

# SUMMARY OF FINDINGS FROM THE BENCHMARKING OF FEMA P-58 SEISMIC LOSS PREDICTIONS VERSUS HAZUS

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June 27, 2018

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## SCOPE OF REPORT

This executive summary presents a short overview of the methods and results from a recent study comparing FEMA P-58 loss predictions to Hazus for a broad range of buildings and locations. For more information on the complete findings and current progress of the study, please contact the Haselton Baker Risk Group at (530) 531-0295 or [support@hbrisk.com](mailto:support@hbrisk.com); a webinar on this topic is also being planned for the summer of 2018.

## INTRODUCTION

One of the pressing challenges of new and evolving seismic risk assessment methods is the need to validate, confirm, and/or verify the outcome of these assessments to support their broader use. This task is particularly difficult due to the absence of empirical evidence from past earthquakes that can be used to systematically validate these approaches. Recent developments in seismic risk analysis and performance-based design have opened doors to statistically rigorous and systematic frameworks for the quantification of seismic risk for buildings. One such method was recently developed by the Applied Technology Council through \$16 million of FEMA funding, and is known as FEMA P-58: Seismic Performance Assessment of Buildings (FEMA, 2012). FEMA P-58 provides a statistical approach to assess the seismic risk to individual buildings and quantifies the risk in terms of performance metrics that are valuable to engineers, building owners, and the public, such as dollars, deaths, and downtime, facilitating decisions among design or mitigation alternatives.

As the adoption of FEMA P-58 grows, the question remains: Can we trust FEMA P-58 results? Are there unnecessary conservatisms, or underestimations, in the predictions? To evaluate the results obtained through a FEMA P-58 assessment, this study compares the mean losses predicted using the FEMA P-58 methodology with losses predicted by Hazus (FEMA, n.d.), for over 50,000 building models representative of typical construction across the United States. Hazus is selected for comparison because it is based, at

least in part, on observations from several major U.S. earthquakes, and has been relied upon by the engineering and risk assessment community for over 20 years.

## BENCHMARKING METHODOLOGY

This study investigates general trends in mean losses calculated from FEMA P-58 and compares them to corresponding Hazus loss predictions. Comparisons are performed for a set of 55,300 models that represent over 20 different structural systems, buildings designed from 1933 to 2016, one to 20 stories in height, and for 36 sites across the U.S. shown in Figure 1. The models are calibrated to meet the expected strength and stiffness properties of a typical structure given its building type and year of construction, including minimum requirements of the building code edition they are designed for and expected overstrength. However, all of the models assessed as part of this study represent regular structures, and buildings with irregularities such as foundation deficiencies and weak story irregularities are not included.

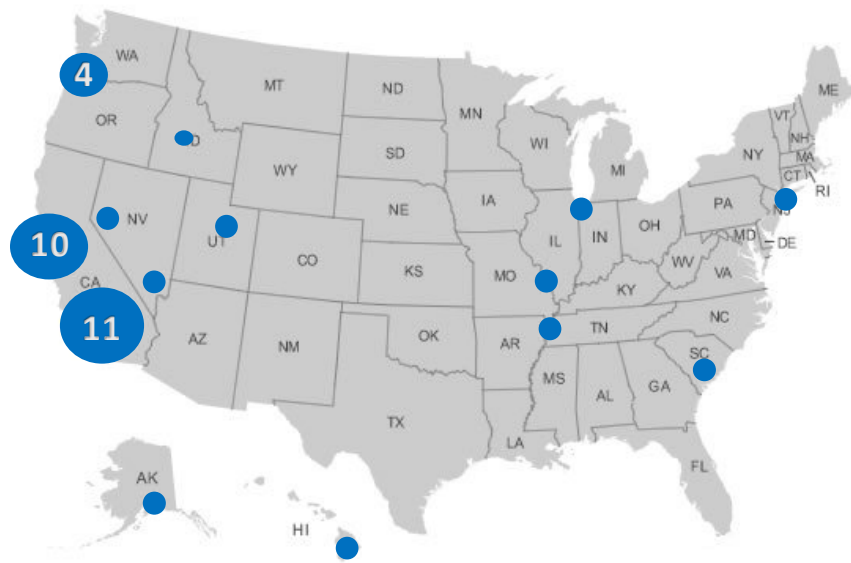


Figure 1 – Locations of the 28 U.S. sites considered in this study.

To construct FEMA P-58 performance models, this study utilizes the Haselton Baker Risk Group’s FEMA P-58 Risk Model (*SP3-RiskModel*). *SP3-RiskModel* can develop performance models for a building based on a limited set of building characteristics through embedded modeling algorithms, described in more detail below, and then perform FEMA P-58 assessments for a large set of models utilizing cloud computing. Figure 2 illustrates the steps involved in the methods used in this study and the process used to make the comparisons.

## SP3-RISKMODEL FOR FEMA P-58 LOSS PREDICTIONS

The *SP3-RiskModel* uses embedded algorithms to generate structural properties, building configurations, and building components from a simplified set of building inputs based on typical building configurations and inventories, engineering analysis, and expert judgment. This tool facilitates analyses for applications where all information may not be available, either because the assessment is being carried out early in the design process, or as part of a portfolio assessment. The *SP3-RiskModel* requires a minimum of the building

location, structural system, age and height to generate FEMA P-58 loss predictions, and additional information can be incorporated if available.

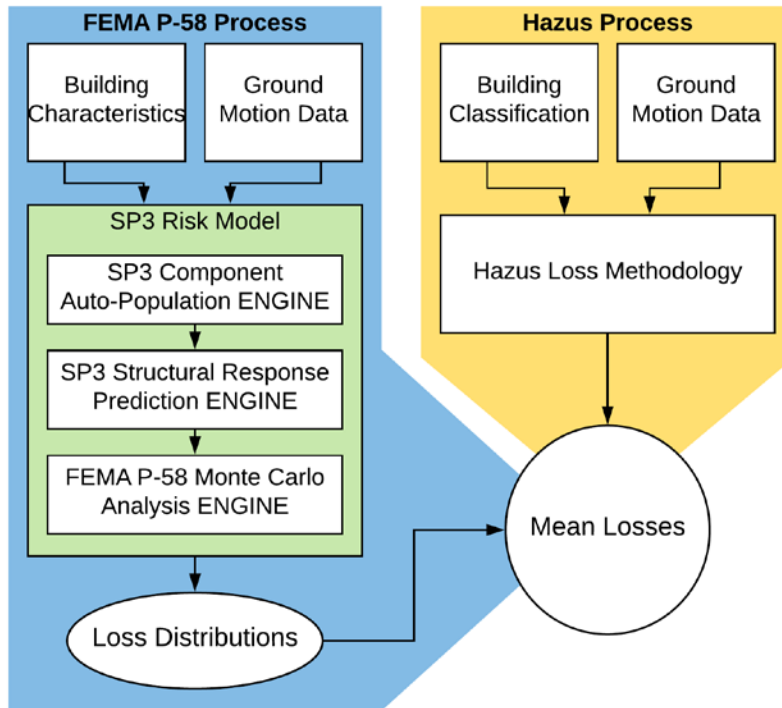


Figure 2 - Illustrative view of benchmarking process.

### Hazard Analysis

USGS hazard data (USGS, 2018) is used to select ground motion levels with the desired probabilities of exceedance at each of the sites considered in this study. The hazard curves provide the peak ground accelerations and response spectra for each level of hazard.

### Design Requirements and Structural Properties

Based on the age and location of the building, *SP3-RiskModel* employs seismic and wind design criteria from the various editions of ASCE 7 and the Uniform Building Code dating back to the 1930s, to estimate the design criteria for the structure. These design criteria are then combined with estimated over-strengths to calculate key dynamic properties of the building, such as fundamental periods, mode shapes, and base shear strengths. The intent of the estimated structural properties is to create a performance model that represents the response characteristics of the full structure, including strength and stiffness contributions from nonstructural and gravity systems. These calculations are based on implementation and extensions of existing research to estimate mode shapes (Miranda, 1999), fundamental periods (Chopra & Goel, n.d.), and over-strength (FEMA, 2009).

### Structural Responses

Structural responses are calculated at each ground motion level for various building types using the SP3 Structure Response Prediction ENGINE (SPRE). The engine uses estimated dynamic properties of the building to calculate linear responses using modal response history analysis. The linear responses are then adjusted for expected nonlinear behavior based on calibration factors from ASCE 41, and factors calibrated

from a large database of responses of nonlinear models (Haselton & Baker, 2017). The models that form the database are an assortment of nonlinear models of various building types, typically analyzed using the OpenSEES software program (PEER, 2006). The models are sourced from other research, such as Haselton (Haselton & Deierlein, 2008), Liel (Liel, 2008), ATC 123 (Debock et al. 2018), and ATC 78 (ATC, 2011), as well as additional models created in-house by the HB Risk team. The engine estimates the maximum, variance, and correlation of the peak floor accelerations and story drift ratios for each story of the model, at each ground motion level. Residual drift demands are also estimated using an HB Risk extension of the simplified method outlined in the FEMA P-58 document. The collapse capacity of the performance model is quantified using the FEMA 154 rapid screening protocol (FEMA, 2015), which has been adjusted for the increased collapse potential of taller wood light frame buildings, based on FEMA P-695 collapse analysis of models of wood buildings (FEMA, 2009).

### **Building Components**

The building component inventory of each FEMA P-58 performance model is selected using the SP3 Component Auto-Population ENGINE, which uses typical component inventory information provided by FEMA P-58, along with information about the building's location, structural system, occupancy, age, and configuration to fill the building with structural and nonstructural components. The *SP3-RiskModel* utilizes the over 700 building component fragilities provided by the FEMA P-58 method, along with over 170 other component fragilities developed by HB Risk in collaboration with industry experts, to create building specific performance models.

### **Damage and Loss Prediction**

Once the performance model is assembled, FEMA P-58 losses are calculated through the FEMA P-58 Monte Carlo Analysis ENGINE. The engine performs 700+ Monte Carlo simulations to provide probability distributions of loss in terms of repair cost, repair time, and casualties for each hazard level assessed. FEMA P-58 assesses damage on the building component level, therefore the *SP3-RiskModel* is able to provide breakdowns of loss contributions from each component in the building, which provides insight to the driving factors behind loss.

## **HAZUS IMPLEMENTATION**

Hazus was developed as part of the FEMA Multi-hazard Loss Estimation Methodology, for estimating seismic risk of U.S. infrastructure. Hazus includes prediction models for direct physical damage and loss, induced physical damage, direct economic and social losses, and indirect economic losses. To achieve loss predictions, the Hazus methodology combines site hazards and building classifications (e.g. based on code year and height) with defined fragility functions, which are used to assess the risk of damage and consequences for a building of that class at a particular site.

The prediction models developed for the Hazus methodology are based on a mix of historical data, previous research, and engineering judgment. While Hazus heavily relies on the MMI damage and loss functions and building classifications developed as part of the ATC-13 project (ATC, 1985), the method went through a rigorous calibration process to empirical earthquake data available at the time. In particular, Hazus damage curves were calibrated to observed data from various events, including: 1933 Long Beach, 1971 San Fernando, 1983 Coalinga, 1984 Morgan Hill, 1989 Loma Prieta, and 1994 Northridge earthquakes (Kircher, 2001). As a result, Hazus has been shown to produce good agreement with the Northridge data,

particularly for single family residential buildings built between 1941 and 1976, which represent the major portion of the building stock and earthquake damage data (Webster, 2018).

Rather than employing the Hazus software tool directly, this study utilizes an in-house implementation of the Hazus fragility functions. The program estimates the Hazus losses based on equivalent PGA fragility curves as outlined in section 5.4.4 of the Hazus technical manual (FEMA, n.d.). While Hazus is able to quantify the uncertainty in loss predictions through an assumed lognormal distribution of the calculated capacity curve, this study focuses on comparing the mean FEMA P-58 losses to the expected Hazus losses.

## COMPARISON OF FEMA P-58 AND HAZUS LOSSES

This section compares the mean loss ratios from FEMA P-58 and Hazus for a sample of the 55,300 models assessed as part of this study. This section highlights trends in wood light frame (WLF) and reinforced concrete moment frame (RCMF) structures, without irregularities, at the 10% in 50 year event.

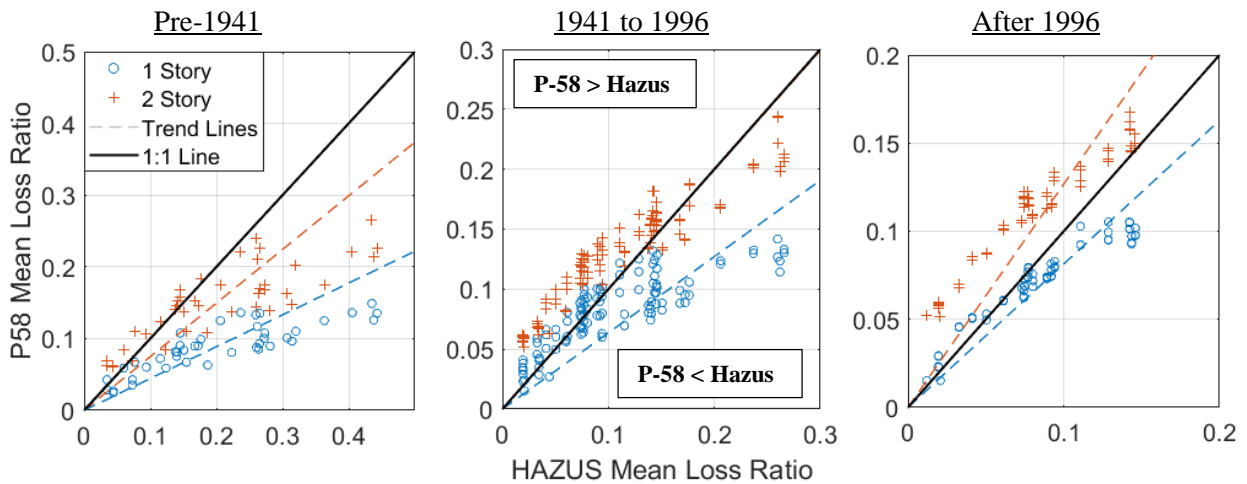


Figure 3 – Mean loss ratio from FEMA P-58 and Hazus, for WLF structures of various code years, without irregularities, in California, at the 10% in 50 year event.

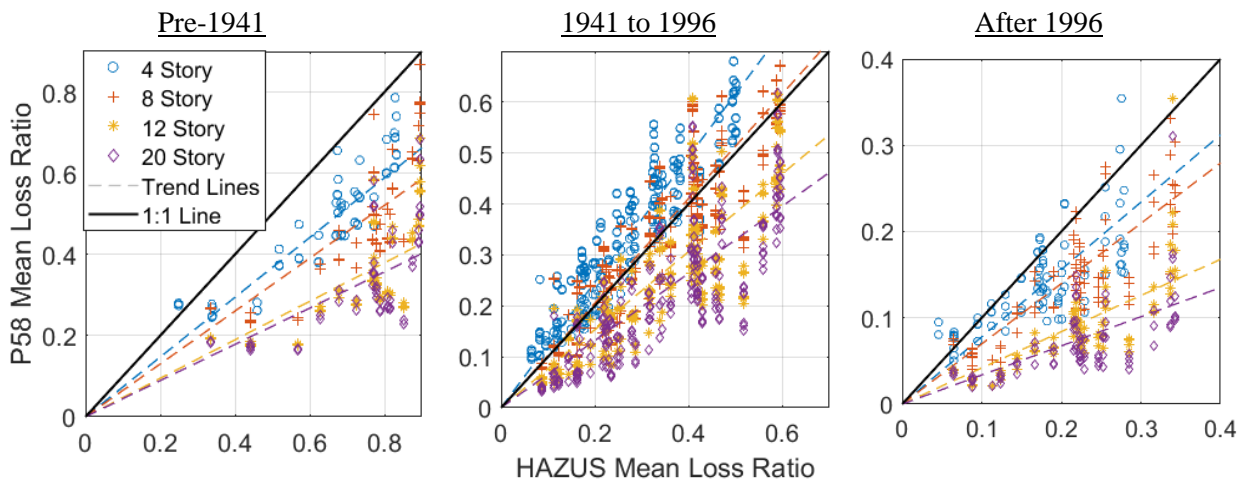


Figure 4 – Mean loss ratio from FEMA P-58 and Hazus, for RCMF structures of various code years, without irregularities, in California, at the 10% in 50 year event.

This study finds that, in general, **mean FEMA P-58 losses tend to be within reasonable proximity of Hazus predictions, for most structural systems, for code years from 1941 to 1997**. Before 1941, FEMA P-58 tends to produce smaller loss predictions than Hazus. This trend is likely attributed to the exclusion of irregular structures examined in this study; in contrast, many pre -1941 buildings are likely irregular, which is characteristic that is reflected in the empirical data used by Hazus. For buildings designed for code years after 1997, FEMA P-58 tends to predict smaller losses than Hazus, on average, for most of the considered structural systems other than WLF. Unlike the FEMA P-58 models, Hazus predictions for post-1997 buildings are, by necessity, based on the buildings that existed at the time of its development, and therefore unable to reflect ongoing changes to the building code and design practice.

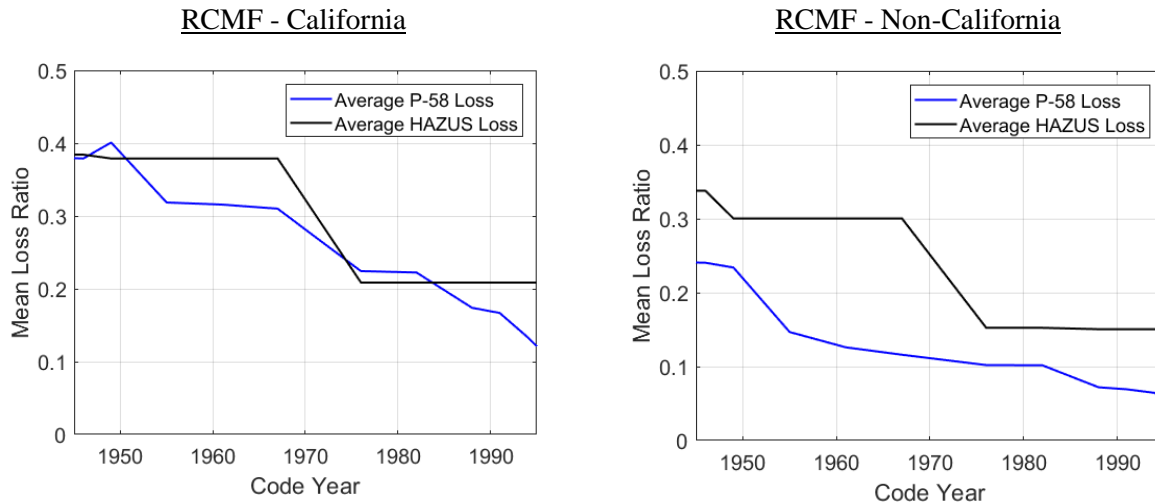


Figure 5 – Average trends in mean loss ratio for FEMA P-58 and Hazus, for RCMF structures designed between 1974 and 1996, and various regions, at the 10% in 50 year event.

While the seismicity of the site is directly considered in both FEMA P-58 and Hazus, this study shows that location of the site affects the comparison of losses. **FEMA P-58 losses tend to match better with Hazus losses for California than for other regions across the U.S.**, as illustrated in Figure 5. Outside California, Hazus tends to produce greater loss predictions than FEMA P-58. This trend is due to the importance of California data in the earthquake observations used to create and calibrate the Hazus method, and illustrates the value added of FEMA P-58 approach to extend beyond empirical evidence.

## CASE STUDY FOR BUILDING-SPECIFIC ATTRIBUTES

To illustrate how variants in specific building characteristics change the comparison of FEMA P-58 results to Hazus, we present results from selected parameter sensitivity studies performed for a site in downtown Los Angeles. First, we investigate how the plan aspect ratio (length/width) affects the mean loss predictions for a precast tilt-up building, constructed in 1985 in downtown LA (Figure 6). As the aspect ratio increases, the longer diaphragm spans become more susceptible to damage, increasing the losses predicted by FEMA P-58. The Hazus analysis is not sensitive to building-specific details such as aspect ratio, and, therefore, predicts constant loss, intersecting the FEMA P-58 results for an aspect ratio between 1.5 and 2, likely representing the typical characteristics of precast tilt-up construction. Another investigation examines the effect of building height on a 1985 RCMF office building at the downtown LA site (Figure 7). For RCMFs, FEMA P-58 loss predictions decrease for taller structures, due to the localization of damage into a smaller

portion of the building. For shorter structures, damage is more likely to occur over more stories, driving up the normalized repair costs. For the same structure, Hazus predicts three levels of loss: one for low-rise, mid-rise, and high-rise groupings. Contrary to FEMA P-58, Hazus predicts that high rise structures have the largest potential loss ratio.

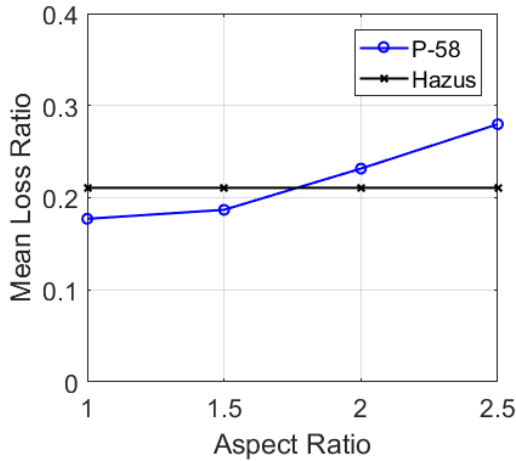


Figure 6 - Effect of aspect ratio on P-58 and Hazus mean loss ratios at the 10% in 50 year event, for a precast tilt-up warehouse, built in 1985 in downtown LA.

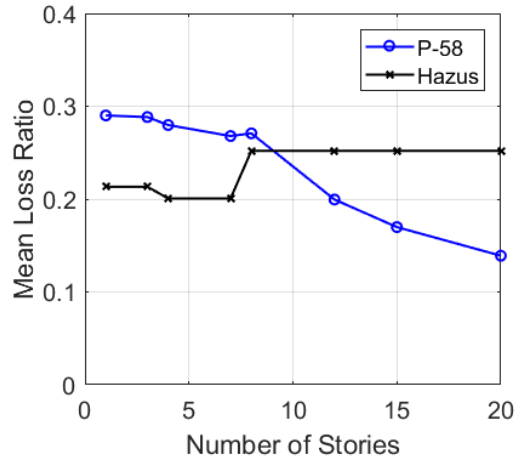


Figure 7 - Effect of building height on FEMA P-58 and Hazus mean loss ratios at the 10% in 50 year event, for a RCMF office building, built in 1985 in downtown LA.

## SUMMARY AND CONCLUSIONS

This paper compares seismic loss predictions for over 50,000 building models obtained from the FEMA P-58 method to mean loss predictions for the same building models from Hazus.

The primary findings of this study are as follows:

- Mean loss predictions from FEMA P-58 compare well with Hazus for building types and sites where Hazus developers had the most empirical earthquake data available. Specifically, predictions for the most prevalent building types (e.g. low-rise wood light frame structures) built between 1941 and 1997, in California, show exceptionally good agreement between the two methods.
- FEMA P-58 loss predictions have more resolution with respect to parameters such as building height and age, as compared with Hazus predictions. In particular, Hazus loss predictions are based on classification of a building by structural system, occupancy, age, and height, and represent losses for typical buildings of that classification.
- For older (pre 1941) buildings, FEMA P-58 predicts lower losses than Hazus, likely due to the assumption of “regular” buildings in this study, which may not represent typical older construction.
- For newer (post 1997) buildings, FEMA P-58 generally predicts lower losses than Hazus, since Hazus predictions for post-1997 buildings are, by necessity, based on the buildings that existed at the time of its development, and therefore unable to reflect ongoing changes to the building code.

The results provide confidence that the FEMA P-58 methodology is consistent with our engineering judgment and the Hazus methodology, which has seen widespread use by the engineering community. At the same time, these comparisons demonstrate the power of the FEMA P-58 methodology to (a) extend reliable loss predictions beyond the limited set of building types and configurations for which there is empirical evidence, and to (b) account for many building-specific attributes in the risk assessment, enabled by the fact that FEMA P-58 is an engineering-analysis-based method rather than an empirical and judgement-based method. These attributes of FEMA P-58 provide more comprehensive and reliable risk information for risk assessment of existing infrastructure, the planning of mitigation strategies, and the design of resilient structures.

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