17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

HINDCAST LOSS ESTIMATES FOR THE 1994 NORTHRIDGE EARTHQUAKE: IMPLICATIONS FOR LOSS ASSESSMENT AT LOW INTENSITY SHAKING

D. T. Cook(1)(5), A. B. Liel(2), D. J. DeBock(3) (5), C. B. Haselton(4) (5), K. F. Wade(5), E. L. Almeter(5), A. Gupta(6)

(1) *Ph.D. Candidate, University of Colorado, Boulder, dustin.cook@colorado.edu*
(2) *Associate Professor, University of Colorado, Boulder*
(3) *Assistant Professor, California State University, Chico*
(4) *Professor, California State University, Chico*
(5) *Member of the Haselton Baker Risk Group*
(5) *Resilience Engineering Lead, OneConcern Inc.*

Abstract

Understanding the seismic risk to infrastructure and buildings is critical for facilitating risk-informed decision making about design and mitigation strategies that can support building resilient communities. FEMA P-58 provides engineers with a more powerful toolset for quantifying risk to buildings in terms of decision metrics such as dollars, deaths and downtime. This methodology has seen increased use in recent years by the engineering profession around the world for both new building design and the assessment of existing structures. However, as the adoption of P-58 grows, the question remains: can we trust P-58 results? In particular, how well do loss predictions from a FEMA P-58 analysis match what we have observed from previous earthquakes? And how do analysis and modeling decisions affect predicted losses?

To evaluate the predictions of economic loss obtained through FEMA P-58, this paper compares the repair costs from FEMA P-58 with observed losses from the Northridge earthquake using the *SP3-RiskModel*. Losses from the assessment of 2.6 million buildings are aggregated and compared with documented losses from the event. The hindcast losses are on the order of $31 billion, compared to observed losses of $25 to $32 billion. A particularly important factor affecting the losses calculated are modeling decisions for light frame wood buildings. These buildings make up a majority of the building stock, and much of the region was subject to low to moderate shaking intensities. The results show, in general, hindcast losses from FEMA P-58 are similar to estimates of observed loss when variation in the damping of wood structures is correctly accounted for.

Keywords: Northridge; FEMA P-58; Performance Based Earthquake Engineering; Seismic Risk Assessment

1. Introduction

Developments in performance-based earthquake engineering over the last decade have opened doors to statistically rigorous and systematic frameworks for the quantification of seismic risk to buildings. One such method coordinated by the Applied Technology Council formalizes and integrates advancements made by many researchers and engineers, and is known as FEMA P-58: Seismic Performance Assessment of Buildings [1]. FEMA P-58 provides a probabilistic approach to assess the seismic risk of individual buildings. Through FEMA P-58, seismic risk is quantified in terms of performance metrics that are valuable to engineers, building owners, and the public, such as economic losses, potential casualties, and disaster recovery time. These metrics can facilitate decisions among design or mitigation alternatives. There has been an uptick in applications of this method in practice for both new building design and the assessment of existing buildings [2].

Nevertheless, to support the broader use of the new and evolving seismic risk assessment methods, the outcomes of these procedures need to be verified against empirical data, and modeling assumptions that affect these outcomes need to be defined. To evaluate the results obtained through a FEMA P-58 assessment, this study examines the 1994 Northridge earthquake, comparing the losses expected from a FEMA P-58 assessment, in terms of repair costs of buildings, with observed losses from the event. It also explores modeling decisions that affect possible outcomes. The 1994 Northridge earthquake provides a unique set of empirical data for this comparison in a U.S. context. This (moment) magnitude 6.7 earthquake ruptured part of a blind thrust fault underneath the San Fernando Valley. The earthquake affected a large urban region, home to over 9 million people, including Ventura, Los Angeles, and Orange counties, with some records exceeding 1g of peak ground acceleration [3]. Comprehensive damage and loss data from the earthquake is available for wood frame residential buildings, for which over 340,000 insurance claims were reported [4]. This study benchmarks hindcast losses from the FEMA P-58 method against reported estimates of economic loss for various building types from the 1994 Northridge earthquake, with a particular focus on wood frame buildings.

2. Methods

This study follows the procedure outlined in Figure 1 to compare losses hindcast through the FEMA P-58 method with historical data. We perform a FEMA P-58 scenario loss assessment for an inventory of 2.6 million buildings, representative of the building stock in the greater Los Angeles area at the time of the 1994 Northridge earthquake. USGS ShakeMap data is used to define the ground shaking during the event and the SP3-RiskModel is used to perform the FEMA P-58 loss assessment. Aggregated losses from the scenario assessment are compared with best estimates of direct building loss from the empirical data from the earthquake. Only losses due to direct repair costs from building components are considered, i.e. repair time and casualty comparison are not made. Details about each of these steps are described next.

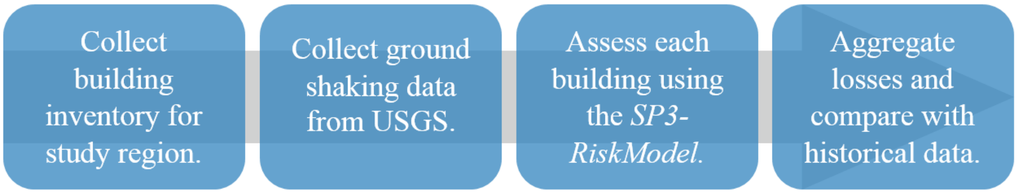

Figure 1 - Process for comparing hindcast losses from FEMA P-58 on the regional scale with historic data from the Northridge earthquake.

2.2 Building Inventory

This study uses a building inventory containing 2.6 million buildings in the greater Los Angeles area including Los Angeles, Orange, and Ventura counties. The inventory used in this study is obtained from Corelogic which is based on data collected from modern tax assessors data. The database provides information on building type (e.g., reinforced concrete moment frame), use, size, value, age, and location for each building within the region as of 2018. As tax assessor's databases do not typically inventory publicly-owned buildings, the inventory database is augmented with a dataset of public buildings in Los Angeles County [5]. No public buildings from Ventura and Orange County are added as Los Angeles County contains a majority of the significant shaking and damage, so the effect on total loss from these structures in other counties would be negligible.

However, the collected inventory database represents a modern inventory, so the inventory is modified to represent the estimated building stock around 1994. First, all buildings built after 1994 are eliminated from the database. Then, the remaining buildings are sampled from to match the cumulative building inventory documented in the 1995 EQE Northridge Post-Earthquake reconnaissance report [3]. For example, of the 1993 tax assessor's data presented in the EQE report, 96.3% of the buildings are of wood frame construction, 3.5% are categorized as brick/block/other concrete, and 0.2% are steel or concrete frame construction. Residential buildings represent over 93% of the building inventory. Building values are adjusted to represent values in 1994 USD by assuming a median value for a single family dwelling of $140,000 [4]. Figure 2 shows a regional view of the entire 1994 building inventory used in this study. In total, 2.6 million buildings are assessed.

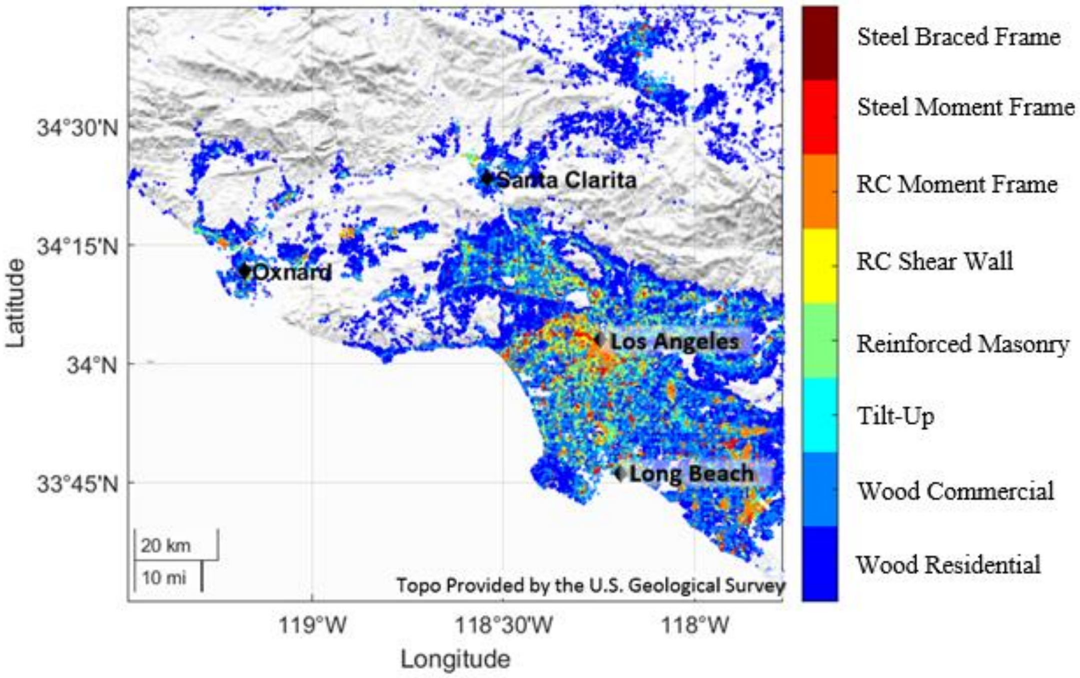

Figure 2 - Los Angeles and surrounding counties' building inventory used for the Northridge assessment.

2.3 Ground Shaking

The USGS ShakeMap for the Northridge Earthquake [6] is used to quantify the actual ground shaking and its spectral properties for each building. The ShakeMap is based on acceleration time histories recorded at stations across the region and uses site amplification characteristics and ground motion prediction equation distance relationships to interpolate accelerations to all sites in the region. The ShakeMap provides mean peak ground accelerations and spectral accelerations at 0.3, 1, and 3 seconds for each site based on a databased at evenly spaced grids, as illustrated in Figure 3 for the Northridge earthquake. Shaking at each building location was linearly interpolated based on the nearest four grid points. The ShakeMap database also quantifies uncertainties for each shaking parameter, but these are not used as part of this study.

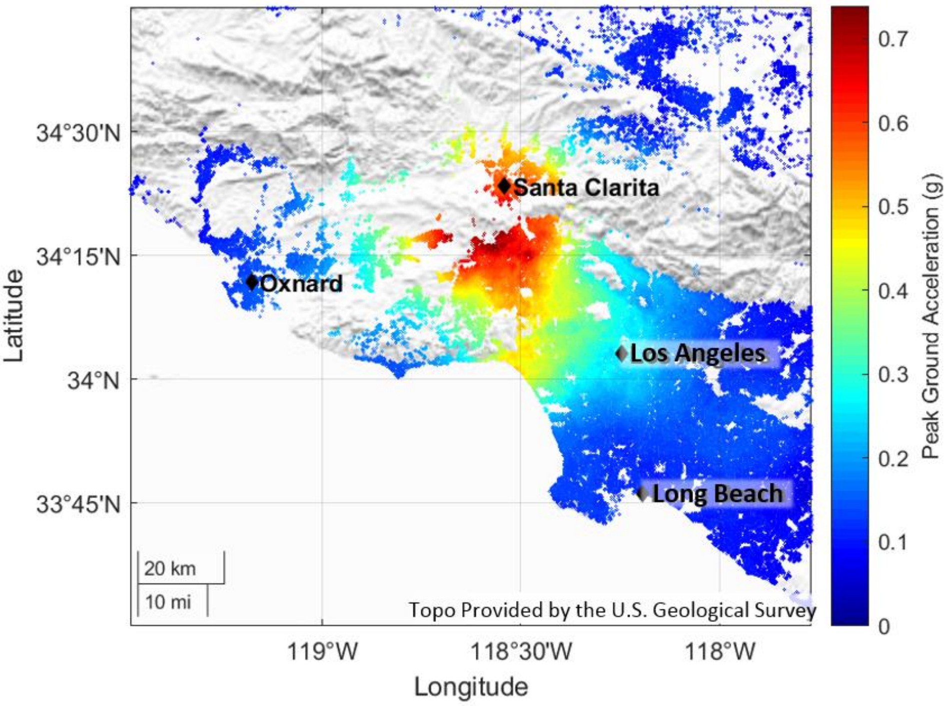

Figure 3 - Peak ground acceleration from USGS Northridge ShakeMap [6] for each building assessed as part of this study.

2.4 Seismic Losses

A FEMA P-58-based risk model called SP3-RiskModel, a proprietary tool developed by the Haselton Baker Risk Group, is used to perform the FEMA P-58 loss assessment for each building in the study region. The SP3-RiskModel provides predictions of seismic loss (risk) based on building, site, and earthquake properties. The key advantage of using the SP3-RiskModel in this study is that it contains a suite of embedded algorithms based on typical building configurations and inventories, engineering analysis, and expert judgment to assess seismic loss based on a simplified set of building inputs. In other words, a full nonlinear analysis is not necessary for each building.

First, the SP3-RiskModel incorporates historical seismic and wind design criteria along with estimates of mode shape [7], fundamental period [8], and overstrength factors [9] to estimate the key dynamic properties of the building as a function of the structural system, age, and location of the building. Second, the SP3-RiskModel estimates structural responses based on relationships derived from a large database of nonlinear model response histories [10]. The models that form the database are an assortment of nonlinear models of various building types sourced from other research, such as Haselton et al. [11], Liel et al. [12], FEMA P-2012 [13], and FEMA P-2018 [14], as well as additional models created by the HB Risk team. Third, the SP3-RiskModel uses typical inventories of building components information provided by FEMA P-58, along with information about the building's location, structural system, occupancy, age, and configuration to populate the building model with structural and nonstructural components. The SP3-RiskModel contains a database of over 700 building component fragilities provided by the FEMA P-58 method, along with over 170 additional component fragilities developed by HB Risk in collaboration with industry experts. Finally, once the building properties and responses are estimated, the SP3-RiskModel assesses damage and loss for each component in the building on the basis of these fragilities. Results for each component are aggregated to determine expected building level losses. Uncertainty is quantified through

Monte Carlo simulation and considers record-to-record variability, structural response uncertainty, and uncertainty in component damage.

The SP3-RiskModel helps to expedite the FEMA P-58 analyses for large building inventories with limited building information, such as the building data available in tax assessor databases, and allows for millions of FEMA P-58 assessments to be analyzed in a batch setting. In doing so, it layers assumptions about building configuration, structural properties, and response, on top of the well-documented FEMA P-58 methodology. As a result, other implementations of the FEMA P-58 method may result in different outcomes than the SP3-RiskModel. Therefore, hindcast losses presented in this study are dependent upon the underlying assumptions within the SP3-RiskModel and represent one possible example of a FEMA P-58 scenario assessment of the Northridge Earthquake.

2.5 Observed Losses in the Northridge Earthquake

Previously unprecedented levels of damage were observed in the Northridge earthquake, with total estimated losses ranging between $40 and $44 billion (1994 USD), making it the costliest earthquake in U.S. history [4]. Sources also estimate an additional $8 billion in indirect losses from business interruption, lost tax revenue, vacated housing, and defaults on Small Business Administration loans [15]. Widespread damage was observed in many different types of buildings across a large region. Wood frame structures make up a majority of the building stock in the US, and represent around 96% of the buildings in Los Angeles County, accounting for around 85% of the value of the building stock at the time of the Northridge earthquake.

Table 1 provides an overview of reported and estimated losses from the Northridge earthquake. Damage to wood frame structures was extensive due to the large number of buildings that were affected. Considering both insured and uninsured damage, losses from wood frame residential structures are estimated around $20 billion to $22 billion, representing about half of the total losses from the earthquake [15]. Severe damage was also observed in nonductile concrete frame buildings, mostly due to column shear failures, especially for captive columns. Damage to tilt-up structures in the Northridge earthquake was estimated to be over $1 billion [16] and 40% of pre-1976 tilt-up structures had wall-to-roof anchorage failures [17]. There were also significant failures in welded steel moment frame connections throughout the region and buckling of steel braced frame structures [18]. Significant damage was observed in unreinforced masonry buildings, but none collapsed.

Table 1 - Losses from the Northridge earthquake reported in 1994 USD.

Type of Loss	Loss
Reimbursed loss[1]	$21 to 26 billion [4,15,19]
Estimated direct loss	$40 to 44 billion [4,15]
Estimated direct and indirect loss	$48 to 52 billion [15]
Reimbursed Residential loss[1]	$8 to $13 billion [4,19]
Estimated direct residential loss	$20 to 22 billion [15]
Estimated direct tilt-up loss	>$1 billion [16]
Estimated direct loss from building damage (for comparison with FEMA P-58)	$25 to 32 billion (estimated here)

Note 1: Reimbursed losses represent only the losses that were directly recorded and reimbursed by insurance companies, government agencies, and non-profit aid organizations, and therefore represents a lower-bound of loss.

A wide range of estimates of observed loss from the Northridge earthquake exists in the literature, as summarized in Table 1. Each of these estimates represents a different scope of damage and loss. Reimbursed losses of $21 to $26 billion define the low end of the range, and represents a record of losses to commercial and residential buildings that was directly reimbursed by insurance companies and government and non-profit aid entities. The upper end of the loss estimates reported in literature of $40 to $44 billion, including deductibles not covered by insurance companies (typically 10% of the building replacement cost [20]) and buildings with no earthquake coverage (it is estimated that 60% of the affected region did not have earthquake insurance [4]). These reported losses represent losses to the structure (structural and nonstructural), losses to detached structures, such as garages, losses to contents, and loss of use (excluding business interruption).

Predicted losses from FEMA P-58 only quantify direct losses of the building, i.e. structural and nonstructural components, and do not represent losses to contents, detached structures, and loss of use. Therefore, we make adjustments to the estimated total direct losses to derive a best estimate of direct loss from building damage, to compare against FEMA P-58 predictions. In the Northridge earthquake, based on data from insurance claims, direct building loss represented about 67% of the total loss [4,15]. Multiplying the reported estimated direct loss of $40 to $44 billion [15] with this ratio produces an estimate of $27 to $30 billion of direct loss from building damage. This ratio can similarly be applied to the estimate of $20 to $22 billion in total residential loss [15] to estimate $13 to $15 billion in residential loss from building damage.

Of course, there is significant uncertainty in both the reported total estimated loss of $42 billion and the reduction factor of 67%. It is likely that the reduction factor relating reported loss to losses comparable to FEMA P-58 prediction is somewhere between 60% and 75%, resulting in a range of estimated loss from $25 billion to $32 billion. Applying a similar logic, the likely range of observed loss for residential buildings would be around $12 to $16 billion. This estimated range of possible observed loss is used for comparison with predicted FEMA P-58 loss throughout this study.

3. Modeling Considerations for Low Intensity Loss Estimates

For many seismic performance assessments, building structural response and behavior is assessed at design or “maximum considered earthquake” levels. At these levels of shaking, many buildings undergo significant damage. Assumptions made in these assessments, such as cracked section properties and effective damping, may not provide for accurate responses at lower shaking levels. This is important as results from this study show that over 50% of the cumulative losses to wood frame residential buildings during the Northridge earthquake are at sites with peak ground accelerations less than 0.4 g.

There are two main challenges associated with predicting structural response at low levels of shaking. First, the amount of damping provided by the shaking of the building depends significantly on the degree of nonlinearity in the structure. For wood buildings, damping levels before the yielding of structural elements can be as high as 20% [21] due to slip damping at nailed connections [22], which is vastly different from the typical assumption of 5% damping. The 5% damping presumes significant energy dissipation through hysteresis that will not occur at lower shaking intensities. Second, for concrete buildings, stiffness is often modeled assuming cracked sections. However, at lower levels of shaking, member stiffness will likely retain stiffness properties that are closer to the un-cracked stiffness properties for many of the building members. This variation in model stiffness may have a significant impact on the responses and losses associated with concrete buildings.

To investigate how modeling considerations at low shaking intensities affect loss predictions, we present two sensitivity studies for buildings in Los Angeles. First, the effect of damping on losses is investigated for a single-story wood frame home built in 1975. Four damping assumptions are considered: a constant damping of 5% (a typical assumption), 10%, 20%, and a variable damping model that accounts for higher damping levels prior to yielding following the recommendations of Newmark & Hall [21]. Losses are assessed according to FEMA P-58 using the SP3-RiskModel and are shown in Figure 4. The losses for the variable damping model are similar to the 20% damping model at low intensities and then increases to match the 5% damping model as shaking increase (Figure 4a). A common metric that is used in risk assessment is the expected annual loss, which is calculated by integrating the loss curve with the annual rate of exceedance of each shaking intensity. The expected annual loss represents the average repair cost the building onwer can expect to pay each year due to earthquake damage. Annualized losses are more sensitive to the expected losses at low shaking intensities, as these intensities are more likely to occur. The variable damping model has 35% less expected annual loss compared with the 5% damping model. These results indicate that damping assumptions can make a significant difference when quantifying losses to wood buildings that are sensitive to low shaking hazard.

Second, the effect of section stiffness is investigated for a 6-story reinforced concrete moment frame office building, constructed in 2005. Three stiffness assumptions are investigated using: cracked stiffness properties (a typical assumption), uncracked stiffness properties, and a variable stiffness model that softens the structure from uncracked to cracked as the shaking increases. Losses are assessed according to FEMA P-58 using the SP3-RiskModel, shown in Figure 5. Perhaps surprisingly, the differences between the cracked section and uncracked section losses at low shaking intensities are minimal, making the variable stiffness losses very similar to the cracked stiffness losses overall. These negligible differences between the loss for the cracked and uncracked model at low shaking intensities are due to a trade of between drift-based and acceleration-based damage. When the structure is stiffened, displacements and damage to drift sensitive components are reduced. However, when the structure is stiffened, the acceleration demands increase due to the shorter period, leading to increased damage potential of acceleration-sensitive components. While results from this sensitivity study indicate that stiffness assumptions may not be important for concrete buildings, trends with stiffness may differ for other buildings. For example, buildings with more robust acceleraion-sensitive components and more vulnerable drift sensitive components, such as shear and infill walls, may result in larger differences in loss for the various stiffness assumptions presented here.

There are other factors that may contribute significantly to loss predictions at low shaking levels, such as accounting for the reduction in damage to wood walls due to connection slip at low shaking intensities. Additionally, if building damage is small or insignificant at low levels of shaking, it may go unnoticed, not be repaired, or may not be reported. FEMA P-58 has no threshold for when damage becomes significant enough to create actionable loss, and the summation of these types of losses over a large set of buildings, such as the Northridge scenario, may cause predictions of loss to be larger than observed losses.

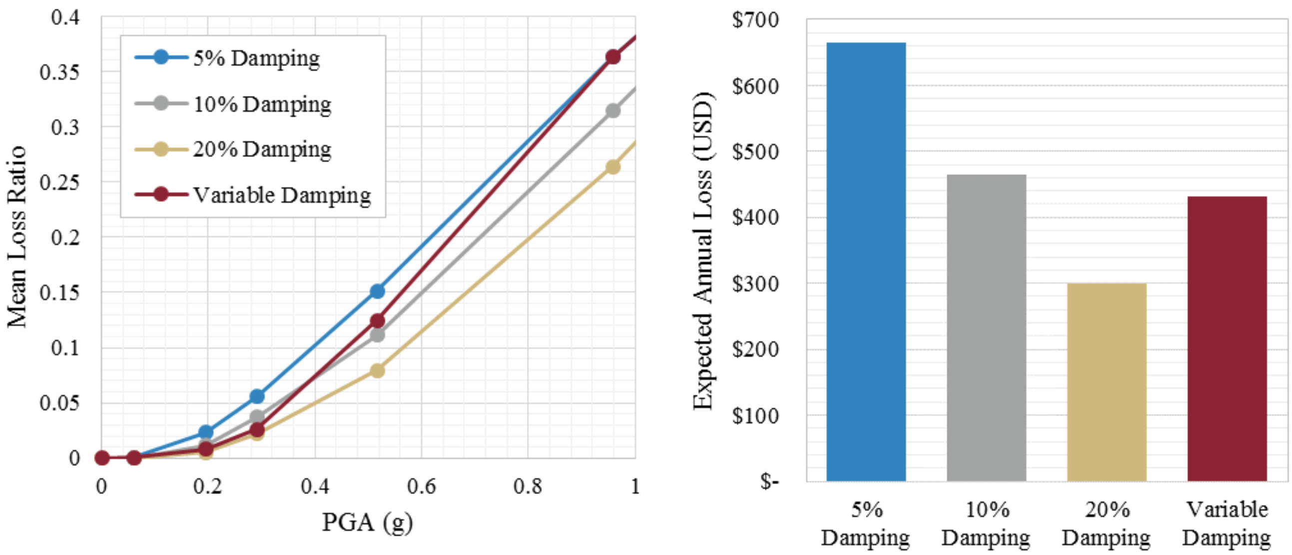

Figure 4 - Effect of damping on (a) mean loss ratio as a function of peak ground acceleration and (b) expected annual loss, for a 1975 wood frame single family dwelling in Los Angeles, CA. Mean loss ratio is the expected repair costs normalized by the replacement value of the building.

Based on these and similar sensitivity studies for other buildings not reported here, for the Northridge scenario assessment presented in this study, the quantification of total predicted loss from FEMA P-58 is presented for both the 5% damping assumption and variable damping assumptions for wood frame buildings. However, no modifications were made to account for variable stiffness in concrete buildings.

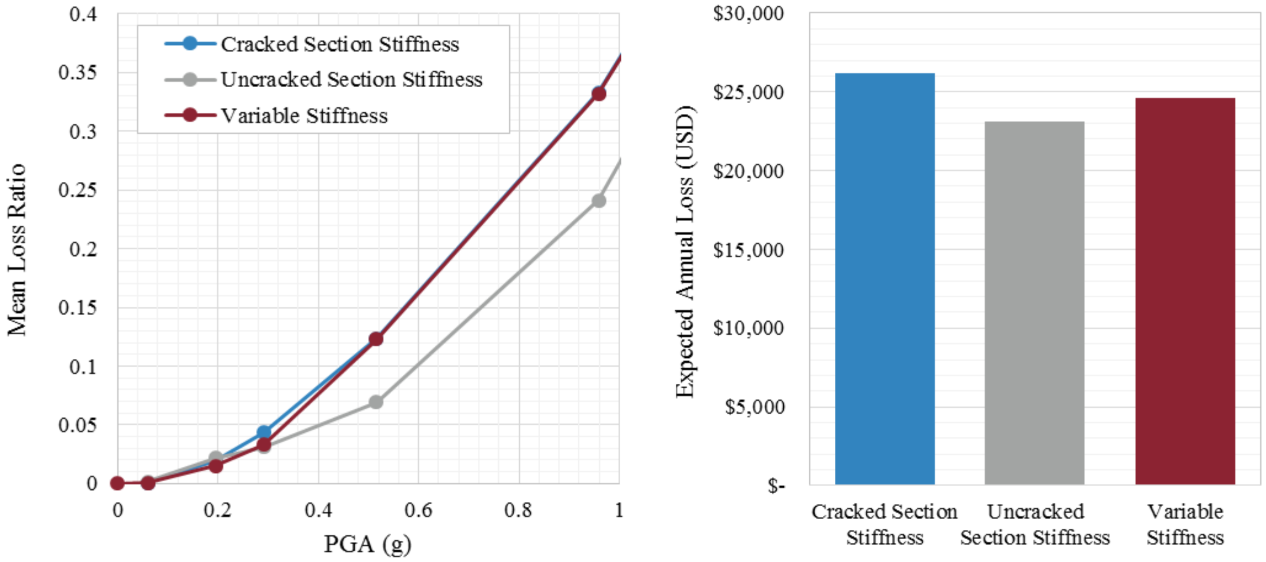

Figure 5 - Effect of section stiffness on (a) mean loss ratio as a function of peak ground acceleration and (b) expected annual loss, for a 2005 reinforced concrete moment frame office building in Los Angeles, CA. Mean loss ratio is the expected repair costs normalized by the replacement value of the building.

4. Comparison to Northridge Scenario: Observed vs. Hindcast Loss

The Northridge Scenario results from FEMA P-58, calculated as the summation of the mean loss results for all buildings in the study region, are shown in **Error! Reference source not found.**. Mean loss results from the FEMA P-58 assessment presented here represent the average cost, in 1994 USD, to repair structural and nonstructural components in each building.

Table 2 – Comparison of hindcast and observed losses for the 1994 Northridge earthquake.

	FEMA P-58 Hindcast Loss		
Type of Building	**Variable Damping for Wood Frame**	**5% Damping for Wood Frame**	**Estimated Observed Loss**
All Buildings	$31 billion	$45 billion	$25 to 32 billion
Residential	$16 billion	$28 billion	$12 to 16 billion
Tilt-Ups	$5 billion		> $1 billion

For the assessment with variable damping for the wood frame buildings, the total mean loss for all buildings hindcast from the FEMA P-58 assessment of the Northridge scenario compares well with estimated observed loss. This assessment hindcasts $31 billion in total direct building loss, slightly on the higher end but well within the likely range of $25 to $32 billion. However, the total mean loss from the 5% damping assumption overpredicts the estimated observed loss range by $13 billion. Total hindcast losses from residential buildings are $16 billion for the variable damping model, which compares well to the estimate observed loss, but increase to $28 billion for the constant 5% damping assumption. Significant losses are also observed and hindcast for tilt-up buildings. Hamburger et al. [16] roughly estimates there to be more than $1 billion in losses from tilt-up construction alone. Our FEMA P-58 assessment hindcasts total losses from tilt-up construction slightly less than $5 billion, which is much larger than $1 billion. However, there is significant uncertainty in the observed loss of “more than $1 billion” estimated from tilt-up construction. Figure 6 shows the distribution of losses throughout Los Angeles County for the assessment with variable damping. Overall, hindcast losses from the FEMA P-58 method produce very similar quantifications of loss compared with historic data when the more detailed damping/response model for wood structures is used.

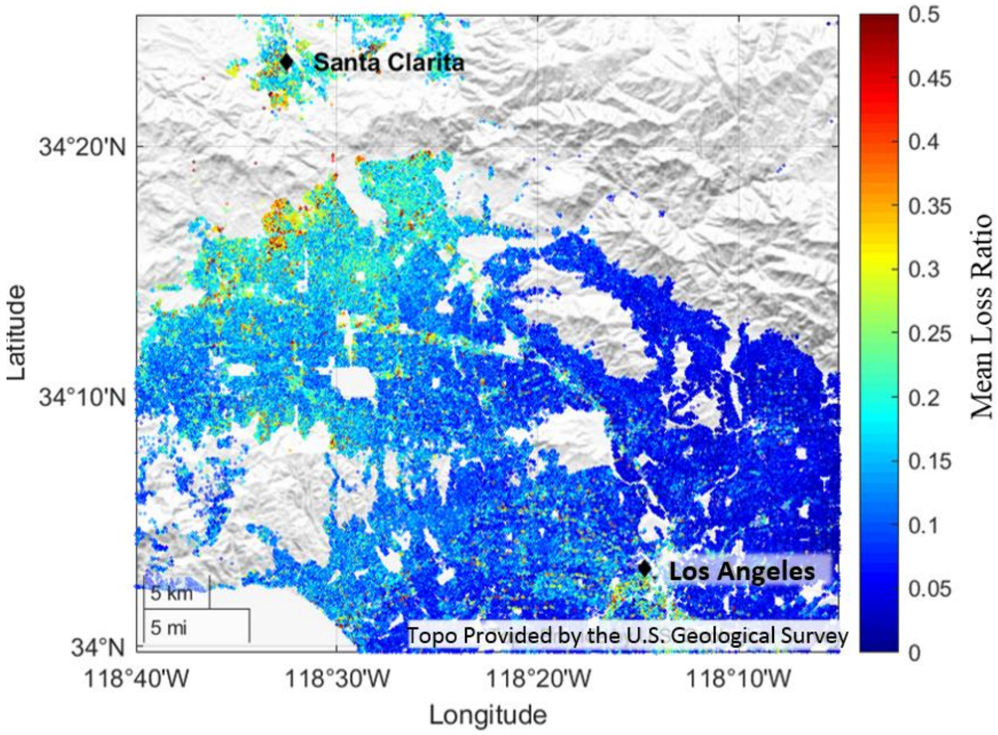

Figure 6 - Zoomed Regional loss hindcast by FEMA P-58 in the 1994 Northridge earthquake for each building in a section of the study region.

To further evaluate the hindcast results, we refer to Wesson et al. [20], which used recorded insurance loss data from the Northridge earthquake to develop empirical relationships between observed losses and shaking intensity. Wesson et al. [20] used more than 80,000 insurance claims for single-family homes of wood frame construction to regressions that represent expected repair costs as a function of shaking intensity. Figure 7 shows a deaggregation of loss contributions to our FEMA P-58 Northridge scenario assessment at various levels of shaking compared with predictions from the regressions provided in Wesson et al. [20]. For this comparison, Wesson et al. [20] losses are calculated by taking the expected values from the Wesson et al. [20] regression for each building in the Los Angeles area inventory based on the PGA value at each building site. We multiply the Wesson et al. [20] curves by the same 0.67 factor to modify the losses to represent direct building damage (i.e. excluding contents and detached structures). When 5% constant damping is assumed for wood buildings, our FEMA P-58 loss assessment significantly overpredicts the losses at low intensities compared with the Wesson et al. [20] empirical relationships. However, when the effective damping varies based on model nonlinearity, hindcast losses from FEMA P-58 show good agreement with the Wesson et al. [20] trends. However, differences still exist between FEMA P-58 loss and loss relationships in Wesson et al. [20]. One important uncertainty is Wesson et al. [20] predictions for low losses, as insurance data is lacking below the deductible (around 10% loss). Comparing the FEMA P-58 losses with and without low intensity wood damping modifications highlights the importance of improving structural responses at low levels of shaking when quantifying potential losses from earthquakes.

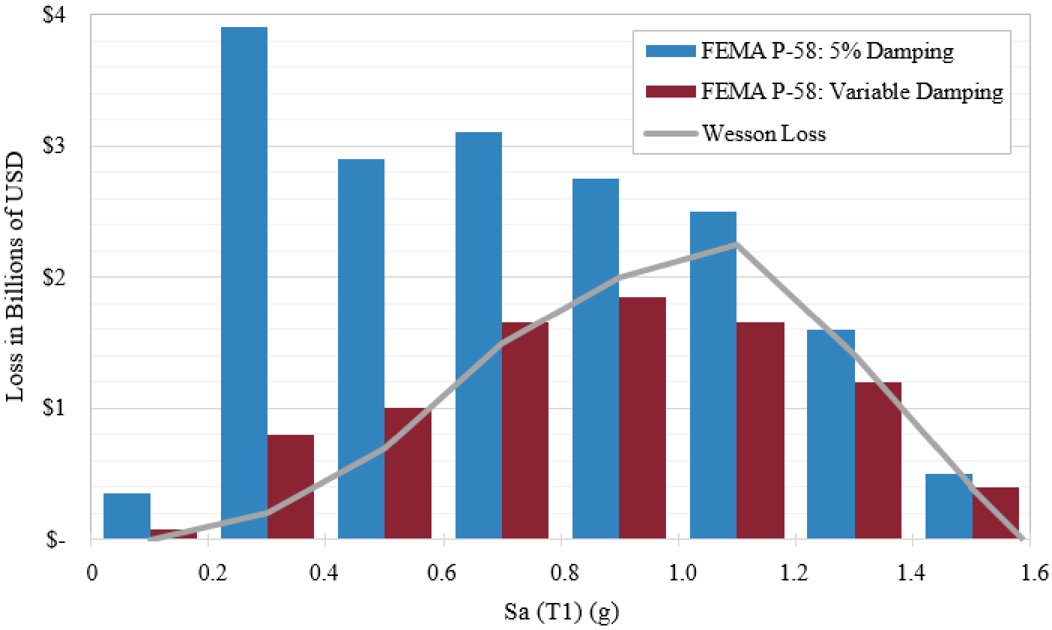

Figure 7 - Comparison between FEMA P-58 predicted loss and loss predicted by Wesson et al. [20].

5. Conclusions

A regional scenario assessment of the Northridge earthquake is performed using FEMA P-58 method for an inventory representative of the 1994 building stock over a large region around Los Angeles. The hindcast scenario loss results are compared to estimates of observed direct building loss. Based on this comparison, the study finds that repair costs predictions from FEMA P-58 compare well with estimates of observed loss, when properly considering the structural response of wood buildings at low shaking intensities. Wood frame residential buildings made up significant portions (50%) of the loss from the Northridge earthquake. Therefore, the loss assessment is extremely sensitive to the modeling considerations that went into the structural response estimations for wood buildings and especially those assumptions that affect loss at low to moderate shaking intensities. When using the variable damping assumption for wood frame buildings, FEMA P-58 predicts $31 billion in total loss and $16 billion in residential loss compared with an estimated observe loss of $25 to $32 billion for all buildings and $12 to $16 billion for residential buildings. This study also performs a sensitivity study to explore modeling decisions that affect structural response at low shaking intensities. While modifying the stiffness of concrete sections based on cracked properties had negligible effects on loss, higher levels of effective damping prior to wall yielding for wood building dramatically improved loss estimates in comparison to observations from Northridge.

This study verifies FEMA P-58 loss predictions against observed losses and indicates that probabilistic methods such as FEMA P-58 can provide accurate predictions of post-earthquake economic losses. However, as highlighted by this study, results from probabilistic methods are heavily dependent upon modeling decisions. Other implementations of FEMA P-58 besides the SP3-RiskModel may result in different outcomes when compared with the losses from the Northridge earthquake. Significant uncertainty also exists in the selection of the building inventory used in this study. Variations in building inventory characteristics may lead to different outcomes.

6. Acknowledgments

This study was conducted as a collaboration between the University of Colorado, the Haselton Baker Risk Group, and OneConcern. OneConcern provided the modern building inventory of the greater Los Angeles region. The Haselton Baker Risk group provided access to the *SP3-RiskModel.*

7. References

[1] FEMA, “FEMA P-58: Seismic Performance Assessment of Buildings Volume 1 - Methodology Second Edition,” 2018.

[2] C. B. Haselton, R. Hamburger, and J. W. Baker, “Resilient Design and Risk Assessment using FEMA P-58 Analysis,” *Struct. Mag.*, no. March, pp. 12–15, 2018.

[3] EQE, “The Northridge Earthquake of January 17, 1994, Report of Data Collection and Analysis, Part A, Damage and Inventroy Data,” 1995.

[4] R. Eguchi, “Direct Economic Losses in the Northridge Earthquake: A Three Year Post Event Perspective,” *Earthq. Spectra*, vol. 14, no. 2, 1998.

[5] L. A. County, “County of Los Angeles Open Data,” 2019. [Online]. Available: https://data.lacounty.gov/Parcel-/Assessor-Publicly-Owned-Parcels-Listing/a9jw-tqfp.

[6] C. B. Worden and D. J. Wald, “ShakeMap Manual Online: technical manual, user’s guide, and software guide,” 2016.

[7] E. Miranda, “Approximate Seismic Lateral Deformation Demands in Multistory Buildings,” *J. Struct. Eng.*, vol. 125, no. April, pp. 417–425, 1999.

[8] A. K. Chopra and R. K. Goel, “Building Period Formulas for Estimating Seismic Displacements.” 2000.

[9] FEMA, “FEMA P-695: Quantification of Building Seismic Performance Factors.,” 2009.

[10] C. B. Haselton and J. W. Baker, “SP3 Webinar Series: The new SP3 Structural Response Prediction Engine,” *Haselton Baker Risk Group*, 2017. .

[11] C. B. Haselton, A. B. Liel, G. G. Deierlein, B. S. Dean, and J. H. Chou, “Seismic collapse safety of reinforced concrete buildings. I: Assessment of ductile moment frames,” *J. Struct. Eng.*, vol. 137, no. 4, pp. 481–491, Apr. 2011.

[12] A. B. Liel and G. G. Deierlein, “Using Collapse Risk Assessments to Inform Seismic Safety Policy for Older Concrete Buildings,” *Earthq. Spectra*, vol. 28, no. 4, pp. 1495–1521, Nov. 2012.

[13] FEMA, “FEMA P-2012: Assessing Seismic Performance of Buildings with Configuration Irregularities.,” 2018.

[14] FEMA, “FEMA P-2018, Seismic Evaluation of Older Concrete Buildings for Collapse Potential,” 2018.

[15] W. J. Petak and S. Elahi, “The Northridge Earthquake, USA, and its Economic and Social Impacts,” in *EuroConference on Global Change and Catastrophe Risk Management Earthquake Risks in Europe*, 2001.

[16] R. O. Hamburger, S. K. Harris, S. C. Martin, D. L. McCormick, and P. G. Somerville, “Response of Tilt-up Buildings to Seismic Demands: Ob servations and Case Studies From the 1994 Northridge Earthquake,” San Francisco, CA, 1996.

[17] ICBO and SEAOC, “Guidelines for seismic evaluation and rehabilitation of tilt up buildings and other rigid wall/flexible diaphragm structures,” 2001.

[18] NIST, “1994 Northridge earthquake,” *Disaster Prev. Manag. An Int. J.*, vol. 8, no. 1, pp. 843–853, 1999.

[19] M. C. Comerio, “Public policy for reducing earthquake risks: A US perspective,” *Build. Res. Inf.*, vol. 32, no. 5, pp. 403–413, Sep. 2004.

[20] R. L. Wesson, D. M. Perkins, E. V. Leyendecker, R. J. Roth, and M. D. Petersen, “Losses to single-family housing from ground motions in the 1994 Northridge, California, earthquake,” *Earthq. Spectra*, 2004.

[21] N. M. Newmark and W. J. Hall, *Earthquake Spectra and Design*, 3rd ed. Berkeley: Earthquake Engineering Research Institute, 1982.

[22] C. T. Yeh, B. J. Hartz, and C. B. Brown, “Damping Sources in Wood Structures,” *J. Sound Vib.*, vol. 19, 1971.