through broad-brushed building code requirement changes (which would necessarily be more conservative, because they would need to work for all buildings and situations) and/or more surgical changes to design of individual component types. The next section shows some examples for how this building can be designed to be more resilient, showing the quantitative outcomes of each design decision. Note that this type of analysis process can be used both for direct resilient design of individual buildings, and also can be used to complete a study that can determine what prescriptive design requirements would be needed to deliver a desired functional recovery target (e.g. building functioning as intended in less than a week).

5.5 Expected Downtime for Enhanced Design Requirements Aimed at Functional Recovery

This section shows options for resilient design, and how the design decisions affect the building repair time and repair costs. This section first starts by looking at the effects of turning standard code "nobs" and then the second part of this section shows how a more direct approach could be taken for resilient design (likely resulting in better outcomes and reduced costs of implementation).

Figure 2 shows the improved building performance from the following four candidate changes to building design requirements (i.e. "code nobs"). This shows that these design changes do tend to improve the performance, but not by much when looking at the Design Level earthquake. These "code nobs" are:

1. Make the structural system 50% stronger (Ie = 1.5)
2. Also, design the non-structural components and anchorages 50% stronger (Ip = 1.5)
3. Also, design the building to be stiffer (drift limit of 1%)
4. And then also include the bracing requirements for full Risk Category IV design (like the design of an essential facility like a fire station)

For lower levels of earthquake motion, the onset of damage is expected to be delayed some by these design changes (and this could be looked at in later studies), but at the Design Level, all of these building design options result in the expectation that the building is non-functional after the earthquake and will require some time to mobilize before completing the repairs. Even so, some building types do show more improvement stemming from these design changes (as compared with this specific example), but the conclusion is consistent that these changes do no substantially improve the functional recovery times for Design Level ground motion levels (since the building is expected to be non-functional after the earthquake either way).

The results shown in Figure 2 can also be counter-intuitive because our Structural Engineering design practice is so used to these nobs being used for better design in the code. The problem is that the structure of our current building code is still highly focused on safety and reduces design strengths substantially (e.g. a strength factor on the order of 1/6 to 1/8) and also does not focus on functionality of non-structural components. If one increases the building design strength by 1.5 (after already dividing by 6 or 8), this makes very little difference in expected damage at Design Level ground motions. Similarly, if one increases the non-structural anchorages by 1.5, this also does not typically result in functionality of the non-structural

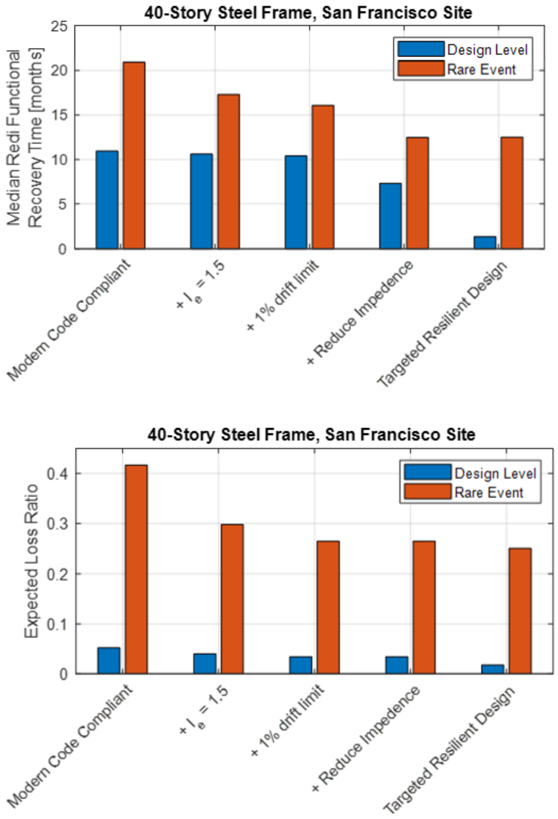

Figure 2. Expected performance for a 40-story steel frame building with enhanced prescriptive design requirements including (a) functional recovery time and (b) repair costs

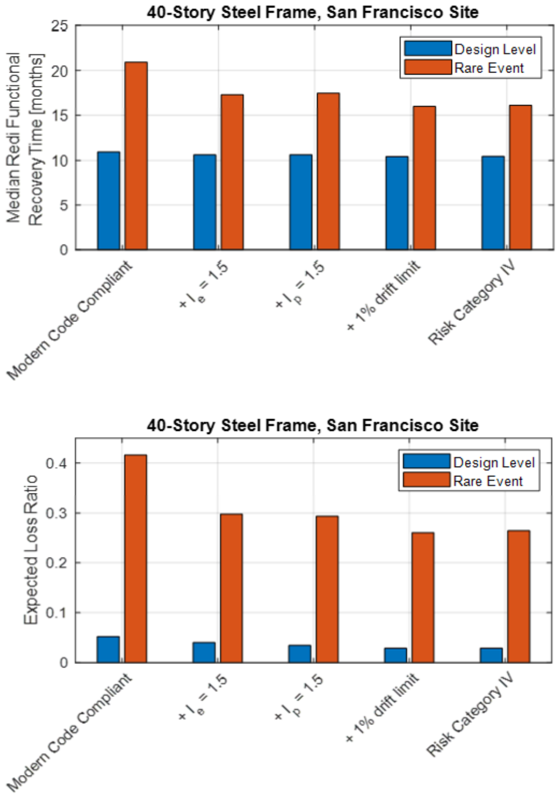

Figure 3. Expected performance for a 40-story steel frame building with targeted steps for resilient design for Functional Recovery, including (a) functional recovery time and (b) repair costs

components. Even though this is bad news that adjusting the typical “code nobs” does not provide the levels of functional recovery often being desired, it is still possible to achieve resilient design using prescriptive code requirements; these prescriptive requirements just need to be more targeted at the specific types of components that are making the building to be non-functional and often some of the design requirements (e.g. Ie = 1.5) can actually be omitted in a more direct design process for functional recovery design.

After design is completed up to Risk Category IV, the FEMA P-58 and REDi analysis methods can be used again to identify which specific building components are driving the building closure (as was done in Section 5.3 for a code-compliant design). These results (listed below) can be compared with the impedance rates for the code-compliant building (Section 5.3) and this shows that Risk Category IV has measurable benefit, but not enough to make the functional recovery time meaningfully shorter. The next design sequence in this example shows how a more direct functional recovery design process might look.

- Structural damage: Primary system (40-50%), gravity system (<10%)
- HVAC: Cooling tower and air handling (70-90%), chiller (30-40%)
- Electrical – motor control and distribution (60-90%)
- Elevators (<10%, so no longer controls)
- Partitions (10-20%, so no longer controls)
- Building envelope (glazing) (<10%)

Figure 3 shows additional options for how this example 40-story steel frame could be designed in a more direct manner to be resilient and to achieve Functional Recovery performance objectives. This includes the following steps. This shows that quick functional recovery of a building can be achieved for the Design Level earthquake through intentional and targeted resilient design, or a combination of design and planning to reduce delays for getting repairs made on the building. Functional recovery is shown to not be achieved for the Rare Event (but could be if desired) because the goal of this example was functional recovery at the Design Level earthquake (and we presume that the performance goal at the Rare Event would be more safety-focused than recovery-focused).

a) Design the structural system to be 50% stronger (Ie = 1.5); note that this was important in this example, to reduce damage localization in the building, but is not necessary for some other types of structural systems.
b) Design the non-structural components and anchorages 50% stronger (Ip = 1.5).
c) Design the building to be stiffer (drift limit of 1%).
d) Improve planning by having financing in place and by having an engineer and contractor on retainer (after page 3-20 of ATC 2018). Note that this step has meaningful impacts on reducing functional recovery time, but this step may not be necessary once the following step is accomplished (i.e. if there not enough damage to prevent building function, then having a good plan to fix damage becomes less important).
e) Strengthen the following specific components so they are not damaged enough to prevent building use (and note that exact design requirements may be a topic of a follow-up paper on this topic).
    - Elevator
    - HVAC chiller
    - HVAC cooling tower
    - HVAC air handling units
    - Electrical motor control center
    - Electrical distribution
    - Note #1: Some items were already resolved by previous design steps (e.g. partitions, by using the tighter drift limit).
    - Note #2: The following are also needed for some building types but were not needed for the resilient design of this 40-story steel frame building – further structural system changes (beyond Ie = 1.5), design changes to reduce damage to the gravity system, plumbing, fire sprinklers, cladding and glazing, interior partitions, lighting, and HVAC distribution.

6. Possible Prescriptive Building Code Requirements for Functional Recovery

FEMA P-58 studies, such as the example studies shown in Section 5 and Appendix A, can be used calibrate prescriptive requirements for resilient design. Table 6 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. The 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 for higher ground motion levels such as the Maximum Considered Earthquake motion level.
- 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 equipment must be functional, so additional pre-qualification requirements may be needed to confidently deliver such functionality.

Table 6 - Example Prescriptive Requirements for Resilient Design (numbers for illustrative purposes only)

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	2.0%	n/a	n/a	III
Bronze	2.5%	n/a	n/a	II

7. Summary of Findings

This paper used five building examples to look at the performance of both current code design and various possible approaches to future resilient design for functional recovery. The primary conclusions are as follows:

- Current code-compliant buildings do not deliver functional recovery. This is because functional recovery is not a goal of the current code. Many are now referring to new buildings as “safe but disposable,” and the functional recovery time for the Design Level earthquake ranges from six months to two years. These time ranges are consistent with prior studies looking at functional recovery times [9, 13].
- General changes to prescriptive building code “nobs” (e.g. Ie = 1.5, Ip = 1.5, and Risk Category IV) are shown by FEMA P-58 and REDi analysis to result in improved performance but the benefit is larger for repair cost and less for recovery time, and these standard code “nobs” do not result in short functional recovery times that may be desired. Note that these nobs could likely be “turned up more” to achieve acceptably low functional recovery times, but this would increase design requirements on all components (many of which are not impeding building function) so a more targeted approach may be desirable.
- More targeted resilient design can be used to improve the specific components that are impeding function of the building. This can be done to both (a) achieve the desired time to regain function, and (b) avoid overdesigning components that do not need it.
- This type of analysis process can be used electively right now (and is being used in the structural engineering practice) for resilient design of individual buildings.
- This type of analysis process can also be used to run parametric studies to determine what design requirements are needed (and are not needed) to provide an acceptably low functional recovery time for buildings in general. This can then be packaged into prescriptive design requirements in the appropriate format to be easily adopted into building codes and standards.

8. Recommended Immediate Next Step Forward Toward Design for Functional Recovery

A planned extension of this study is to run a broader set of resilient design examples, and then use those results to draw generalized conclusions about what prescriptive design requirements would lead to acceptable building functional recovery times (e.g. use these requirements if you are okay with your building being non-functional for a year or more, these requirements if you want to be functional in months, these requirements for functionality in weeks, and further requirements for functionality that is within days (or close to immediate). This study would also necessarily include a close look at which exact building components/systems are needed for building function, and these will differ by building occupancy (e.g. a smaller apartment building may be functional without an elevator, but a 40-story building would not).

In addition to this suggested next step, the authors of this paper are open to input regarding further studies or work that would help the community make collective progress toward resilient design for Functional Recovery.

9. Other Possible Follow-On Studies

Another possible extension to this study, and use of this new risk assessment technology, would be to look at expected building recovery times for groups of buildings (e.g. all tall buildings in San Francisco), and show how the recovery times would reduce over the region as the building design requirements are improved. This would be very similar to the resilient design examples included in this paper, but this can now be done for thousands of buildings in a community, to provide a better view of how improved design for functional recovery could radically change the expected building recovery times of a community. This may be a useful way to communicate the benefits of better design and how it will positively impact the functionality of buildings in an overall community.

10. Acknowledgements

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11. Copyrights

12. Appendix A: Additional Examples of Resilient Design for Functional Recovery

This section simply replicates the same type of design example as Section 5, but for additional structural systems, building heights, and site locations. This is meant to begin to generalize the conclusions in the steel frame examples, and the list of examples can be greatly expanded in the future in order to help calibrate prescriptive design requirements that are expected to result in functional recovery of buildings.

12.1 Example 40-Story Buckling-Restrained Braced Frame in San Francisco

This example is for a 40-story buckling-restrained braced frame at the same site in San Francisco. Note that this example extends the same example used in the recent ATC-119 study [2] and shows how that example building can be designed to be resilient and have a short time to functional recovery. These results were compared with the ATC-119 study results and the repair costs match well at the design earthquake ground motion level (which was used in the ATC study) but our repair times are slightly higher because we are using the REDi method impeding factors without the scaling done in the ATC-119 example. This example similarly shows that the prescriptive “code nobs” do not deliver quick functional recovery and the following resilient design process was used to achieve quick recovery. Note that the recovery planning step was excluded from this example and resilience was achieved through building design to achieve damage reduction, since this approach would likely be easier to implement into national building codes (and the recovery step was excluded from all the following examples as well).

a) Start with an initial design that is code-compliant, but that also has a moment-connected back-up frame to help control residual drifts.
b) Design the structural system to be 50% stronger (Ie = 1.5).
c) Design the non-structural components and anchorages 50% stronger (Ip = 1.5).
d) A reduced drift limit was not needed for this building, because it was already strength controlled.
e) Strengthen the following specific components so they are not damaged enough to prevent building use (and note that exact design requirements may be a topic of a follow-up paper on this topic) - Column splices, elevator, HVAC (chiller, cooling tower, and air handling units), and electrical (motor control center, and distribution)

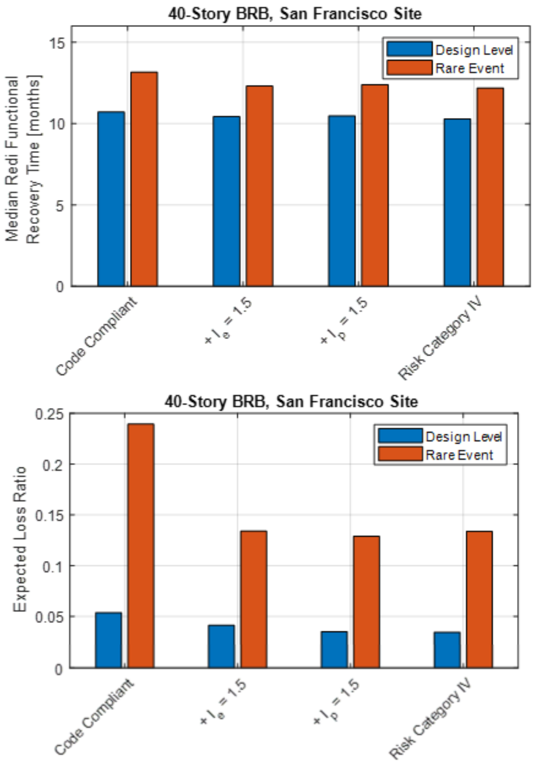

Figure 4. Expected performance for a 40-story buckling-restrained braced frame building with enhanced prescriptive design requirements including (a) functional recovery time and (b) repair costs

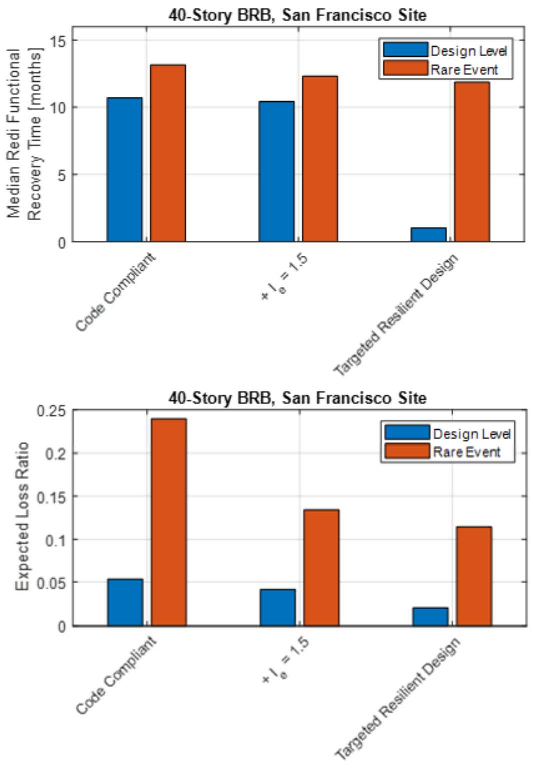

Figure 5. Expected performance for a 40-story bucking-restrained braced frame building with targeted steps for resilient design for Functional Recovery, including (a) functional recovery time and (b) repair costs

Example Wood Apartment Building in Los Angeles

This example is for a common type of new residential building, specifically a wood light-frame apartment building with four stories of wood sitting on a one-story reinforced concrete podium. This example is done at an example site in Los Angeles (110 South Main Street). This example focuses on one the resilient design approach and the following resilient design process was used to achieve quick recovery:

a) Design the structural system to be 50% stronger (Ie = 1.5).
b) A general increase in the non-structural components and anchorages was not needed (so used Ip = 1.0).
c) A reduced drift limit was not needed for this building, because this is a wood light-frame building, and increasing strength leads to similar increases in stiffness.
d) Add Simpson Strong Frames® in the first story to increase strength and reduce structural damage localization.
e) Strengthen the following specific components so they are not damaged enough to prevent building use (and note that exact design requirements may be a topic of a follow-up paper on this topic).
    - Elevators
    - HVAC: distribution only
    - Electrical: distribution only
    - Plumbing
    - Fire sprinklers

Example 12-Story Steel Frame Building in Los Angeles

This example is for a 12-story steel frame building located at an example site in Los Angeles (110 South Main Street). This example is provided to have a mid-rise variant (rather than all high-rise) to show that the conclusions are similar for mid-rise, but also to show that the repair cost ratios tend to be higher for shorter buildings (because the repair cost ratios for the 40-story buildings were shown to be fairly low as compared with the more general building stock). This example focuses on one the resilient design approach and the following resilient design process was used to achieve quick recovery:

a) Design for a reduced drift limit of 1%.
b) Design the structural system to be 50% stronger (Ie = 1.5).
c) In this example, the non-structural components and anchorages were not designed to all be stronger (used Ip = 1.0) but this resulted in four more component types being required to be addressed in the final resilient design step (see list below).
d) Strengthen the following specific components so they are not damaged enough to prevent building use (and note that exact design requirements may be a topic of a follow-up paper on this topic).
    - Elevators
    - HVAC chiller
    - HVAC cooling tower
    - HVAC air handling units
    - Electrical distribution
    - Electrical motor control center
    - Also included in the resilient design step since Ip = 1.5 was not used in the earlier design step: Raised access floors, ceilings, lighting, and fire sprinklers.

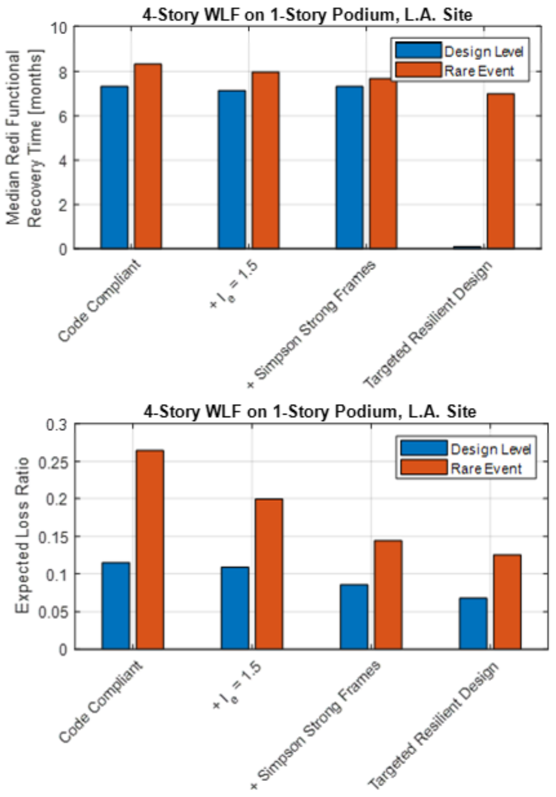

Figure 8. Expected performance for a 4-story wood light-frame apartment building (on one story podium) with targeted steps for resilient design for Functional Recovery, including (a) functional recovery time and (b) repair costs

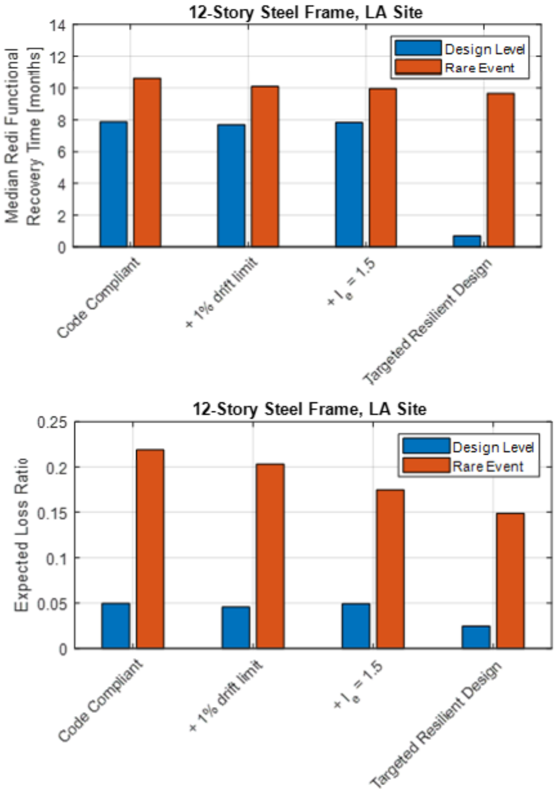

Figure 9. Expected performance for a 12-story steel frame building with targeted steps for resilient design for Functional Recovery, including (a) functional recovery time and (b) repair costs

13. References

[1] AB-393 (2019). AB-393 Building Codes – Earthquake Safety – Functional Recovery Standard, a bill of the California State Assembly, introduced by Assembly Member Nazarian on February 6, 2019, available at http://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201920200AB393 (last accessed 7/4/19).

[2] ATC (2018). "San Francisco Tall Buildings Study." An Applied Technology Council project (ATC-119) for the City and County of San Francisco, CA.

[3] Moehle J. and G. Deierlein. (2004). A Framework Methodology for Performance-Based Earthquake Engineering. *13th World Conference on Earthquake Engineering*, Vancouver, Canada.

[4] FEMA 2012, *FEMA P-58-1: Seismic Performance Assessment of Buildings*, Applied Technology Council Project 58, Redwood City, CA.

[5] REDi 2013. *Resilience-based Earthquake Design Initiative for the Next Generation of Buildings*, Ibrahim Almufti and Michael Willford, Arup.

[6] Terzic, V. and D. Yoo (2016). *Repair Time Model for Buildings Considering Earthquake Hazard*, 2016 Proceedings of the Convention of the Structural Engineering Association of California, pp. 562-571.

[7] Almufti, I., J. Krolicki, and A. Crowther (2016). *The Resilience-Based Design of the 181 Fremont Tower*, Structural Magazine, pp. 42-46, June 2016.

[8] Hata, O.,et al. (2016). *Emerging Concepts in Structural Design of Tall Buildings – Long Beach Civic Center*, Los Angeles Tall Buildings Structural Design Council Conference, May 6, 2016, Los Angeles, CA.

[9] Kakoty, Monfared, and Molina Hutt (2019). *Seismic Performance of Tall Buildings Following Non-Prescriptive Design Procedures*, 12th Canadian Conference on Earthquake Engineering, Quebec Canada, June 17-20, 2019.

[10] Seismic Performance Prediction Program (SP3) (2019). © Haselton Baker Risk Group, available at www.hbrisk.com and https://www.hbrisk.com/products/risk (last accessed 7/4/19).

[11] San Francisco (SF), City and County (2019). *Tall Building Inventory*, online database, available at https://data.sfgov.org/Housing-and-Buildings/Map-of-Tall-Buildings/xnf9-cudk and https://data.sfgov.org/Housing-and-Buildings/Tall-Building-Inventory/5kya-mfst/data (last accessed 7/4/19).

[12] FEMA 2015, *FEMA P-154: Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook, Third Edition*, Prepared for FEMA by the Applied Technology Council, Redwood City, CA.

[13] Wade K., D.J. DeBock, C.B. Haselton, D. Cook, and E. Almeter (2018). *Expected Performance of New Building-Code-Compliant Buildings in California*, 2018 Convention of the Structural Engineering Association of California, September 12-14, 2018, Palm Desert, California.