

Resilient Design and Risk Assessment using FEMA P-58 Analysis

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The Need for FEMA P-58

Most building codes worldwide have been developed to protect building occupant health and safety under likely loading, including earthquakes. Severe wind, snow, and live loads occur frequently during a building's life and therefore, in addition to protecting life safety, code requirements for these loads also result in a very low probability that buildings will be damaged by these loads. Earthquakes, however, occur rarely and most buildings will never experience a significant earthquake. Therefore, building codes do little to limit building damage, repair cost, and building closure time resulting from even moderate events. Recent studies of code compliant buildings indicate they may be closed for six to 24 months after a design level earthquake, and demolished after a maximum considered earthquake. Essentially, we are designing "safe but disposable" buildings. Can we do better?

In the period 1971-1994 California experienced damaging earthquakes somewhere in the state every 18 months or so. The mounting losses prompted owners to ask engineers to evaluate and upgrade existing buildings to perform better, but engineers had no tools to do this. The Federal Emergency Management Agency (FEMA) initiated a series of projects with the Applied Technology Council (ATC) that culminated in 1997 with publication of the *FEMA 273/274 Guidelines for Seismic Rehabilitation of Buildings*. This landmark document, which has since evolved into the *ASCE 41* standard formed the first generation of true performance-based seismic design criteria. However, owners also wanted better performing new

buildings and *FEMA 273/274* applied only to existing buildings. Engineers began to demand similar procedures for design of new buildings. FEMA again turned to ATC to respond to this need and funded development of the FEMA P-58 methodology through the ATC-58 project series, which ultimately required more than \$16 million in funding, and produced a comprehensive risk assessment methodology applicable to both new and existing buildings.

Early in the development process, ATC solicited input from stakeholders including engineers, owners, building officials, insurers and lenders. These stakeholders indicated that rather than discrete performance levels inherent in *ASCE 41*, it would be preferable to acknowledge the continuous range of performance buildings experience, to be quantitative in description of this performance, and to acknowledge the uncertainties inherent in assessing building performance in future events.

The FEMA P-58 method provides *quantitative* description of building performance in terms of repair cost, repair time, life safety, occupancy and environmental impacts. It is building-specific and can be used in an iterative manner to design buildings with desired performance, just as engineers use structural analysis software to design buildings for code compliance (where the goals are limiting drifts, making components strong enough, etc.). It can also be used to assess the risk of an existing building.

Overview of the FEMA P-58 Method and the Quantitative Information it Provides

Figure 1 shows major steps in the P-58 process:

- 1) **Ground Motions.** Expected ground motion intensities are quantified using seismic hazard analysis (or default U.S. Geological Survey data). This step may also include selection of ground motions if required for structural analysis (Step 2).
- 2) **Structural Response.** Building response quantities are computed for each ground motion level of interest. These include peak story drifts and floor accelerations, residual story drifts, and other predictive parameters. This step can be completed using either response-history analysis or linear static response prediction approaches calibrated to nonlinear analysis based on building strength and modal properties.
- 3) **Component Damage.** Damage to individual structural and nonstructural components is computed by combining the structural responses with fragility (damage) functions (e.g. functions for partition walls that relate story drift to wall damage). This step is supported by a comprehensive database of fragility functions provided in the FEMA P-58 documentation.

4) **Losses and Repair Times.** First, repair costs and repair times are computed for each component based on the predicted damage, then these are aggregated to compute total repair cost and repair time for the building. Repair costs include regional modifiers to reflect construction costs by region, and do not typically include post-earthquake demand surge (though that could be included).

These four steps of the FEMA P-58 method are combined using Monte Carlo simulation, such that the uncertainties are tracked and the risk predictions quantified by mean values and variability.

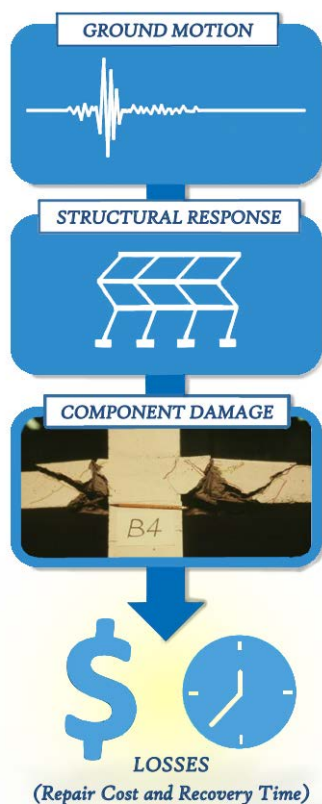


Figure 1. Overview of the FEMA P-58 analysis method.

Some highlights of the FEMA P-58 method are that:

- In addition to safety metrics, FEMA P-58 predicts important metrics of building resilience including.
 - Repair costs
 - Repair time
 - Potential occupancy tagging
- FEMA P-58 predicts building-specific risk using a quantitative engineering-based assessment process, in contrast to most other loss prediction methods that are empirical or judgment-based, and use building class rather than building-specific information.

- FEMA P-58 is open-source, standardized, and repeatable, with the assessment process being supported by a wide range of databases created in the project (fragility functions, loss functions, etc.)

Figure 2 provides a loss vulnerability curve for an example mid-rise office building in Los Angeles with a reinforced concrete frame. For this example, the 10% in 50 year and 2% in 50 year ground motions produce 0.47g and 0.78g peak ground accelerations, and mean repair costs of 18% and 42% of replacement cost, respectively. FEMA P-58 also provides full statistical distributions of losses and repair times (e.g. 90th percentiles, etc.).

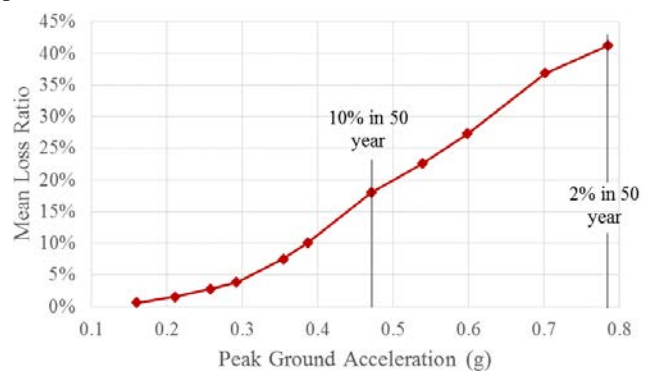


Figure 2. Example mean repair cost curve predicted by FEMA P-58 analysis.

In addition to the aggregated results of Figure 2, FEMA P-58 also predicts repair costs for specific components. Figure 3 shows a breakdown of repair costs for 10% in 50 year ground motion for the same example building. In this case, two-thirds of the loss comes from items other than structural damage, with significant contributions from partitions and finishes, as well as some contribution from excessive post-earthquake drift (“residual drift”) indicating that the building would need to be demolished.

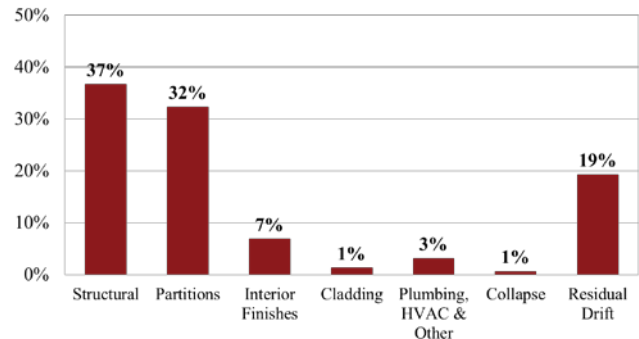


Figure 3. Breakdown of repair cost sources for a 10% in 50 year level earthquake motion.

FEMA P-58 also provides detailed information on repair times, which is useful for predicting building closure and business disruption. Companion methods, like the Resilient Design Initiative (REDi) build on FEMA P-58 to provide enhanced repair time estimates. Figure 4, constructed using the REDi procedure shows the expected repair times for the same 10% in 50 year ground motion level, and predicts that it will take 6 months to reoccupy the building and 9 months to have the building restored to pre-earthquake conditions.

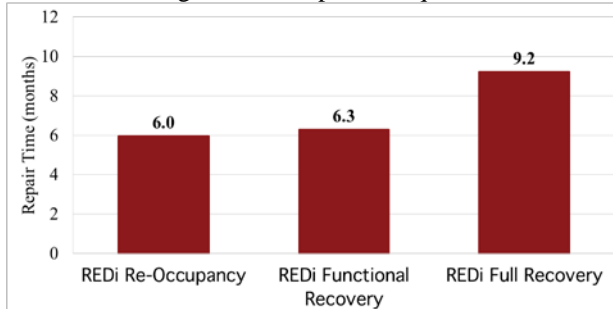


Figure 4. Building closure and repair times for a 10% in 50 year level earthquake motion.

The FEMA P-58 method enables quantitative resilient design of buildings, but is equally applicable to risk assessment of existing buildings (and is commonly used for existing buildings as well).

Recent Developments that Build upon FEMA P-58

The debut of P-58 in 2012 spurred additional research and development to extend and enable effective use of the method. Examples include the Resilient Design Initiative (REDi) system in 2013 and the U.S. Resiliency Council (USRC) rating system in 2015—two systems that provide building ratings based in large part on FEMA P-58 calculations. To enable efficient use of the FEMA P-58 method, the Seismic Performance Prediction Program (SP3) software was created and released in 2014. Additionally, the National Science Foundation has funded the extension of FEMA P-58 to cover other structural systems including tilt-up buildings.

Use-Cases for FEMA P-58

FEMA P-58 enables engineers to provide a wide range of new services, as listed below and illustrated in the following few sections.

- Resilient design of new buildings
- Retrofit of existing buildings
- Risk assessment for mortgage decisions (PML+)
- Risk assessment for insurance decisions
- Risk assessment for investment decisions
- Risk assessments of special facilities that require post-earthquake operability

Quantitative Resilient Design

Traditionally, we make a building “better” by adding strength or stiffness, or by designing to the immediate occupancy objective using ASCE 41. This can be difficult to sell to clients, however, because it is hard to quantify the effects of better design. FEMA P-58 enables structural engineers to quantify the impacts of better design, in terms that more building owners understand and care about.

Exact design requirements will depend on the circumstance. Common goals are:

- Avoid structural damage, and limit residual drifts, to ensure post-earthquake functionality (i.e. no red tag and no damage would require structural repair).
- Prevent damage to non-structural drift sensitive components that would inhibit building functionality.
- Prevent damage to acceleration sensitive components that would inhibit building functionality, including equipment and their anchorages.

Figure 5 shows an example of a recent resilient design project, the Long Beach Civic Center (LBCC) in Southern California (with information coming from the 2016 Structural Engineers Association of California, SEAOC, convention). This complex includes an 11 story building for the City of Long Beach, an 11 story building for the Port of Long Beach, and a one-story city council chambers. This project was designed with the collaboration of Nabih Youssef and Associates and Skidmore Owings & Merrill. The overall resiliency goals for this design included the following performance goals for 10% in 50 year ground motion:

- Safe (code-compliant, low risk of fatality or injury)
- Repair cost < 5% of building value.
- Reoccupancy time < 1 week
- Complete recovery time < 1 month



Figure 5. Rendering of the Long Beach Civic Center, which was designed iteratively using FEMA P-58 (with image credit to Skidmore Owings & Merrill).

The design of the LBCC buildings was driven directly by iterative FEMA P-58 analysis and redesign. The list below outlines the primary design steps and Figure 6 shows approximately how the repair costs and repair time dropped as each of the resilient design steps were implemented:

- **Step 1:** Decide to use a reinforced concrete core wall and start with a code-compliant design.
- **Step 2:** Increase wall strength to limit flexural damage such that repair is not required.
- **Step 3:** Remove coupling beams (and instead use a punched wall design) such that coupling beams do not require repair.
- **Step 4:** Ensure equipment is functional through strengthening anchorages and prequalifying important equipment.
- **Step 5:** Strengthen one elevator to ensure post-earthquake functionality.
- **Step 6:** Reduce the shear stress in the gravity slab-column connections to limit their damage.
- **Step 7:** Stiffen structural walls (to meet a 1% drift target), to further protect slab-column connections and to protect partition walls.

Exact cost comparisons for this building are not yet available, but other similar projects suggest that this type of resilient design only costs 1-3% more than a baseline code-compliant design.

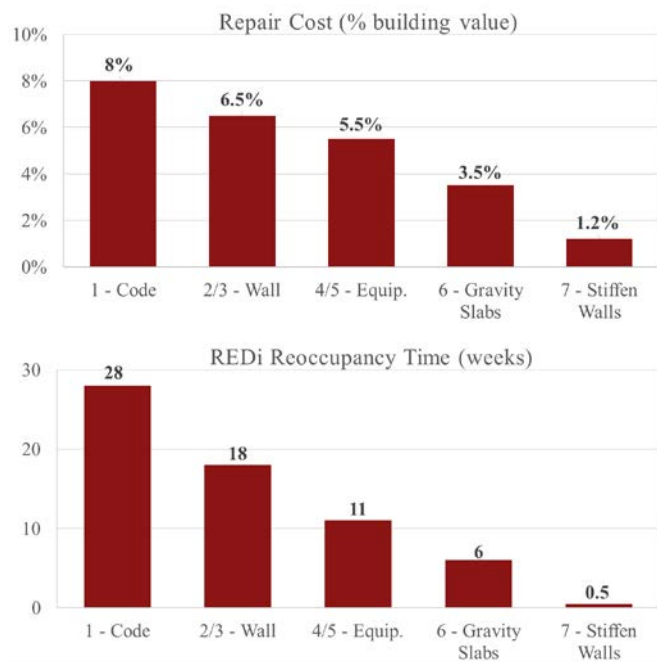


Figure 6. Example resilient design showing approximate (a) reduction in repair cost, and (b) reduction in REDI reoccupancy time.

Figure 7 shows a commercial property developed by Watson Land Company. Watson Land Company develops and leases their properties, and have been designing their properties to exceed minimum requirements for many years as a means of creating more marketable properties, reduce the chance that their occupants will be displaced after an earthquake, and to reduce required earthquake insurance costs. This building was designed for an Immediate Occupancy objective using ASCE 41 and now FEMA P-58 is being used to quantify the risk reduction in terms of reduction in dollar losses, which will provide a stronger basis for pursuing an insurance benefit. The current FEMA P-58 study is showing an approximate factor of 2-3 reduction in repair costs for 10% in 50 year ground motion level, but the study is ongoing. When comparing the resilient design to a typical code-compliant design, the building only cost \$1.27 more per square foot.



Figure 7. Rendering of Watson Land Company commercial tilt-up building, designed using an ASCE 41 Immediate Occupancy objective, with reduction in risk quantified using FEMA P-58 (with image credit to Watson Land Company).

Building-Specific Risk Assessment

The same FEMA P-58 method is used regularly to complete high-resolution building-specific risk assessments of existing buildings; for a wide range of purposes (retrofit decisions, mortgage risk assessments, insurance risk assessments, investment risk assessments, etc.).

Figure 8 shows an example assessment completed to support a possible building purchase decision; this is an older building that had been structurally upgraded, but which still has older and brittle unreinforced masonry cladding. A full FEMA P-58 assessment was completed by Holmes Structures to estimate building damage and repair costs at multiple levels of ground motion. Damage to the brittle cladding was an important component and Figure 7 illustrates the expected damage states of the cladding on multiple elevations of the building (for a 10% in 50 year ground motion).



Figure 8. Image of damage predictions for historic façade using FEMA P-58; this was done as a part of a comprehensive risk assessment of this building, in support of a purchase decision.

Conclusions

The FEMA P-58 assessment methodology represents a great leap forward in capability to quantify and improve earthquake performance. By linking specific building properties to repair cost and repair time, society can better understand and manage earthquake risks. The examples above show how engineers are using this tool to design resilient buildings, and to better quantify the risks posed by existing buildings. Based on the first five years of experience with this tool, we see that new buildings can be designed with greatly improved performance at a very low cost premium. With each passing year, further research and advances such as new software tools and rating systems continue to make this approach more accessible and useful. We look forward to a day when all building owners and insurers understand their earthquake risk, and when all new buildings are designed to be seismically resilient.