FEMA P-58 RESILIENCE ANALYSIS OF BUILDING PORTFOLIOS CONSIDERING GROUND MOTION CORRELATIONS

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Abstract: *FEMA P-58 has emerged as the state-of-the-art method for building-specific assessment of repair costs and building closures. However, the procedure focuses on individual buildings and is rarely used for portfolio risk analysis. This study presents an extension of the method to consider risk to portfolios of buildings distributed throughout a region. Monte Carlo simulations of potential future earthquake ruptures and resulting ground motion intensities are generated in a manner that reproduces ground motion hazard curves at all locations while also preserving correlations across locations and across intensity measures. In parallel, FEMA P-58 assessments of all buildings in the portfolio are performed to create building-specific vulnerability data. Then the intensity measure simulations are paired with building vulnerability data to generate realizations of impacts to buildings in the portfolio. The analysis can produce a portfolio-level Exceedance Probability (EP) curve—the annual probabilities of exceeding various levels of loss—for metrics such as repair cost or loss of occupiable space. Results from an example analysis are provided to demonstrate the output metrics and the ways that they can be used to support risk management decisions. The roles of spatial and cross-intensity-measure correlations are quantified by running the analyses with and without correlations considered. The presented procedure further extends the utility of the FEMA P-58 assessment methodology by supporting the important use case of portfolio risk assessment.*

1. Introduction

Seismic portfolio loss assessments generally rely on generic fragility or vulnerability curves that predict individual buildings' losses as a function of their membership in some class of buildings, rather than their specific features. These vulnerability predictions may be based on HAZUS, ATC-13, or similar judgment/experience-based curves often used in catastrophe models (Rojahn and Sharpe 1985, Grossi et al. 2005, FEMA 2015). This creates challenges for evaluating risk of buildings for which little data are available to constrain experience-based curves. Examples of challenging but common building types in the United States include 3-5 story wood light-frame buildings, modern tilt-up up concrete buildings, steel moment frame buildings, and tall concrete-core-wall buildings. These systems have all gained popularity since the last large earthquakes to strike urban areas in the U.S., limiting the applicability of empirical observations and simplified empirical models. Generic vulnerability models also restrict the analyst's ability to incorporate building-specific information about configuration, structural system, contents, or recovery planning, when performing loss assessments.

At the individual building level, the FEMA P-58 seismic performance assessment method has grown rapidly in popularity in the past decade (FEMA 2018). This method allows analysts to consider building specific features in loss predictions, due to its use of response history analysis to predict building responses with a structural analysis model, and its use of component fragility functions to quantify damage to the specific contents of a given building (Haselton et al. 2018). And while the FEMA P-58 assessment approach allows for predicting financial losses due to damage, similar to traditional vulnerability models, it can also predict a wider array of performance metrics such as reoccupancy time and functional recovery time (Cook et al. 2021).

To address this challenge, we describe here a computational approach for coupling FEMA P-58 analyses with portfolio losses assessment techniques, to compute portfolio risk metrics that utilize high-resolution assessments of individual buildings in the portfolio. To date, some regional performance assessments have been performed utilizing FEMA P-58 analysis in their workflows (e.g., Deierlein et al. 2020, Hulsey et al. 2022), but there has been little detailed description of effective algorithmic workflows, and none of the analyses have evaluated financial metrics of interest in insurance applications. This paper aims to advance the discussion of the methods required to effectively merge these modelling paradigms and the opportunities provided by this approach.

2. Analysis workflow

Regional portfolio seismic risk calculations typically utilize a Monte Carlo simulation approach. With this approach, a series of potential rupture scenarios are simulated, and resulting ground motion intensities at each location are simulated for each rupture scenario. These simulated intensities are then used as inputs for calculations of building loss (Baker et al. 2021). The building loss calculations traditionally utilize vulnerability functions specified per building class of interest. The per-building losses can then be aggregated and passed through a financial model to compute total losses, insured losses, and other metrics. Each stage of this calculation is relatively inexpensive computationally, leading to a calculation that is feasible to perform directly (Crowley and Bommer, 2006).

FEMA-P-58-based simulations of loss per building, on the other hand, are more computationally expensive. Analyses may take a second or a few seconds for a building, but over many simulations and many thousands of buildings, aggregate analysis time could be substantial. Further, it is not feasible to load the entire building inventory and simulate one realization of loss for each building for each earthquake rupture simulation. Some pre-calculation of loss per building will be computationally and logistically advantageous. The more effective approach is to pre-simulate loss metrics for each building and each level of ground motion intensity of interest, effectively creating a building-specific vulnerability function for each building in the portfolio. These results can then be stored for look-up during the portfolio risk analysis stage.

Figure 1 illustrates the major steps in the proposed analysis process, as described in more detail below. Initially, building characteristics are specified to allow the earthquake rupture simulation and FEMA P-58 analysis. The left column of Figure 1 focuses on steps related to the building inventory and P-58 analysis. The portfolio properties are specified at the start, and flow into later analysis stages. For each building in the portfolio, a FEMA P-58 analysis is run. The range of intensity levels of interest is specified, and a set of Monte Carlo simulations of performance is run at each intensity level. The output metrics of interest are then captured from each simulation and stored. If more than one metric is of interest (e.g., repair cost and closure time), the metrics are stored in a structure that aligns the metrics associated with a given simulation. This is important, for example, if the ultimate financial metric of interest includes both direct losses due to building repairs and indirect losses due to lost income from tenant occupancy; in this case, the repair cost and closure time simulations need to be aligned. The realizations of performance metrics per building and intensity level are stored in a large data structure for later access.

The top right portion of Figure 1 illustrates the steps associated with hazard analysis. Building locations and periods are used in the ground motion intensity simulation steps, to simulate relevant intensity measure metrics (i.e., spectral acceleration and building fundamental periods) at all relevant locations. Soil characteristics (measured via average shear wave velocity over the top 30 meters of the site, $V_{s,30}$) are also specified, as these characteristics affect ground motion prediction. The result from these simulations is a large table of ground motion intensity for each building and each rupture simulation, along with the annual occurrence rate of each rupture simulation. This is sometimes referred to as a stochastic event set.

The Figure 1 box labeled "Portfolio engine" indicates the step where the simulations are merged to assess portfolio level impacts per earthquake rupture. For each rupture in the event set table, the ground motion intensity at each building location is used in a look-up from the building vulnerability information, and a sample of building performance metrics associated with that intensity is returned. Once all buildings are sampled, loss and closure time information is available for the full portfolio, and the results can be aggregated via a financial model. For total losses, costs may simply be a sum of the per-building simulated losses. The financial model can also consider per-building and per-portfolio insurance deductibles and limits for insured losses, or per-building rental incomes to combine direct and indirect losses. The building inventories can also be modified to consider hypothetical retrofit programs where some or all buildings undergo a structural retrofit that enhances their seismic performance (via strength and stiffness improvements that then influence the FEMA P-58 structural response predictions).

The results from the portfolio engine include simulations of per-rupture portfolio level loss metrics, that can then be used to compute a loss exceedance curve, per-building loss metrics, and other results that can be tabulated, mapped, and plotted to assist with risk management decision making.

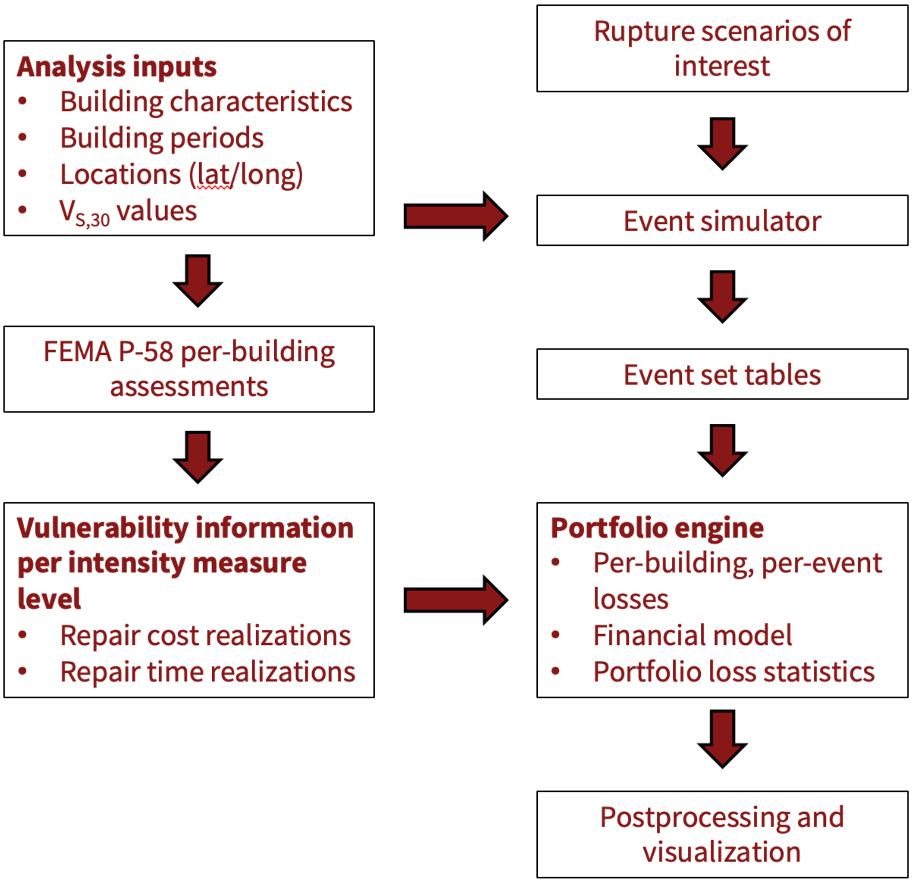

Figure 1: Major steps in the portfolio analysis workflow.

3. Case Study

To illustrate the above workflow, we analyze an example portfolio of 1452 nonductile concrete buildings in Southern California. Building input characteristics such as age, number of stories, square footage, structural type, and occupancy were available from a prior research study (Anagnos et al. 2008). The building locations are shown in Figure 2. Building first-mode periods were estimated based on the building heights and structural systems, and a histogram of these periods are shown in Figure 3. Ground motion intensity measures were then simulated for each location of interest, and for each relevant spectral acceleration period per location.

The earthquake rupture simulations are based on the UCERF2 seismic source model, and are sampled using the OpenSHA event set simulator, which also provides a per-location estimate of $V_{s,30}$ based on local topographic slope (Field et al. 2003, Allen and Wald 2009, Field et al. 2009). Medians and standard deviations of ground motion intensity measures are predicted using three ground motion models, equally weighted in a logic tree (Abrahamson et al. 2014, Boore et al. 2014, Chiou and Youngs 2014). Intensity measure residuals are sampled using a custom SP3 software tool, which combines the residuals with the medians and standard deviations, and interfaces the sampled intensity maps with the FEMA P-58 analysis results. Residuals were sampled from a model that incorporates correlations across locations and across spectral acceleration periods, to reproduce intensity measure correlations observed in past earthquakes (Markhvida et al. 2018).

The FEMA P-58 analyses in this case study are performed using the SP3 software, and utilizing its automation features to infer detailed building characteristics based on known characteristics, and utilizing its response prediction engine to generate structural responses utilizing a statistical model calibrated on millions of response history analyses (Cook et al. 2018). More detailed approaches can also be used to perform P-58 analyses using building-specific structural models and building inventories. We anticipate that the most appealing use of this approach would be to utilize detailed building-specific analysis for buildings with available data, more general analyses with inferred properties for other buildings, followed by iteratively refined analyses for the buildings identified as critical contributors to potential portfolio risk.

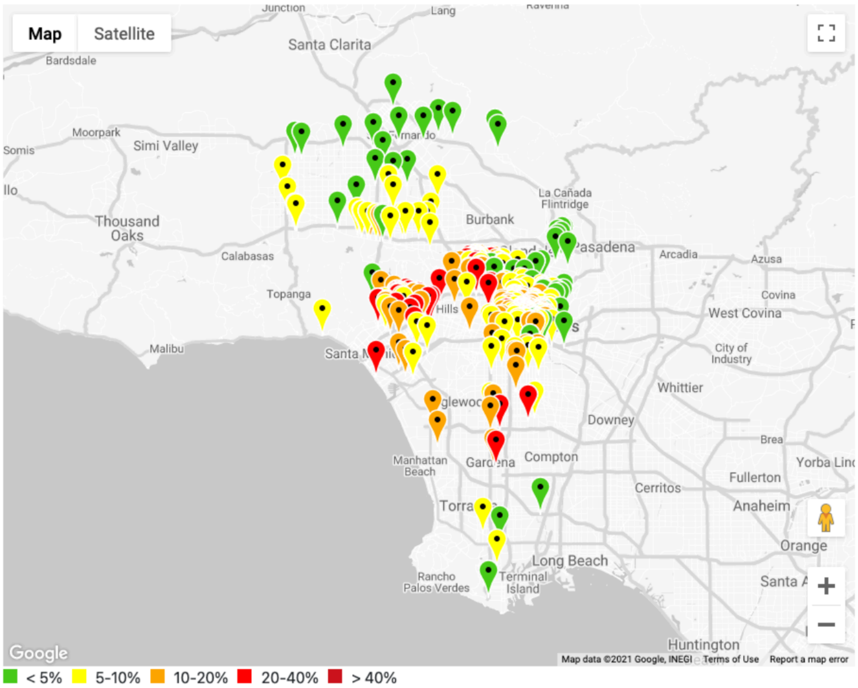

Figure 2: Locations of buildings considered in the case study analysis.

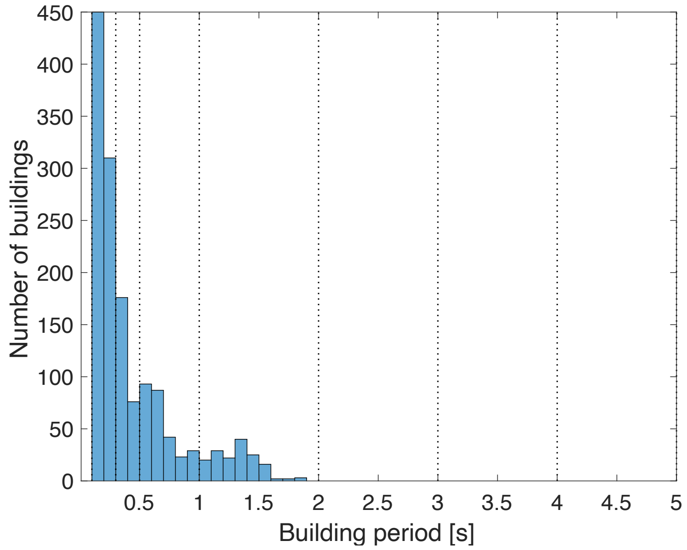

Figure 3: Histogram of first-mode periods of buildings considered in the case study analysis.

Figure 4 shows loss exceedance curves for a hypothetical client who owns all of these buildings and so is responsible for costs of repairing seismic damage. With the inventory data, FEMA P-58 analysis results, and simulated intensity measure maps, we generate suites of per-building repair cost data, that are fed through a financial model. Exceedance curves with and without an insurance policy are shown, along with exceedance curves for losses under the retrofit schemes. These results illustrate how a portfolio-level assessment can be used to inform risks faced by an owner, and to support decision-making about potential investments in insurance or retrofits. These investments can be reflected on a per-building level, allowing owners to target retrofits or insurance for only the highest-risk buildings in the portfolio, while choosing to retain the risk from better-performing buildings.

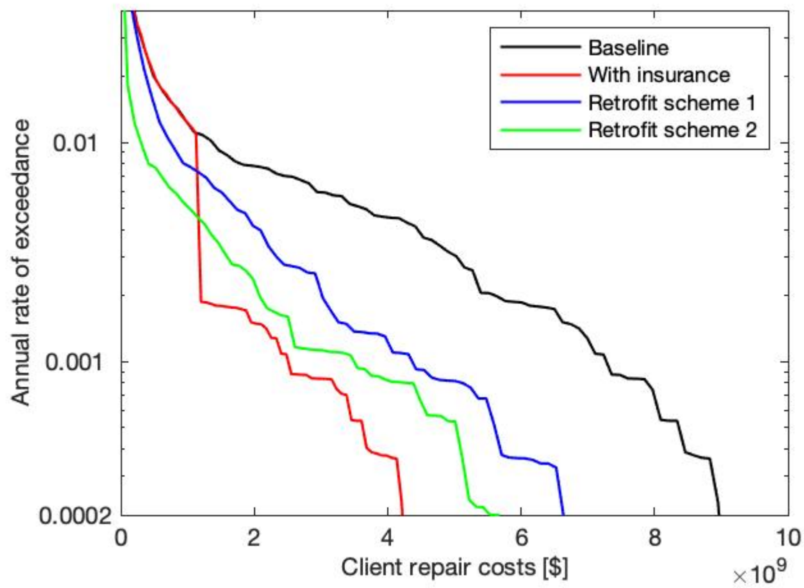

Figure 4: Loss exceedance curves for the case study portfolio, showing client losses for the case study portfolio without an insurance policy ("Baseline") and with insurance. Additionally, losses (without insurance) for two hypothetical retrofit schemes are shown.

Figure 5 shows loss exceedance curves for total loss, insured loss, and client loss, for the case study portfolio, demonstrating additional outputs from the financial model. Multiple insurance layers can also be considered, allocating per-event losses to multiple parties, for more complex risk transfer cases. This analysis workflow can also produce additional metrics, such as loss-exceedance curves for building closure metrics, and average annual losses per building and per portfolio.

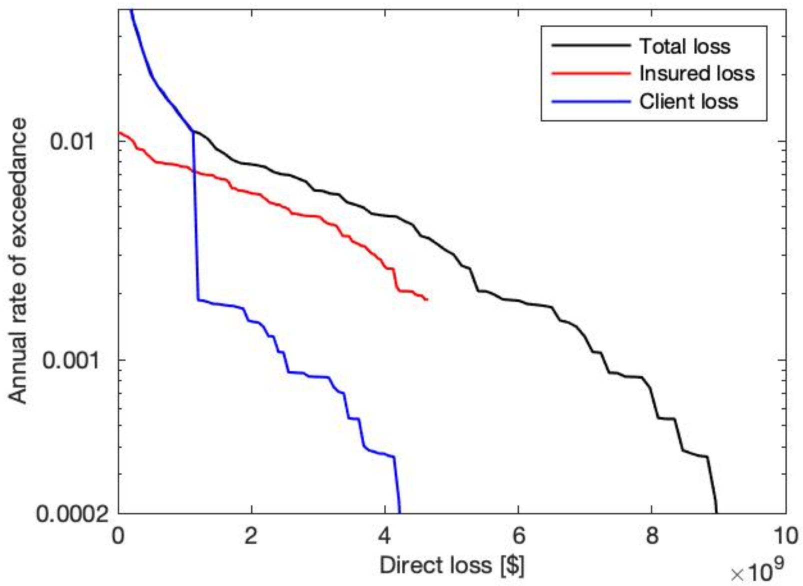

Figure 5: Loss exceedance curves for total loss, insured loss, and client loss, for the case study portfolio.

4. Opportunities and Further Refinements

While the above workflow is highly effective for the considered case-study, several further extensions would be straightforward and would further enhance the generality of this approach.

While our case study analysis used an independent FEMA P-58 analysis for each building in the portfolio, it would be straightforward to group some buildings' vulnerability models if desired, for computational efficiency or because the buildings are effectively identical. All that is required with this analysis is that there is vulnerability data to look up, for each building in the portfolio. It is straightforward for multiple buildings to point to the same vulnerability data in the "Vulnerability information" box of Figure 1.

Our current analysis utilizes the OpenSHA Event Set Generator to generate the ruptures and ground motions for this analysis. This is helpful for the California and U.S. context, as it ensures compatibility with the seismic models used for other analyses such as building code checks. However, this tool does not include a global source model, and it is also expensive to run for the UCERF3 source model, which includes substantially more rupture scenarios (Field et al. 2014). Other rupture generators, such as from OpenQuake (Pagani et al. 2014) could potentially be utilized as well to extend generality.

5. Conclusions

This paper has described the workflow used to efficiently couple FEMA P-58 building-specific loss analysis calculations with a portfolio loss assessment. By pre-calculating and storing per-building P-58 analysis results in a structured manner, they can be used in a look-up format as a building-specific vulnerability function in a portfolio risk analysis, instead of using a traditional generic building-class-based vulnerability function. The feasibility and utility of this modelling approach is demonstrated here, considering an example portfolio of approximately 1500 buildings distributed through the Los Angeles metro area. Several permutations of the portfolio (considering hypothetical retrofit schemes) and permutations with and without an insurance policy, were analyzed, to demonstrate how loss exceedance curves can be generated for each case and utilized to support risk management decision-making.

To date, FEMA P-58 analysis has been popular for assessing individual buildings, for either designing new buildings or assessing existing buildings and designing retrofits. But as the method grows in popularity, and stakeholders build familiarity and confidence in its results, it is increasingly being used for a wider range of applications such as calibration of building codes, due diligence assessment for the financing of building purchases, and risk management for portfolios of buildings. Existing science and engineering models, coupled with cloud-based computational workflows, already enable these types of applications. Given the great leap forward in quantifying building performance that FEMA P-58 provides, it is natural that it will also grow in popularity for other applications such as financial risk management.

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