WHITE PAPER ON RESILIENT SEISMIC DESIGN USING PRESCRIPTIVE AND NON-PRESCRIPTIVE DESIGN METHODS

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INTRODUCTION AND INTENDED AUDIENCE

This short white paper is written for audiences interested in resilient design of new buildings. In this paper, "resilient design" means that the goal is for the building to have limited damage in an earthquake, such that the repair costs and repair time are low. This is in contrast to the typical building-code-based design approach, which focuses primarily on safety (not controlling repair costs and repair time) and often leads to a building that is essentially disposable in a large earthquake.

This paper is also targeted at an audience that is interested in a *quantitative* approach to resilient design rather than an empirical/judgmental approach. This paper is also currently written in language tailored toward a structural engineering audience, but the content is also useful to other audiences such a building code organizations, municipal officials interested in resilient design for their jurisdiction, etc.

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 then how prescriptive design methods could be calibrated to provide a resilient design.

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 to make a building be 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 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 the anchorages and the equipment being specifically designed to remain functional under the imposed floor accelerations.

Contemporary resilience-based design approaches (e.g. REDi 2013 and 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

RESILIENT DESIGN USING NON-PRESCRIPTIVE DESIGN METHODS

There are approaches in the building code with the goal of making the building "better," such as making the building stronger, stiffer, and/or enforcing the combined requirements for a higher Risk Category. However, the primary focus of the building code is to ensure safety and these requirements were created based on judgement and experience and it has not been demonstrated that they actually deliver the desired resilience (as evidenced by the performance of the Oliveview Hospital building in the 1994 Northridge earthquake; e.g. http://articles.latimes.com/1994-01-19/local/me-13343_1_parking-lot).
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.

In the absence of prescriptive design requirement for resilience, a resiliency 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), which quantitatively estimates the repair cost and repair time of the building, and then can be used to iteratively design the building to meet stated resiliency goals. The FEMA P-58 approach is complete and accounts for all of the important components of resilience – ground motion hazard, structural responses (with 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. This resiliency assessment could also be subject to random peer review to ensure quality control (such as that offered by the U.S. Resiliency Council).

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 section. The follow results shown in Table 2 and Figure 1 outline an example resilient design process that could be used based on FEMA P-58 analysis. This uses the same baseline 12-story reinforced concrete special moment frame used in the design studies in the next section (with Ie = 1.0 and 2% drift limits). 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 resiliency target (e.g. reducing drift limits would also be a good step). 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 no 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.

Table 2 - Example of Resilient Design Process using FEMA P-58

ID	Design Changes	Mean Loss at 10% in 50yr	Mean Loss at 2% in 50yr	Median REDi Functional Recovery at 10% in 50yr
11251	Baseline	17%	43%	37 days
11253	Self-Centering Frame (No Residual Drift)	11%	27%	32 days
11254	Cladding Detailed for No Damage	7%	17%	29 days
11255	Slab-Column Connections Detailed for No Damage	4%	11%	27 days
11256	Lateral Frame Connections Detailed for No Damage	2%	5%	27 days
11257	Elevators Detailed for No Damage	2%	5%	4 days

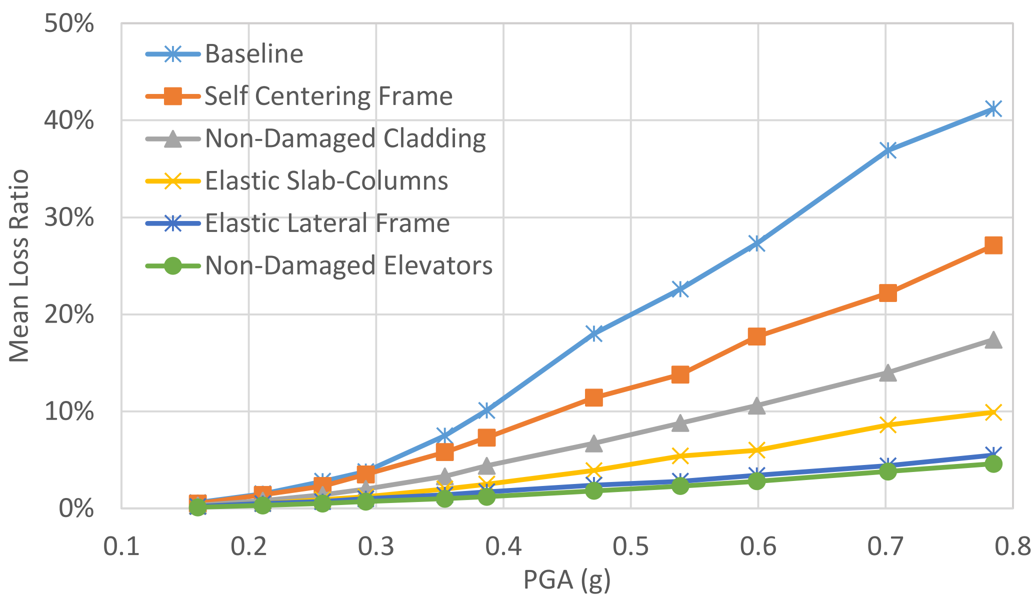

Figure 1 - Example Results from a Resilient Design Process using FEMA P-58

Resilient Design using Prescriptive Design Methods

To meet the need for a prescriptive method for resilient design, based on quantitative estimates of resiliency, 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 use a baseline 12-story reinforced concrete special moment frame office occupancy building designed for a site in Los Angeles, based on current building code requirements. We then modify this building design to see the effects of varying design requirements.

Effects of Increased Strength

For the first step in this study, Table 3 - *Effects of Increased Design Strength (Ie > 1.0)* and Figure 2 shows the effects that increased building strength (Ie > 1.0) has on resilience for a 10% in 50 year and 2% in 50 year earthquake. In this study, the building is full 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 values and the recovery time (where recovery time is computed in accordance with REDi, 2013 and excludes impeding factors). This shows that, for this example mid-rise RC SMF building, that the increased strength has very little effect on the performance for the 10% in 50 year motion and has some modest beneficial impacts on the performance for the 2% in 50 year motion.

Table 3 - Effects of Increased Design Strength (Ie > 1.0)

ID	Design Year	Stories	Design Drift	Period [sec]	Yield Base Shear Coefficient [g]	Design Changes	Mean Loss at 10% in 50yr	Mean Loss at 2% in 50yr	Median REDi Functional Recovery at 10% in 50yr
11271	New	12	2.0%	2.58	0.125	Ie = 1.0	18%	51%	14 weeks
11272				2.53	0.156	Ie = 1.25	18%	46%	14 weeks
11273				2.41	0.188	Ie = 1.5	15%	38%	11 weeks

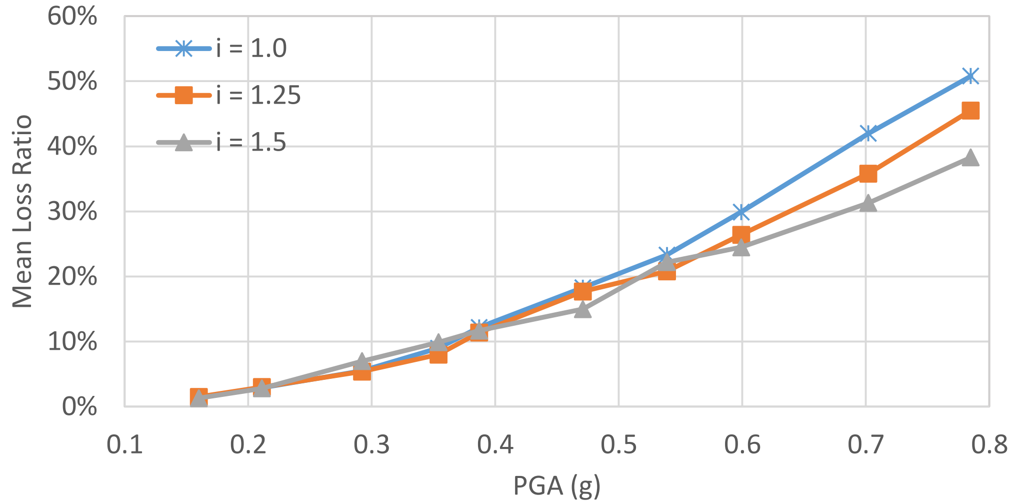

Figure 2 - Effects of Increased Design Strength (Ie > 1.0)

Effects of Increased Stiffness

The next study looks at the effects of design drift requirements and the results are provided in Table 4 and Figure 3. 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 some 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.

Table 4 - Effects of Reducing Drift Limits

ID	Design Year	Stories	Design Drift	Period [sec]	Yield Base Shear Coefficient [g]	Design Changes	Mean Loss at 10% in 50yr	Mean Loss at 2% in 50yr	Median REDi Functional Recovery at 10% in 50yr
11261	New	12	2.5%	2.6	0.125	Baseline	29%	70%	60 days
11251			2.0%	2.1	0.125	Baseline	17%	43%	37 days
11241			1.5%	1.6	0.125	Baseline	10%	34%	27 days
11231			1.0%	1.1	0.125	Baseline	6%	18%	29 days
11221			0.75%	0.8	0.125	Baseline	5%	14%	27 days
11211			0.5%	0.4	0.125	Baseline	4%	15%	27 days

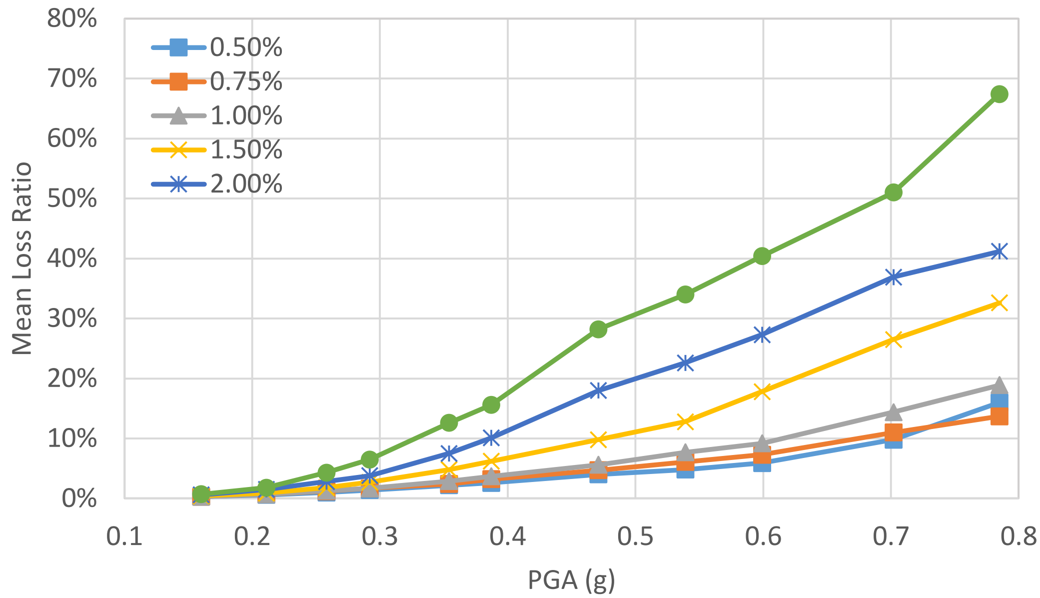

Figure 3 - Effects of Reducing Drift Limits

Effects of Full Risk Category IV Requirements

The next study looks at the effects of the components of Risk Category IV requirements and how they affect building resiliency; these results are provided in Table 5 and Figure 4. This shows that the bracing requirements have some effects, but the primary benefit comes from the reduced drift limits.

Table 5 - Effects Risk Category IV Requirements

ID	Design Year	Stories	Design Drift	Period [sec]	Yield Base Shear [g]	Design Changes	Mean Loss at 10% in 50yr	Mean Loss at 2% in 50yr	Median REDi Functional Recovery at 10% in 50yr
11251	New	12	2.0%	2.1	0.125	Baseline	17%	43%	37 days
11252			2.0%	2.1	0.125	Risk Category IV bracing only	15%	42%	34 days
11232			1.0%	1.1	0.1875	Full Risk Category IV (bracing, Ie = 1.5, drifts)	3%	14%	26 days

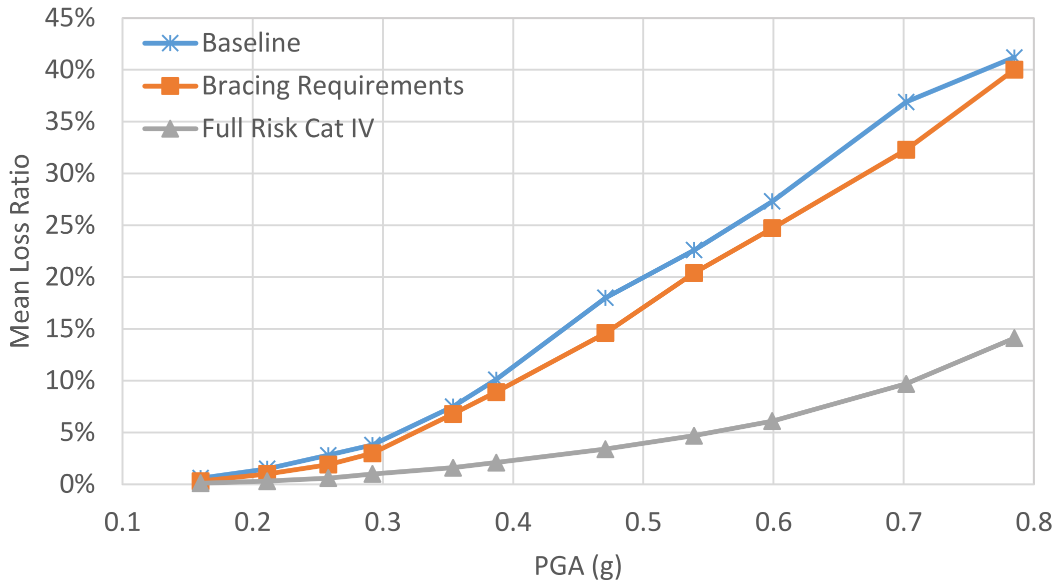

Figure 4 - Effects Risk Category IV Requirements

Possible Prescriptive Code Requirements

FEMA P-58 studies, such as the example studies shown in this section, could 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.
- 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.

Table 6 - Example Prescriptive Requirements for Resilient Design

Level of Resilience	Drift Limit	Maximum R Factor	Maximum Rp Factor	Risk Category for Nonstructural
Platinum	0.75%	3.5	1.5	IV
Gold	1.25%	5.5	4.0	IV
Silver	2.0%	8.5	9.0	III
Bronze	2.5%	8.5	12.0	II

References

Cheevers 1994, *Earthquake: The Long Road Back: Hospitals Strained to the Limit by Injured: Medical care: Doctors treat quake victims in parking lots. Details of some disaster-related deaths are released*. Los Angeles Times, http://articles.latimes.com/1994-01-19/local/me-13343_1_parking-lot.

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

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

Seismic Performance Prediction Program (SP3) (2017). © Haselton Baker Risk Group, www.hbrisk.com.

USRC 2015. *USRC Building Rating System for Earthquake Hazards*, United States Resiliency Council.