PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

Seismic Performance of Single-Family Wood-Frame Houses: Comparing Analytical and Industry Catastrophe Models

A Report for the "Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings" Project

Evan Reis, SE
Reis Consulting

PEER Report 2020/24
Pacific Earthquake Engineering Research Center
Headquarters, University of California at Berkeley

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ABSTRACT

This report is one of a series of reports documenting the methods and findings of a multi-year, multi-disciplinary project coordinated by the Pacific Earthquake Engineering Research Center (PEER and funded by the California Earthquake Authority (CEA). The overall project is titled "*Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings*," henceforth referred to as the "PEER–CEA Project."

The overall objective of the PEER–CEA Project is to provide scientifically based information (e.g., testing, analysis, and resulting loss models) that measure and assess the effectiveness of seismic retrofit to reduce the risk of damage and associated losses (repair costs) of wood-frame houses with cripple wall and sill anchorage deficiencies as well as retrofitted conditions that address those deficiencies. Tasks that support and inform the loss-modeling effort are: (1) collecting and summarizing existing information and results of previous research on the performance of wood-frame houses; (2) identifying construction features to characterize alternative variants of wood-frame houses; (3) characterizing earthquake hazard and ground motions at representative sites in California; (4) developing cyclic loading protocols and conducting laboratory tests of cripple wall panels, wood-frame wall subassemblies, and sill anchorages to measure and document their response (strength and stiffness) under cyclic loading; and (5) the computer modeling, simulations, and the development of loss models as informed by a workshop with claims adjustors.

This report is a product of Working Group (WG) 6: *Catastrophe Modeler Comparisons* and focuses on comparing damage functions developed by the PEER–CEA Project with those currently contained in modeling software developed by the three largest insurance catastrophe modelers: RMS, CoreLogic and AIR Worldwide. A semi-blind study was conducted in collaboration with the modeling companies to compare damage estimates for a selection of the Index Buildings developed in the PEER–CEA Project Study. The WG6 Project Team conducted several meetings with these modeling companies to gather feedback on the structure of and assumptions made by the PEER–CEA Project. The comparative results are evaluated and presented herein.

ACKNOWLEDGMENT AND DISCLAIMER

ACKNOWLEDGMENT

This research project benefited from the interaction of many researchers and practitioners. The author would like to thank the following project team members for their input and feedback: Yousef Bozorgnia, Henry Burton, Kelly Cobeen, Greg Deierlein, Bret Lizundia, Tara Hutchinson, Grace Kang, Charlie Kircher, Thor Matteson, Sharyl Rabinovici, Brandon Schiller, David Welch, Farzin Zareian, Colin Blaney, and Charlie Scawthorn.

DISCLAIMER

This research study was funded by the California Earthquake Authority (CEA). The support of the CEA is gratefully acknowledged.

EXECUTIVE SUMMARY

This report is one of a series of reports documenting the methods and findings of a multi-year, multi-disciplinary project coordinated by the Pacific Earthquake Engineering Research Center (PEER) and funded by the California Earthquake Authority (CEA). The overall project is titled "*Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings*," henceforth referred to as the "PEER–CEA Project."

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This report is a product of the efforts of Working Group (WG) 6: *Interaction with Claims Adjustors and Catastrophe Modelers*. This working group focused on interaction with the catastrophe modelers to compare damage functions developed by the PEER–CEA Project with those currently contained in modeling software developed by the three largest insurance catastrophe modeling companies: RMS, CoreLogic, and AIR Worldwide (hereafter known as the Modelers"). A study was conducted in collaboration with the Modelers in order to compare damage estimates for a selection of the Index Buildings developed in the PEER–CEA Project. The WG6 Project Team conducted several meetings with the Modelers to answer questions regarding the comparative results described herein.

The WG6 report detailing the interaction with claims adjustors is published under a separate cover [Vail et al. 2020]

The PEER–CEA Project WG6 Team formulated a framework for comparing damage functions derived from the PEER–CEA Project with those used by the Modelers to develop a comparison of the Index Buildings derived within the scope of PEER–CEA Project's WGs 2 [Reis 2020; Vail et al 2020] and 5 [Welch and Deierlein 2020]. This comparison was used as a way for the Modelers to evaluate the damage functions produced by the Project and determine how best to incorporate the outcomes of the Project into their catastrophe models. The PEER–CEA Project Working Group reports contain various links to the raw data accumulated through the project for use by the Modelers to consider when incorporating this information into their catastrophe models. One-hundred-and forty-four of the PEER–CEA Project Index Buildings were initially selected to compare with the Modelers database of building and were based on the available primary and secondary modifier options of the Modelers' damage models that matched those considered by the Project Team.

One of the variables initially considered was the condition of the building materials, which would require adjusting the analysis model parameters to reflect the quality of the structural materials (to account for deterioration, quality of construction, etc.). The Project Team determined that the only way to include the effects of material condition would have been to use expert judgment to increase or decrease the strength–stiffness and hysteretic behavior of the model components, thus representing merely an estimate of poor or good condition. Ultimately, the Project Team decided that this would introduce another variable into the overall damage functions, i.e., expert judgement, which could not be objectively or numerically justified when comparing the PEER–CEA Project results to those of the Modelers. Consequently, the final number of Index Buildings to be compared with the Modelers database was reduced to 48 from an original list of 144.

In order to make as direct a comparison of damage functions with the parameters of the present study—including ground up loss (a loss assuming zero deductible) as a function of shaking intensity at a specific period—then hazard should be a control variable. The Project Team selected four sites for use in this study by the Project Team and all the Modelers. A soil classification of D (V_{s30} = 270 m/sec) was assumed, and basin and near-field effects were not included.

The difference in hazard-curve ordinates between the Project Team and the Modelers were on the order of +/- 10% to 30%, depending on the range of return periods compared. The differences between the Modelers and the PEER–CEA Project results are, therefore, a result both of the differences in the hazard curves *and* differences in the underlying damage functions themselves. To eliminate the differences associated with hazard, the Modelers were required to match the PEER–CEA Project hazard curves exactly across all return periods, or the Modelers needed to provide the Project Team with the damage functions for the Index Buildings directly.

Key findings from the results of the comparison study include:

1. For unretrofitted raised (2-ft-tall) cripple wall conditions the PEER–CEA Project models consistently and significantly estimated more significant damage (ground-up loss assuming no deductible), both at the 250-year return period and Average Annual Loss (AAL) across all age groups, heights, and locations, compared to the results of the Modelers by between 200% to 700%.
2. Both the Modelers and PEER–CEA Project predicted greater damage for the two-story, raised cripple wall homes versus the one-story homes, but the difference was more significant in the PEER–CEA Project models.
3. For unretrofitted stem-wall conditions, the Modelers consistently estimated lower damage at the 250-year return period across all age groups, heights, and locations on the order of 33% to 50% with respect to the PEER–CEA Project models. In contrast, the AAL values were in much better agreement, on the order of 10% to 25%, compared to the PEER–CEA Project values.
4. For retrofitted conditions, the PEER–CEA Project and Modelers' results compared significantly better compared to unretrofitted conditions, with the values for both the AAL and 250-year return period, for both raised and stem-wall conditions, generally within 10% to 40% of each other.

5. The PEER–CEA Project results showed a consistent improvement in performance with age, regardless of location, number of stories, and exterior siding material (i.e., the use of lighter interior wall finish materials). The Modelers results showed consistent improvement from the 1945–1955 age range over the pre-1945 age range, but poorer performance from the 1955–1970 age range over the 1945–1955 age range.
6. The Modelers results show virtually no difference in performance between stucco and wood siding for any of the conditions considered. In contrast, the PEER–CEA Project models show distinctly better performance for stucco over wood siding in the unretrofitted condition with a raised cripple wall.
7. The PEER–CEA Project results show that retrofitting a two-story, stem-wall house using the ATC-110 plan set resulted in slightly poorer performance because of higher damage concentration in the first story. The Modelers' results show no such increase in damage in the retrofitted stem-wall condition.
8. The significance of these findings should not be overstated. There are many conditions that could lead to poorer performance of unretrofitted two-story stem-wall houses that were not fully evaluated in this limited study. These may include homes where: (1) the existing sill plate connection is weaker than assumed in this study, due to deterioration or lack of nailing; (2) the first-story walls are stronger than assumed in this study; (3) the existing sill plate is narrower than assumed; (4) the floor plan or foundations have irregular configurations; or (5) the flexibility of the first-floor diaphragm can lead to localized areas of increased deformation, thus increasing the risk of the floor separating from the stem wall. There could also be considerable variability in the repair costs of a stem-wall house that does slide partially off its foundation sill plate. Given these and other uncertainties in a study of this scope, retrofitting stem-wall houses according to the ATC-110 plan set remains the preferred engineering recommendation.

An important consideration when comparing the results of the PEER–CEA Project and the Modelers is the deaggregation of building characteristics within the Modelers' damage functions. The comparison study was crafted explicitly to consider primary and secondary modifiers—age, stories, siding, cripple walls, retrofit condition, etc.—that are available inputs in the Modelers' models. All of the Modelers stressed to the Project Team that the differentiation in their damage models was not entirely based on empirical claims data. Much of the claims data incorporated into their models does not contain complete descriptions of the buildings, nor does it identify primary and secondary modifiers. Thus, the Modelers must incorporate expert judgment in assigning damage function adjustment factors to account for the individual building characteristics.

An example is the presence of a raised cripple wall itself. A report from the Department of Housing and Urban Development [1994] that attempted to quantify damage to single-family houses in the 1994 Northridge, California, earthquake included a study of 341 structures, of which only 3% were raised cripple wall houses; the remainder contained slabs-on-grade or stem-wall foundations. Assuming that the claims data used by the Modelers in the development of their own damage functions would have been heavily influenced by the Northridge insurance data, as it comprised a large share of the available empirical data over the past 50 years, it would be credible to conclude that the Modeler functions are heavily weighted toward slab or stem-wall conditions. Thus, the justification for the significant difference in the AAL and losses at the 250-year return period between the Modelers and the PEER–CEA Project results for raised cripple wall homes can quite possibly be explained by the implicit weighting of the former toward non-cripple wall structures.

These key findings suggest that damage estimates should be improved by including the following additional required information in the underwriting data collection process, and the catastrophe Modelers' software:

- The ability to distinguish between a raised cripple wall and a stem wall;
- The ability to distinguish between interior finishes of lath and plaster, and those of gypsum wallboard; and
- The ability to distinguish between unretrofitted and retrofitted conditions.

Furthermore, if engineers and the scientific community are to continue to improve methods of credibly estimating building performance in earthquakes and other hazards, it is essential that their collaboration with insurers should include access to the underwriting and claims inventory at a granular level. Sharing this valuable information, while finding ways to preserve anonymity and proprietary advantage, would be extremely beneficial to the effort of improving insurance pricing/policies for earthquakes and other natural hazards.

A comparison of the damage functions developed by the Project Team with those developed by FEMA's HAZUS program and an empirical study of the HUD 1994 Northridge insurance claims, yielded the following observations:

- The PEER–CEA Project consistently predicts significantly more damage to cripple wall homes that are: unretrofitted, raised, one and/or two story in height, with wood and stucco siding compared to the aggregate HAZUS and Northridge results [HUD 1994] (which were not broken down by individual building characteristics). This may be explained by the expectation that less than 10% of the Northridge dataset were likely based on raised cripple wall homes:
- The PEER–CEA Project predicted less damage than HAZUS for one-story houses with stem walls or retrofitted homes with raised crawl spaces: and
- The PEER–CEA Project predicted similar damage (in general) as HAZUS for two-story houses with stem walls or homes retrofitted with raised crawl spaces.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 Introduction

This report is one of a series of reports documenting the methods and findings of a multi-year, multi-disciplinary project coordinated by the Pacific Earthquake Engineering Research Center (PEER) and funded by the California Earthquake Authority (CEA). The overall project is titled "*Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings*," henceforth referred to as the "PEER–CEA Project."

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Within the PEER–CEA Project, detailed work was conducted by seven Working Groups, each addressing a particular area of study and expertise, and collaborating with the other Working Groups. The seven Working Groups are as follows:

Working Group 1: Resources Review

Working Group 2: Index Buildings

Working Group 3: Ground-Motion Selection and Loading Protocol

Working Group 4: Testing

Working Group 5: Analytical Modeling

Working Group 6: Interaction with Claims Adjustors and Catastrophe Modelers

Working Group 7: Reporting

This report is a product of Working Group (WG) 6: *Interaction with Claims Adjustors and Catastrophe Modelers*. This working group focused on interaction with the catastrophe modelers to compare damage functions developed by the PEER–CEA Project with those currently contained in modeling software developed by the three largest insurance catastrophe modeling companies:

RMS, CoreLogic, and AIR Worldwide (hereafter known as the “Modelers”). A semi-blind study was conducted in collaboration with the Modelers to compare damage estimates for a selection of the Index Buildings developed by the PEER–CEA Project. The WG6 Project Team conducted several meetings with the Modelers to answer questions regarding the comparative results described herein.

The Modelers did not direct the work of the PEER–CEA Project Team. The CEA facilitated initial contacts with the Modelers but also did not direct or influence the work of the Project Team.

A WG6 report detailing the interaction with claims adjustors is published under a separate cover [Vail et al. 2020].

2 Comparison Process

The first task of the PEER–CEA Project WG6 Team (Project Team) was to formulate a framework for comparing damage functions derived from the PEER–CEA Project with those used by the Modelers to compare the response of selected Index Buildings derived within the scope of Working Groups (WGs) 2 [Reis 2020] and 5 [Welch and Deierlein 2020)]. This comparison was used as a way for the Modelers to evaluate the damage functions produced by the Project and determine how best to incorporate the outcomes of the project into their catastrophe models.

Based on discussions with the Modelers, the Project Team developed the following comparison process.

1. The Project Team developed a list of Index Buildings that combined the variants (individual building characteristics) identified by the PEER–CEA Project WG2 [Reis 2020]. The Project Team and the Modelers identified corresponding variants of these Index Buildings with the building characteristics contained within the Modelers' software. Generally, building characteristics within the Modelers' software are referred to as Primary and Secondary Modifiers. Examples of Primary Modifiers are: (1) age and (2) number of stories. Primary Modifiers are required inputs within the Modelers' software. Examples of Secondary Modifiers are: (1) type of siding, (2) presence of retrofit, and (3) presence of cripple walls. Secondary Modifiers are not required inputs within the Modelers' software. Together, the Primary and Secondary Modifiers define a specific damage function that the Modelers use to estimate building risk.
2. The Project Team selected a subset of the PEER–CEA Project's Index Buildings, called the Comparison Set, which would be compared directly to the Modeler Index Buildings with similar characteristics. Section 3 of this report discusses the development of the Comparison Set.
3. The most direct method of comparison between the Project's results and the Modelers' software would compare damage functions for the Comparison Set. A direct comparison of damage (repair costs as a function of replacement cost) vs. ground-motion input [spectral acceleration (*Sa*) at 0.3-sec period) would yield a relatively simple means to identify similarities and differences between the Project's findings and established industry standards. Furthermore, calibrating the damage functions for both unretrofitted and retrofitted conditions would be straightforward; however, the Modelers preferred not to

make their individual damage functions public. As part of the Project requirements, information provided by the Modelers would be included in the Project reports, which will be publicly available. Therefore, the Project Team developed an alternate method for comparing the Project and Modeler information.

4. The Project Team and the Modelers determined that a "semi-blind study" would be the most appropriate way to compare damage predictions developed by the Project with those produced by the Modelers.

   (a) The Project Team and the Modelers agreed to use *Sa* at 0.3 sec as the independent ground-motion parameter for which damage would be calculated.

   (b) The Project Team developed damage functions based on its Index Buildings corresponding to "ground up" damage as a function of the independent ground-motion parameter. The term "ground up" refers to the insurance terminology of losses assuming zero deductible and no coverage limits.

   (c) The Project Team and the Modelers each developed a portfolio of individual buildings that matched the Index Buildings; this comprises the Comparison Set.

5. The Project Team selected four site locations around the state representing different regions of seismicity. The Project Team and the Modelers produced expected values of the ground-motion parameter as a function of return period (a hazard curve) for each of the locations. This effort is described in the PEER–CEA Project WG3 report: *Probabilistic Seismic Hazard Analysis and Selecting and Scaling Ground-Motion Records* [Mazzoni et al. 2020] and in Section 4 of this report.

6. The Project Team and the Modelers independently subjected the Comparison Set to four hazard curves to create damage predictions as a function of return period for each of the four sites.

7. The Project Team and the Modelers produced values of average annual loss (AAL) by integrating the damage estimates produced above, over the return period index for each site. An example of this process is described in Figure 2.1. This integration preserves the anonymity of the individual damage functions (damage as a function of the independent ground-motion parameter), while providing a means to compare results among the Project and the Modelers.

8. The Modelers also provided a single data point along the damage function for each building in the Comparison Set. This point is representative of an insurance term called the Tail Value At Risk, TVAR, which is the predicted damage at what is presumed to be a rare event, usually a 250-year return period. The Project Team asked for the Modelers to provide this single point along the damage function for an additional point of comparison that would indicate

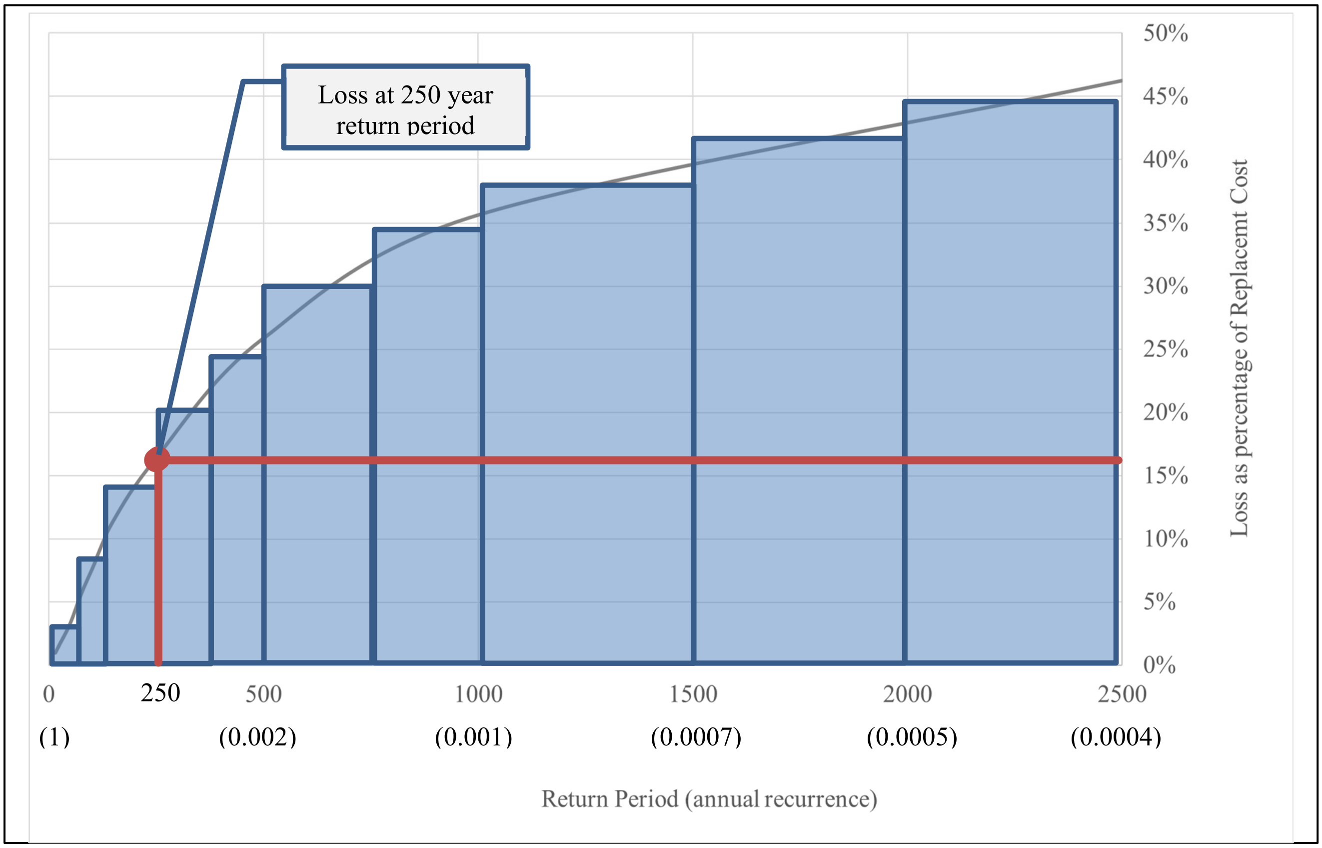
whether the overall damage functions might be weighted more or less heavily along the hazard curve.

9. The Project Team and the Modelers evaluated a subset of the Comparison Set, as described in Section 5 of this report, to iron out any questions or irregularities in the study. Following this evaluation, the Project Team met with Modeler representatives separately to gather feedback and recommendations for revisions to the comparison study. The Project Team and the Modelers then evaluated the entire Comparison Set.

10. The Project Team compared the results of the Comparison Set study along the different index variant dimensions as described in Section 3 of this report. The Project Team again met with the Modeler representatives separately to present these findings. The findings were summarized in an Excel spreadsheet and provided to the Modelers for further internal evaluation.

11. The Project Team identified key findings from the comparison, which are presented in Sections 6 and 7 of this report.

Section 9 of this report compares the damage functions developed by the Project Team with those used in FEMA's HAZUS program and with a study performed by Wesson et al. [2004] using empirical damage data gathered from the 1994 Northridge, California, earthquake. These comparisons are primarily for information only; the Project Team determined that because the HAZUS and Wesson functions did not differentiate among individual building characteristics, it would not be appropriate to modify the results of the PEER–CEA Project to better correlate with the HAZUS or Wesson damage functions.



Calculation of Average Annual Loss

$$AAL = \sum_{\upsilon=1}^{.0004} \overline{L_{\upsilon}} * d\upsilon$$

L = Loss %

ν = annual frequency (1/RP)

Figure 2.1 Calculation of average annual loss from damage function.

3 Index Buildings Comparison Set

The total number of Index Buildings considered within the project, based on the combinations of variables representing building construction characteristics, numbered in the hundreds; see WGs 2 [Reis 2020] and 5 reports [Welch and Deierlein 2020]. Not all variables considered in the study are included within the primary or secondary modifier options of the Modelers' damage models. For example, the PEER–CEA Project Study considered a range of cripple wall heights, from 2 ft to 6 ft, whereas each of the Modelers has only a single variable representing the presence of a cripple wall. Another example is that the PEER–CEA Project models considered interior wall finishes consisting of either gypsum wallboard or lath and plaster, the latter being substantially heavier than the former. None of the Modelers allowed for the selection of interior finish materials. One-hundred-and-forty-four of the PEER–CEA Project Index Buildings were initially selected to compare with the Modelers database. Of these 144, twelve were selected to be evaluated as an initial test of the models.

One of the variables initially considered was the condition of the building materials, which would adjust the analysis model parameters to reflect the quality of the structural materials (to account for deterioration, quality of construction, etc.). The Project Team recognized that the quality of construction and the condition of structures in California varies significantly as a function of age, location, climate, quality of labor, and other factors. The base-shear capacity and damage states of buildings are dependent on these factors. Furthermore, the benefit of seismic retrofit will vary depending on the condition of the existing structures.

The Project Team held a meeting in December 2019 with its Project Review Panel (PRP) to discuss this issue and several others affecting the models. The Team and PRP concluded that no scientific data was available that considers the impact of material condition on the characteristics associated with the performance of wood-frame single-family homes. Furthermore, the testing program implemented as part of the PEER–CEA Project WG4**,** *Cripple Wall Small Component Test Program and Large-Component Seismic Testing for Existing and Retrofit Single-Family Wood-Frame Dwellings* [Cobeen et al. 2020; Schiller et al. 2020(a), (b), (c), (d), and (e)] which incorporated construction detailing and methods appropriate for the eras of construction, but it could not realistically embed "deteriorated" or elements in otherwise poor condition quality into the tests. For example, the testing part of the Project did not artificially rust nails or crack stucco finishes, representing the potential effects of aging.

The Project Team and PRP determined that the only way to include the effects of material conditions that represented an estimate of poor or good condition would have been to use expert judgment to increase or decrease the strength–stiffness and hysteretic behavior of the model components. Ultimately, the group decided that this would only introduce the variable "expert judgment" into the overall damage functions that could not be objectively or numerically justified when comparing the PEER–CEA Project results to those of the Modelers.

Another point of consideration was that within the results provided by the Modelers, there was very little difference within their models in damage based on the condition variable available; see Table 3.1.

Thus, the Project Team noted that the performance of single-family homes may exhibit better or worse behavior dependent on *in situ* conditions, and that insurance pricing/policies should reflect this uncertainty in an actuarially appropriate manner.

Based on these factors, the Project Team decided to remove this condition as a variable in the PEER–CEA Project models; instead, a single "best estimate" of material properties was used, based on the available science and testing. This decision was discussed in the January 2020 meeting during the presentation of results to the Modelers. The Modelers' universal consensus was that this was a rational and defensible decision.

Table 3.1 Variation in Modelers' loss results as a function of condition modifier.

Average results of all Modelers for comparison set				
AAL (% of RCV)				
Condition	**San Francisco**	**San Bernardino**	**Northridge**	**Bakersfield**
Good	0.19%	0.35%	0.29%	0.07%
Average	0.21%	0.37%	0.30%	0.07%
Poor	0.21%	0.39%	0.32%	0.07%
@250-year return period (% of RCV)				
Condition	**San Francisco**	**San Bernardino**	**Northridge**	**Bakersfield**
Good	14.6%	26.2%	19.9%	4.5%
Average	15.4%	27.8%	20.8%	4.8%
Poor	16.2%	29.0%	22.0%	5.0%

Elimination of the "Good" and "Poor" condition variables resulted in reducing the original set of 144 Index Buildings to be compared in the calibration study to 48. Table 3.2 lists the 48 Index Buildings that were ultimately considered in the calibration study. The PEER–CEA Project models assumed the following for each of the Index Buildings.

- All buildings were assumed to have the same plan layout;
- Wood siding refers to a cripple wall with horizontal siding boards and diagonal wood bracing. The consensus of the Project Team and the PRP was that diagonal bracing was a common practice in older construction, providing basic stability of the house prior to the placement of the exterior sheathing;
- A raised foundation refers to a 2-ft-tall cripple wall. The consensus of the Project Team was that this was the most common height of a raised cripple wall, with 4-ft- and especially 6-ft-tall cripple walls being much less common;
- A stem-wall foundation refers to the condition where the first-floor joists rest directly on the sill plate;
- The retrofitted condition refers to seismic mitigation that meets the ATC-110 plan set, given the building's location, number of stories, siding, and interior finish materials;
- Index Buildings in the <=1945 age category were assumed to contain lath and plaster interior wall finishes;
- Index Buildings in the 1956–1970 age category were assumed to contain gypsum wallboard interior wall finishes; and
- Damage estimates for Index Buildings in the 1945–1955 age category were assumed to be the mathematical average between the <=1945. Homes in the 1956–1970 age category represented an assumed equal distribution between buildings with lath and plaster and gypsum wallboard finishes.

Table 3.2 Forty-eight Index Buildings used in Modeler comparison study.

Index Number	Height	Age	Siding	Foundation	Condition	Retrofitted
3	one story	<=1945	Wood	Raised	Best Estimate	Yes
4	one story	<=1945	Wood	Raised	Best Estimate	No
9	one story	<=1945	Wood	Stem Wall	Best Estimate	Yes
10	one story	<=1945	Wood	Stem Wall	Best Estimate	No
15	one story	<=1945	Stucco	Raised	Best Estimate	Yes
16	one story	<=1945	Stucco	Raised	Best Estimate	No
21	one story	<=1945	Stucco	Stem Wall	Best Estimate	Yes
22	one story	<=1945	Stucco	Stem Wall	Best Estimate	No
27	one story	1945-1955	Wood	Raised	Best Estimate	Yes
28	one story	1945-1955	Wood	Raised	Best Estimate	No
33	one story	1945-1955	Wood	Stem Wall	Best Estimate	Yes
34	one story	1945-1955	Wood	Stem Wall	Best Estimate	No
39	one story	1945-1955	Stucco	Raised	Best Estimate	Yes
40	one story	1945-1955	Stucco	Raised	Best Estimate	No
45	one story	1945-1955	Stucco	Stem Wall	Best Estimate	Yes
46	one story	1945-1955	Stucco	Stem Wall	Best Estimate	No
51	one story	1956-1970	Wood	Raised	Best Estimate	Yes
52	one story	1956-1970	Wood	Raised	Best Estimate	No
57	one story	1956-1970	Wood	Stem Wall	Best Estimate	Yes
58	one story	1956-1970	Wood	Stem Wall	Best Estimate	No
63	one story	1956-1970	Stucco	Raised	Best Estimate	Yes
64	one story	1956-1970	Stucco	Raised	Best Estimate	No
69	one story	1956-1970	Stucco	Stem Wall	Best Estimate	Yes
70	one story	1956-1970	Stucco	Stem Wall	Best Estimate	No
75	two story	<=1945	Wood	Raised	Best Estimate	Yes
76	two story	<=1945	Wood	Raised	Best Estimate	No
81	two story	<=1945	Wood	Stem Wall	Best Estimate	Yes
82	two story	<=1945	Wood	Stem Wall	Best Estimate	No
87	two story	<=1945	Stucco	Raised	Best Estimate	Yes
88	two story	<=1945	Stucco	Raised	Best Estimate	No
93	two story	<=1945	Stucco	Stem Wall	Best Estimate	Yes
94	two story	<=1945	Stucco	Stem Wall	Best Estimate	No

Index Number	Height	Age	Siding	Foundation	Condition	Retrofitted
99	two story	1945-1955	Wood	Raised	Best Estimate	Yes
100	two story	1945-1955	Wood	Raised	Best Estimate	No
105	two story	1945-1955	Wood	Stem Wall	Best Estimate	Yes
106	two story	1945-1955	Wood	Stem Wall	Best Estimate	No
111	two story	1945-1955	Stucco	Raised	Best Estimate	Yes
112	two story	1945-1955	Stucco	Raised	Best Estimate	No
117	two story	1945-1955	Stucco	Stem Wall	Best Estimate	Yes
118	two story	1945-1955	Stucco	Stem Wall	Best Estimate	No
123	two story	1956-1970	Wood	Raised	Best Estimate	Yes
124	two story	1956-1970	Wood	Raised	Best Estimate	No
129	two story	1956-1970	Wood	Stem Wall	Best Estimate	Yes
130	two story	1956-1970	Wood	Stem Wall	Best Estimate	No
135	two story	1956-1970	Stucco	Raised	Best Estimate	Yes
136	two story	1956-1970	Stucco	Raised	Best Estimate	No
141	two story	1956-1970	Stucco	Stem Wall	Best Estimate	Yes
142	two story	1956-1970	Stucco	Stem Wall	Best Estimate	No

4 Comparison of Seismic Hazard

Damage functions compare damage, represented as ground-up loss (loss assuming zero deductible and no coverage limits) as a function of shaking intensity at a specific period. As described in the PEER–CEA Project WG3 [Mazzoni et al. 2020; Zariean and Lanning 2020] and WG5 project reports [Welch and Deierlein 2020], the primary period of interest with respect to single-family homes is approximately 0.3 sec. The objective of the catastrophe modeler comparison study was to compare damage functions developed by the Modelers and PEER–CEA Project Team. A direct comparison of damage functions could not be made because data provided by the Modelers were limited to damage at a single return period of 250 years, and an integrated damage value over the hazard curve at all return periods (the AAL). The PEER–CEA Project WG5 [Welch and Deierlein 2020] report provides damage functions for all Index Buildings considered by the PEER–CEA Project to enable the Modelers to make direct comparisons with their damage functions but maintain confidential information.

In order to make as direct a comparison of damage functions as possible within the present study, it was decided to make hazard a control variable. The Project Team selected four sites for the study to be used by the Project Team and all the Modelers, assuming a soil classification D (V_{s30} = 270 m/sec). Basin and near-field effects were not included by the Project Team or any of the Modelers. Each Modeler used hazard curves developed internally within their models. A comparison of the hazard curves for each of the four sites considered is shown in Table 4.1, which compares *Sa* at 0.3 sec period for the 250-year return period provided from each Modeler, with that generated by the Project Team for each site.

One Modeler developed a custom hazard curve to closely match the PEER–CEA Project across most return periods so that the ground-motion variable nearly falls out of the damage function equation. As shown in the figures and Table 4.2, the difference in hazard curve ordinates between the PEER–CEA Project and the other two Modelers are on the order of +/- 10% to 30%, depending on the range of return periods.

The differences found in the AAL and loss at the 250-year return period are a result of the differences in the hazard curves and differences in the underlying damage functions themselves between the Modelers and the PEER–CEA Project. To eliminate the differences associated with the hazard, the Modelers would need to match the PEER–CEA Project hazard curves exactly across all return periods, or the Modelers would need to provide the PEER–CEA Project Team with the damage functions for the Index Buildings directly.

Table 4.1 Comparison of seismic hazard values at 250-year return period.

	San Francisco		San Bernardino		Bakersfield		Northridge	
Latitude	37.779		34.105		35.374		34.228	
Longitude	-122.419		-117.293		-119.020		-118.536	
	*S*a	*Sa*Project /*Sa*Modeler	Sa	*Sa*Project / *Sa*Modeler	Sa	*Sa*Project / *Sa*Modeler	Sa	*Sa*Project / *Sa*Modeler
PEER–CEA	1.00	-	1.30	-	0.62	-	1.17	-
MODELERS	1.00	100%	1.30	100%	0.62	101%	1.04	112%
	1.11	90%	1.42	91%	0.52	120%	1.05	111%
	0.90	111%	1.21	107%	0.52	120%	0.97	120%

Table 4.2 Comparison of seismic hazard values across return periods.

Return-period range	**Average of SaProject / SaModeler**		
	MODELERS		
0–100 Years	109%	130%	131%
110–250 Years	105%	110%	118%
300–2500 Years	103%	94%	111%

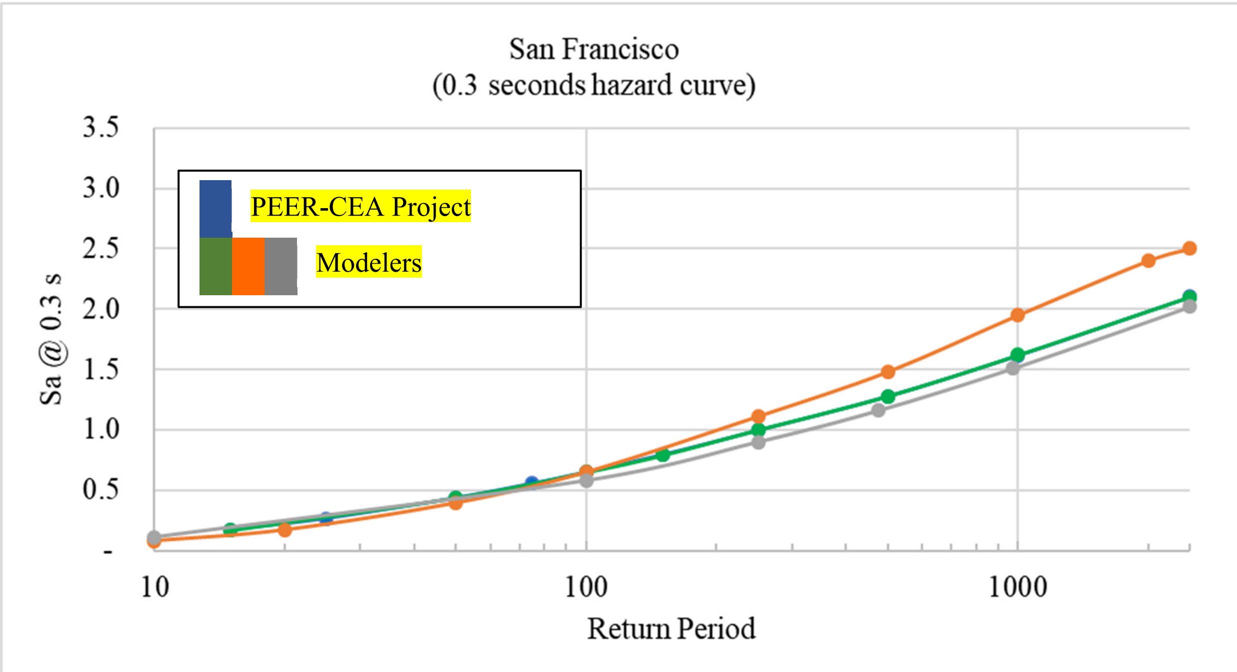


Figure 4.1 **San Francisco: hazard curves by location at *Sa* = 0.3 sec (PEER-CEA hazard curve matches Modeler hazard curve shown in green).**

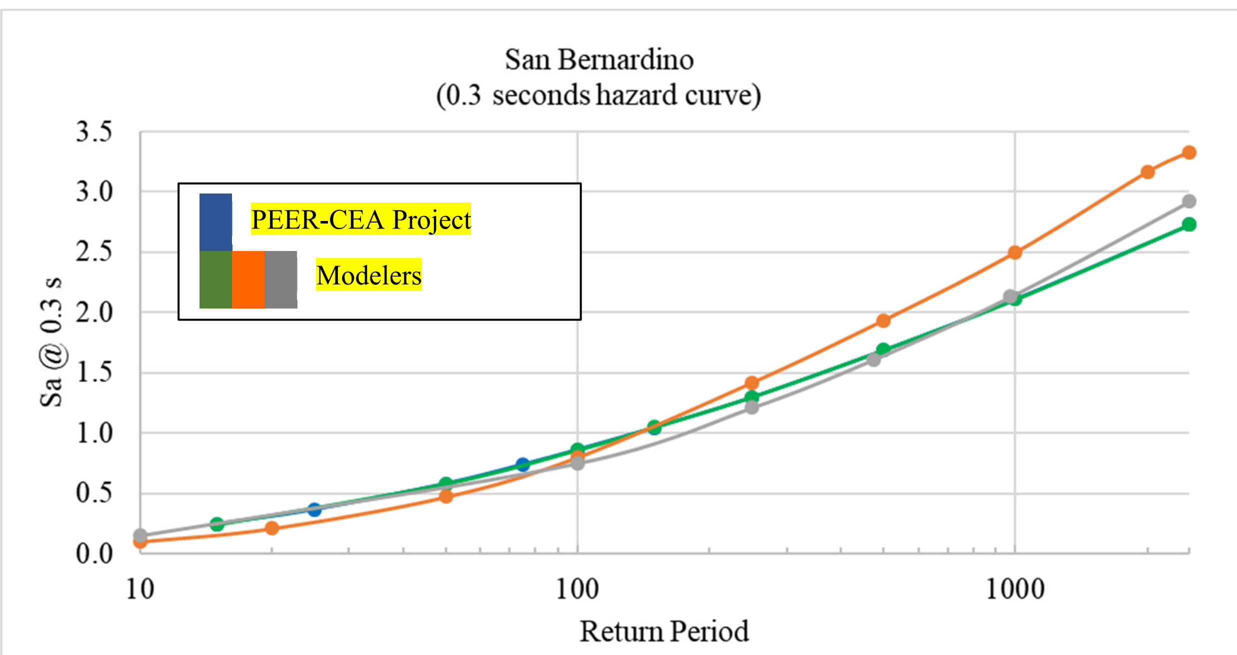


Figure 4.2 **San Bernardino: hazard curves by location at *Sa* = 0.3 sec (PEER-CEA hazard curve matches Modeler hazard curve shown in green).**

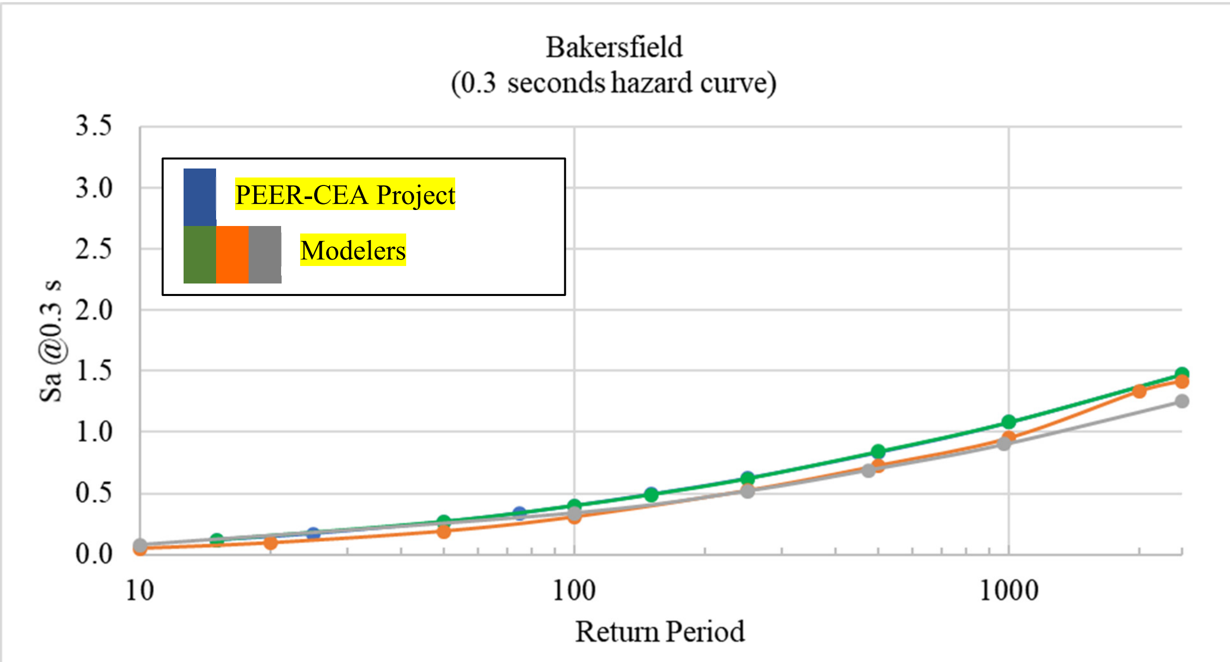


Figure 4.3 **Bakersfield: hazard curves by location at *Sa* = 0.3 sec (PEER-CEA hazard curve matches Modeler hazard curve shown in green).**

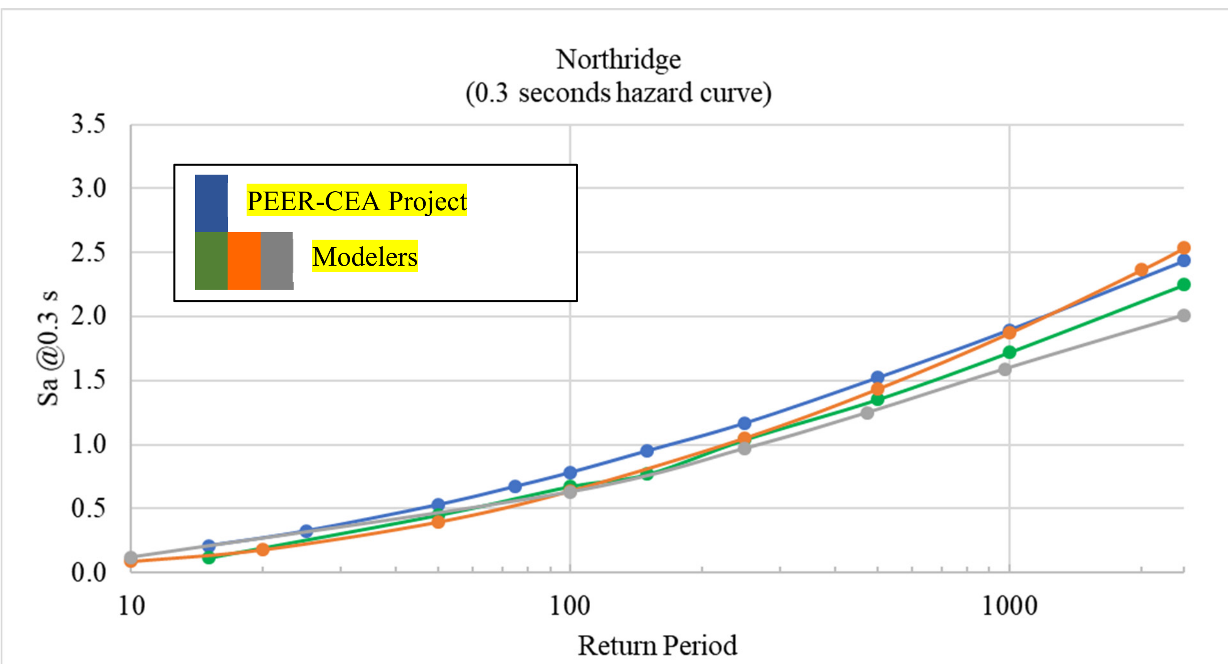


Figure 4.4 **Northridge: hazard curves by location at *Sa* = 0.3 sec.**

5 Interactions with Catastrophe Modelers

Representatives of the Project Team corresponded or met with the Modelers on several occasions to answer questions and present the comparative results described herein. The Project Team held meetings separately with each Modeler for reasons of confidentiality. The Modelers did not direct or influence the work of the PEER–CEA Project Team. In addition, the CEA facilitated initial contacts with the Modelers but did not direct or influence the work of the Project Team. The Project Team invited representatives from CEA to attend all meetings with the Modelers and copied them on all correspondence for their information. No input from CEA was invited or received.

A summary of the discussions follows.

1. June 2017 – The Project Team introduced the project to the Modelers, presenting the proposed outline of the calibration study. The Team presented the study's testing protocols and the information that would be requested of them.
2. April 2019 – The Project Team finalized the list of 144 Index Buildings, i.e., the Comparison Set described in Section 3 above, and distributed it to the Modelers.
3. July 2019 – The Modelers and the Project Team completed evaluations of 12 of the 144 buildings comprising the Comparison Set as an initial test. The Project Team held web meetings with each of the Modelers individually to present the results of this initial test and to discuss questions in preparation for running all 144 index buildings.
4. September 2019 – The Modelers provided the Project Team with a list of questions and information they would like to receive to help them better understand the process and make their own internal comparisons of the results. Table 5.1 contains a list of the Modelers' questions and the Project Team's responses.
5. December 2019 – The Project Team met with its Project Review Panel to discuss initial results and refinements proposed by the Modelers. At this meeting, the group determined that one of the index variables that quantified the condition of the building as "Good, Average, or Poor" could not be confidently modeled by the Project Team; see Section 3. This reduced the total number of index buildings to be compared with the Modelers from 144 to 48.

6. January 2020 – The Project Team and the Modelers completed their runs of the full Comparison Set. The team met individually with the Modelers to present the results.
7. February 2020 – The Project Team provided the Modelers with a spreadsheet comparing the 48 Index Building Comparison Set against the Modelers' results. The Modelers' names were anonymous so that each could compare its specific results against the Project Team's results. The data contained in the spreadsheet is summarized in Chapter 6 of this report.

Table 5.1 Modeler questions following initial model runs of 12 Index Buildings.

No.	Modeler questions and Project Team responses (September 2019)	
	Question	**Response by PEER–CEA Project team**
1	We see that "rigid diaphragms" are used for the floors in the analytical model of the buildings. Can we learn the reason why rigid diaphragms were used instead of flexible diaphragms. Did you do similar analyses with flexible diaphragms?	The Project Team discussed this issue at some length. One of the main driving factors for using rigid diaphragms for cripple wall dwellings is that flooring was commonly diagonal flooring which creates a very stiff material. Secondly, capturing diaphragm displacements requires much more complex modeling for very little benefit. (What do we do with a mid-span diaphragm deflection of 0.5” if our wall materials aren’t considered out-of-plane and we have no fragility information as well?) This still leaves a few open points including “roof diaphragms” which could have a varied level of in-plane stiffness or large plan irregularities that may not allow “rigid diaphragm” behavior in terms of force transfer to perimeter cripple walls. These different considerations were not included in the scope due to one or more of the following: - If an outstanding deficiency exists in the house that is not affected by sub-floor retrofit, it is not included in the variant scope (chimneys, poor roof to wall connections) - types of structures not covered by the ATC-110 plan set are not included (split-levels, highly irregular plans) - if behavior cannot be readily included in structural analysis and loss assessment (without a 15-year project), then they are not included (e.g., we have no data to model out-of-plane response of all wall materials, small (<0.5”) diaphragm displacements are not able to be utilized in our current models from both structural analysis and loss assessment)
2	Is it possible to get the OpenSees files of the models?	Once the analysis models have been finalized and documented by the Project Team (and subject to CEA’s approval), the project team can make the OpenSees input files available to the loss Modelers.
3	One way to verify the difference between retrofitted and unretrofitted cripple walls with respect to the Modelers’ results is to find out the proportion of unretrofitted out of total population of a particular year built, and do a weighted average to check its contribution to entire building stock	This is certainly the approach we would prefer, as we recognize that the Modelers’ empirical data does not typically distinguish between retrofitted and unretrofitted walls, whereas the Project Team models by design do. Unfortunately, despite our extensive research we have been unable to locate data to distinguish losses from past earthquakes between houses with and without cripple walls and between retrofitted and unretrofitted cripple walls. It will essentially have to be left up to the Modelers to individually account for this in some rationale fashion based on the internal information they have from the insurance companies.

No.	Modeler questions and Project Team responses (September 2019)	
	Question	**Response by PEER–CEA Project team**
4	If the project is using lognormal cumulative functions (my guess) to formulate fragility curves, my experience is that they tend to overestimate damage at low intensity and underestimate damage at high intensity because of intrinsic requirement of limiting to 1.0.	Lognormal cumulative functions are used at multiple stages in the *FEMA P58* loss analysis for: (1) the collapse fragility functions; (2) the story drift demands at each earthquake intensity; and (3) the damage functions (relating story drift to wall and component damage). These assumptions of lognormal distributions have been widely studied in past research and are specified in the *FEMA P58* and *FEMA P695* methodologies. We are not aware of evidence that the lognormal collapse fragility curves, drift demand, or component damage curves are biased. Moreover, should there be any slight bias, it is reasonable to assume that this bias would similarly affect the calculated loss (damage) functions for the unretrofitted and retrofitted conditions, such that it would not have a major influence on the difference in loss results.
5	Collapse of the un-retrofitted cripple wall seems to be driving the EAL and 250-year RP losses. We'd like to see more sensitivity studies related to the existing cripple wall assumptions. It would also be informative to show the breakdown of losses due to collapse vs repairable damage.	This is an area of interest among all the Modelers and the CEA review panel. The Project Team had been planning to conduct several sensitivity studies on the cripple wall strength and failure as indicated below.
6	What if the cripple wall collapse isn't a total loss?	Using research from CUREE and others we are running sensitivity analyses to consider the loss if the cripple wall failure can be repaired by (1) jacking the house, retrofitting the wall footing, and replacing the cripple wall, and (2) repairing expected superstructure damage that occurred due to imposed drift demands prior to cripple wall failure. A major source of uncertainty, which are difficult to assess by analysis, is damage to the superstructure that occurs due to racking distortion and impact loading during cripple wall failure. Given the range of uncertainties and opinions on this question, we have asked CEA for guidance on how insurance adjusters deal with situations where the cripple wall has collapsed.
7	How do variations in the assumed strength and stiffness of the existing cripple wall affect the vulnerability? Presumably a reasonable lower bound could be based on the tests of the unbraced cripple wall with the 5 horizontal siding boards, and the upper bound could be constrained by tests of the retrofitted cripple wall. This variation can come from uncertainty in material properties or simply variations in the existing housing stock. What if the siding isn't horizontal wood but is T1-11 or vinyl? Presumably many older homes have replaced the original siding.	Our models consider multiple cripple wall sheathing conditions, including horizontal siding only, stucco only, stucco over siding, and T1-11 siding. In our initial runs which were compared to the Modeler's results we did not consider all of these. So we will present these refinements when completed. We will also be considering a "condition" factor in our analyses, that will adjust the analysis model parameters to account for the quality of the structural materials (to account for deterioration, quality of construction, etc.).
8	What if the cripple wall has minimal bracing (e.g., diagonal let-in bracing or limited sheathing)?	This question has come up multiple times. Our analyses will consider alternative cases where sheathing is present beneath the wood or stucco siding. We are also looking at ways to incorporate let-in bracing as a stiffening element for the cripple walls.

No.	Modeler questions and Project Team responses (September 2019)	
	Question	**Response by PEER–CEA Project team**
9	What if the cripple wall is taller (or shorter) than 2 ft? Is there test data available to support that?	It has always been our intent to consider 4' and 6' cripple walls. They will be included in our subsequent evaluations.
10	What does the existing cripple wall modeling assume about the anchorage to the foundation? Unbolted? Adequately bolted? Some state in between?	We have considered both an adequately bolted condition and an unbolted "wet set sill" condition. Testing of the wet set sill condition has shown to be extremely strong and stiff as compared to sills that are installed on cast concrete with bolted anchors. An unbraced cripple wall is not susceptible to sliding since the cripple wall is the weak link. For the retrofit case, the sliding failure mode is eliminated through detailing and proper capacity design to force a ductile failure mode through yielding of the wood structural panel fasteners. When these details are an issue, it is the framing-to-sill connections (toe-nails) that are the weak leak (from both recon observations and testing). Homes bearing on a perimeter concrete stem wall with inadequate anchorage (i.e., no cripple wall) will be investigated through various levels of sliding resistance.
11	The sensitivity studies are of great interest to us, and we'd like to see more exhibits like those on slides 61-67 of WG5/6 slides. Can we get a list of all the archetypes / variants planned? This will help us to provide feedback. In addition to sensitivity in the assumed material strength and stiffness values, there is also variation in the existing housing stock. Some other variations that should be investigated are: Different floor plans / configurations (e.g., square footage, number of rooms, aspect ratio, length of wall per square foot). At a minimum, changing the effective length of wall should be studied (and the ratio of effective wall lengths in the x versus y direction).	We will provide the Modelers with future runs, which as described above will be considering a multitude of variants, not all of which were included in the 12 examples run for this first pass. We have identified 144 Index Buildings that can match up with the modifiers included in the Modelers' models. We will run those in order to make additional direct comparisons with the Modelers. There are also several hundred additional Index Buildings with variants (like cripple wall height and interior wall sheathing) that do not match up with the Modelers' variants. We will be running those as well and will have to have a future discussion with the Modelers about which additional modifiers they will be willing to add to their models, and which we will have to calculate general weighted average based on best estimates of proportionality. We will not be able to consider different floor plan layouts or x/y wall length ratios. Ideally, we would like to do this, but time and budget constrain us. The selected configuration was based on an extensive research effort by the ATC-110 team to identify the most common building profiles.
12	Different wall finishes: what if the interior walls are lath and plaster instead of gypsum?	We will be considering both lath and plaster wall and gypsum wall finishes.
13	We'd like details on the damage state fragility and repair cost functions for all damageable components (e.g., piping) included in the loss model like what is provided on slides 27-29 of WG5/6 slides.	We will provide as much breakdown of component damage and costs as we can from *FEMA P-58* damage states once we have finalized our models. We would also note that have conducted a benchmarking exercise to compare the *FEMA P-58* losses to those determined from a workshop with insurance adjusters. In general, the agreement

No.	Modeler questions and Project Team responses (September 2019)	
	Question	**Response by PEER–CEA Project team**
		between the two methods is good, but we have made some adjustments based on this information. This information will be summarized in our final reports.
14	Are there variations in the damage state and cost functions for the 2 ft cripple wall based on the presence or absence of wood structural panels (i.e., pre- vs post-retrofit)?	No. The damage states and repair costs are independent of the retrofit condition, although of course a retrofitted building is less likely to reach a given damage state for the same hazard.
15	It's unclear if the same damage fragility was used for full-height and 2 ft Wood Exterior Walls (wood siding wall without bracing). Does testing support using the same damage fragility for the different heights? We note significant differences in the damage fragility of stucco walls based on the height, which we assume is based on testing.	For horizontal wood siding, testing supports using the same damage fragility based on drift (displacement / height). The fragilities for stucco have been adjusted for height since testing suggests that stucco is controlled by the displacement capacity of the fasteners. In terms of drift, there is a large difference between 2 ft and 8 or 9 ft walls. The inclusion of cases with bracing in the framing of siding walls will justify further adjustment of damage fragility for both short (2 ft) and full-height walls. All fragility information will be summarized with final analysis results.
16	Is the repair cost per square foot higher for superstructure exterior walls vs cripple walls for DS3 (stud repair involves embedded utilities and perhaps insulation in the superstructure walls)?	The current repair costs are using the *FEMA P-58* functions which do not distinguish between superstructure and cripple wall. The current functions do not make a distinction in order to reflect the significant amount of utilities affected by a severely damaged cripple wall. Proper adjustments to cripple wall functions for DS3 are being investigated using information from the recent claims adjustor workshop. All modifications and impact of loss results will be reported.
17	Is sliding of the cripple wall due to lack of anchorage considered?	Yes, in the condition where there is no bolting we are assuming a wet set sill condition as this would be the most common type of construction. As it turns out this is a very strong and stiff type of connection. In reality, an unbraced cripple wall is not susceptible to sliding since the cripple wall is the weak link. For the retrofit case, the sliding failure mode is eliminated through detailing and proper capacity design to force a ductile failure mode through yielding of the wood structural panel fasteners. Homes bearing on a perimeter concrete stem wall with inadequate anchorage (i.e., no cripple wall) will be investigated through various levels of sliding resistance.
18	Is modeling uncertainty included for the non-collapse cases? If not, why is the modeling uncertainty considered only for collapse fragility functions?	Modeling uncertainty is kept at a constant value (0.35) for both collapse and non-collapse (i.e., drift) response. The current value represents a standard or "average" value in the *FEMA P695* and *FEMA P58* documents. As the archetype response database broadens, the influence of this parameter on single archetypes could be compared to select combinations of multiple variants (of the same group) with variations in the implicit modeling uncertainty.
19	What is the vintage of the baseline model? How does the vintage of the construction affect the results?	Three age bands are considered: pre-1945, 1945–55, and 1956–70. The configuration of the house was not changed for each but some of the assumptions were for individual components (e.g. T1-11 siding was not considered for the first two age bands and drywall was not considered for the first band)

No.	Modeler questions and Project Team responses (September 2019)	
	Question	**Response by PEER–CEA Project team**
20	Do the return period losses include the uncertainty in the vulnerability? If so, how did you estimate the uncertainty in the damage ratio at a given spectral acceleration level? Can we see the coefficient of variation for the damage ratio conditioned on the spectral acceleration?	If we understand the question correctly, each component in the model contains a mean fragility parameter (damage vs Sa) and a lognormal uncertainty parameter. So, yes the end result for each Sa (or RP) would include the aggregate uncertainties. Upon refinement of the models and completion of the remaining runs it is our expectation that we will provide uncertainty bounds for the building vulnerability functions.
DATA REQUESTS FROM MODELERS		
21	Fragility functions for all Index Buildings	The fragility functions are developed primarily from *FEMA P-58* on a component basis, as modified by the testing results and the results of the claims adjustor workshop. Once our models are completely developed we will consider the best way to provide those to the Modelers.
22	Reports from WG5, ATC 110 and all the existing reports from the PEER–CEA Project.	These will be provided to the CEA, and the CEA will determine how they are to be distributed to the Modelers. Please contact CEA directly for ATC-110 information.
23	Vulnerability function for each index building, in each location	These will be provided to CEA toward the end of the analysis phase when we have refined and rerun our models, and CEA will determine how they are to be distributed to the Modelers. The vulnerability functions themselves so not vary by location. The same buildings are used in each.
24	The final list of test locations: are there only 3 or will more be added?	We will be running one additional site in Northridge to balance what we saw as a slight under design of the ATC-110 retrofit for the San Bernardino hazard with a slight overdesign of the ATC-110 retrofit for the Northridge Hazard. We determined that the change in response spectral shape was not significantly different around the state so that using these four locations would suffice. We will provide the Modelers with the location shortly and ask them to rerun the Index Buildings for this location as well.
25	The digitized HAZUS functions for all the age bands and configurations as shown in slide 32 of WG5/6 slides.	We will have to discuss with Charlie Kircher who developed these curves, outside the Project Team, whether he is willing to provide these to the Modelers.
26	The Northridge claims data from the California DOI as shown in slide 32 of WG5/6 slides	This data was provided to us only in an image format so we do not have the data itself.
27	CEA's claims data from the 2014 South Napa earthquake and the 2003 San Simeon earthquake	Please request this data directly from CEA.

6 Comparison of Results

This section presents the results of the 48 Index Building comparison study. The Modelers are identified as A, B, and C to protect their confidential information. The damage function library will be accessible on the PEER–CEA Project website. This will allow the Modelers to make additional internal comparisons with their models and for use by other researchers. The PEER–CEA Project damage functions are also presented in the WG5 report [Welch and Deierlein 2020].

Figures 6.1 through 6.12 represent results averaged over the results of the three Modelers over the four site locations studied: San Francisco, Northridge, San Bernardino and Bakersfield. Figures 6.13 through Figure 6.60 represent results distinguished by Modeler and location.

Legend for Figure 6.1 through Figure 6.8.

	PEER–CEA Project Results
	Modeler Averages

Legend for Figure 6.9 through Figure 6.12

	PEER–CEA Project Results unretrofitted
	PEER–CEA Project Results retrofitted
	Modeler Averages unretrofitted
	Modeler Averages retrofitted

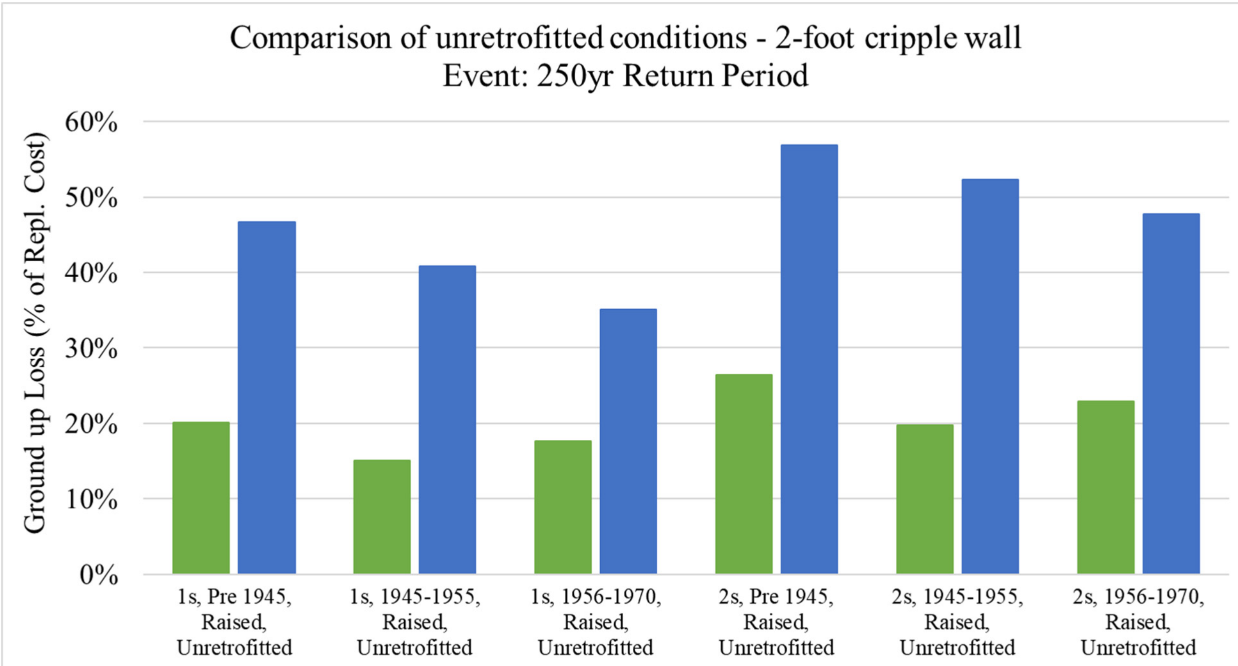


Figure 6.1 **Comparison of unretrofitted conditions: 2-ft-tall cripple wall @ 250-year return period.**

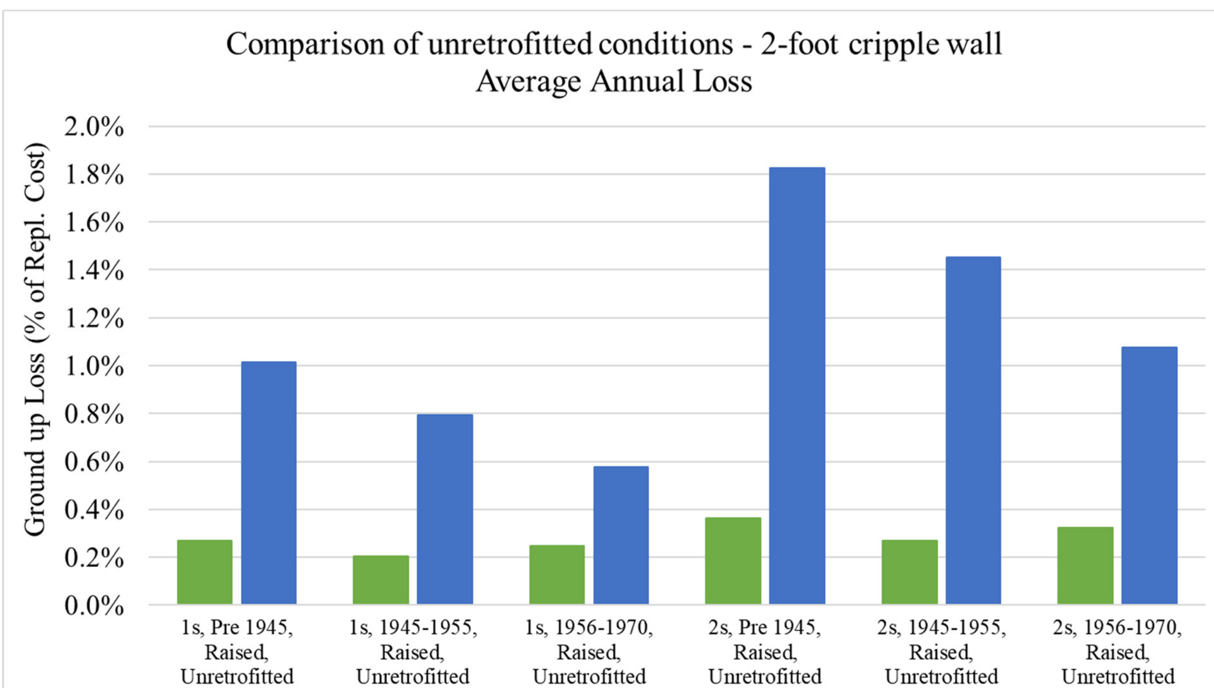


Figure 6.2 **Comparison of unretrofitted conditions: 2-ft-tall cripple wall, average annual loss.**

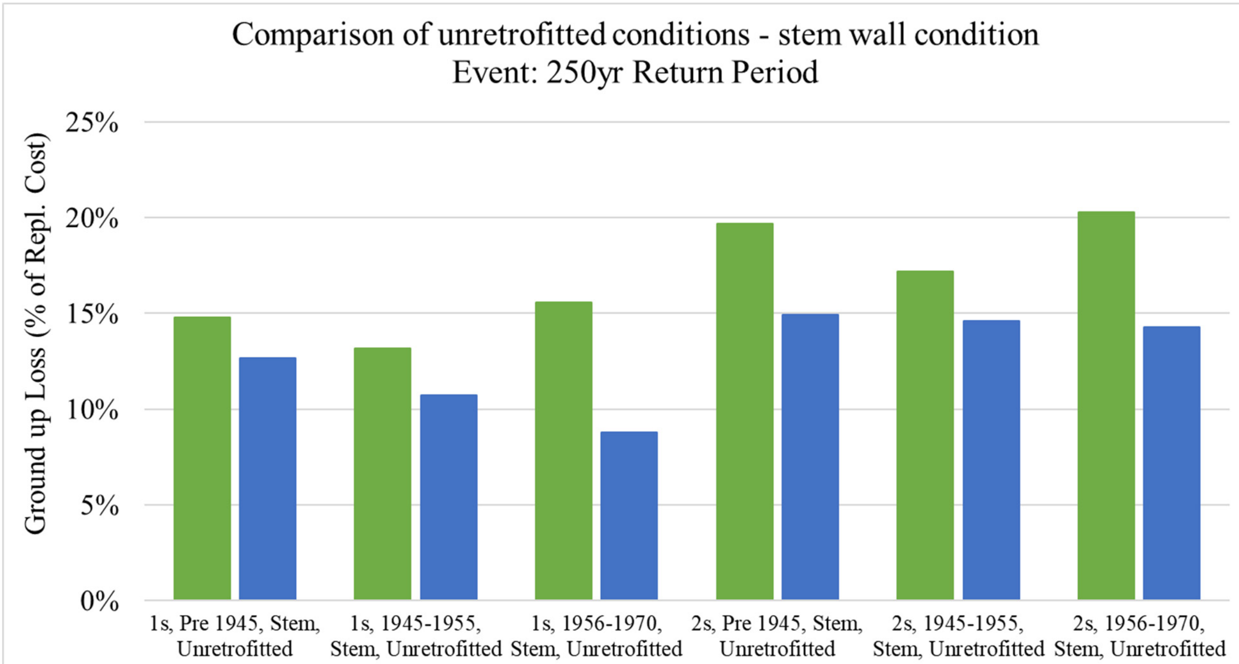


Figure 6.3 **Comparison of unretrofitted conditions: stem-wall condition @ 250-year return period.**

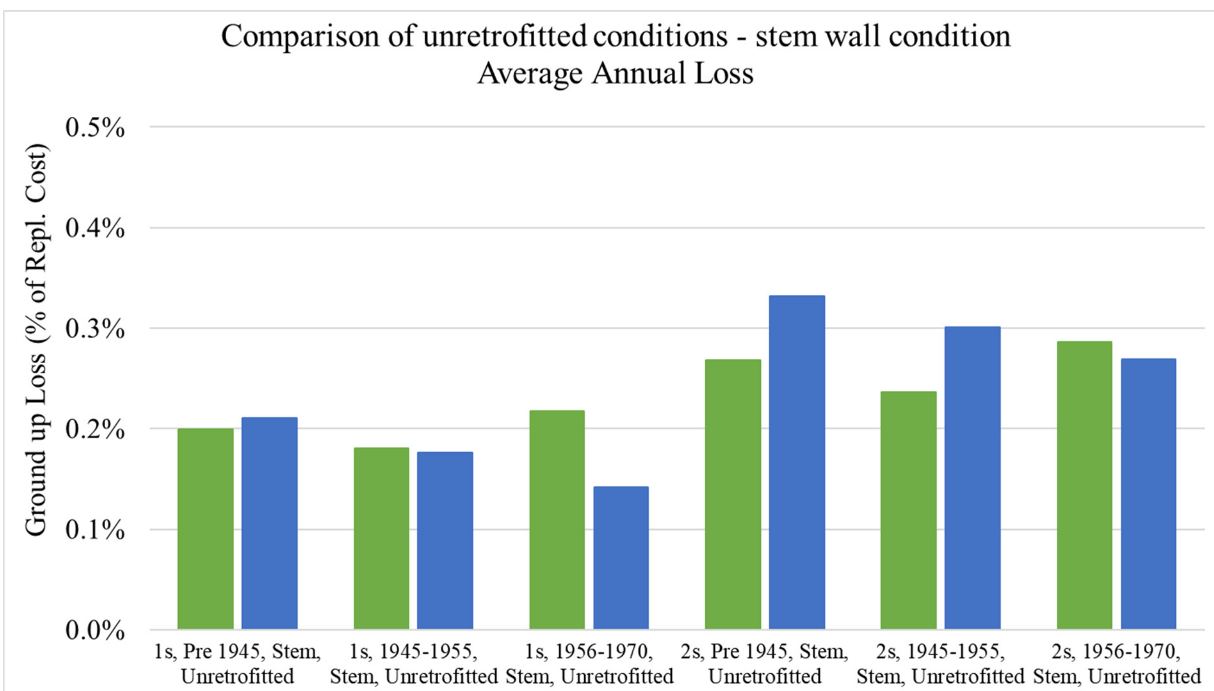


Figure 6.4 **Comparison of unretrofitted conditions: stem-wall condition, average annual loss.**

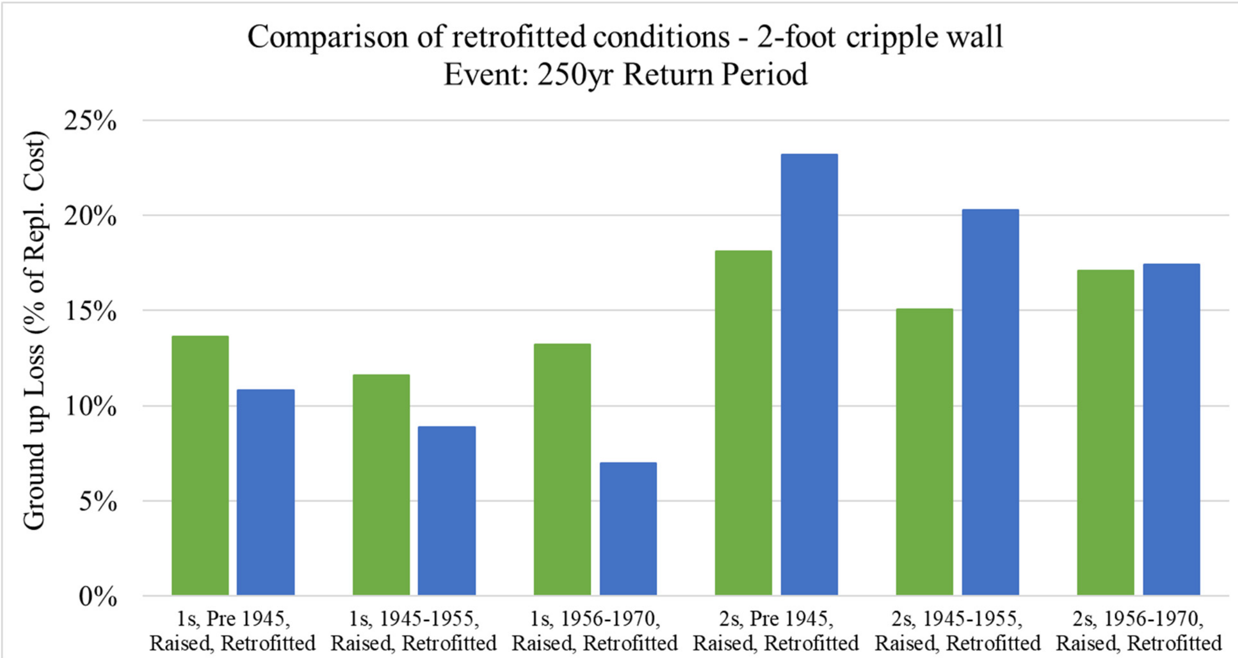


Figure 6.5 Comparison of retrofitted conditions: 2-ft-tall cripple wall @ 250-year return period.

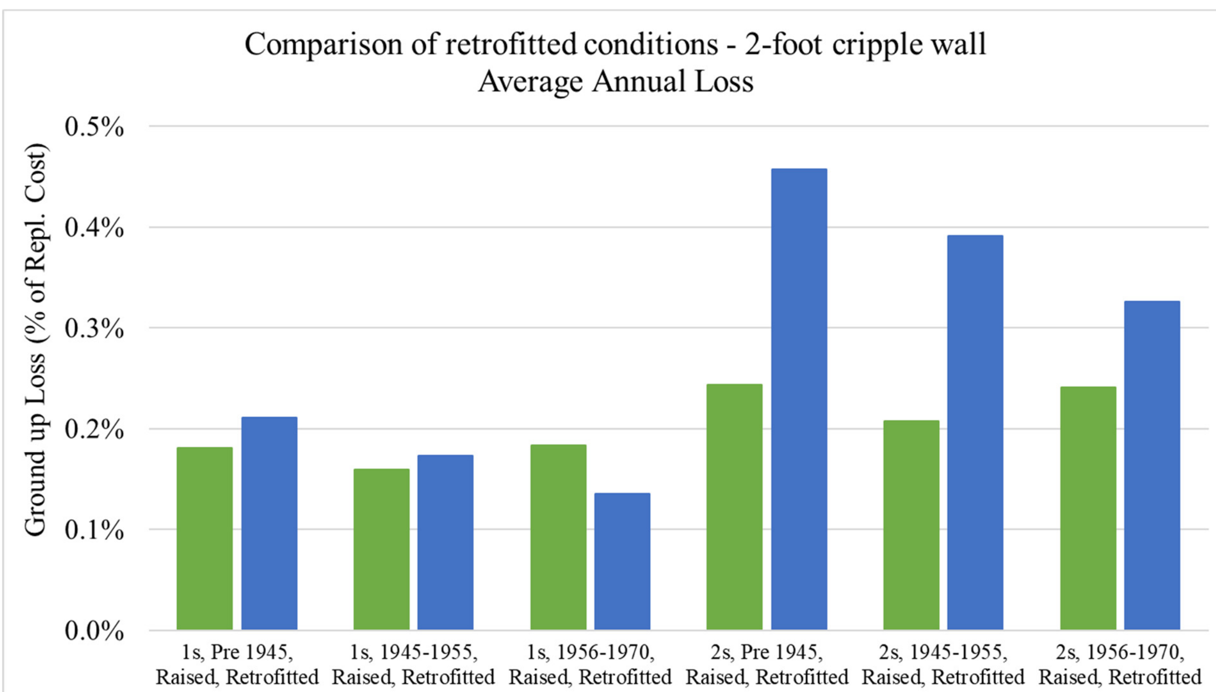


Figure 6.6 Comparison of retrofitted conditions: 2-ft-tall cripple wall, average annual loss.

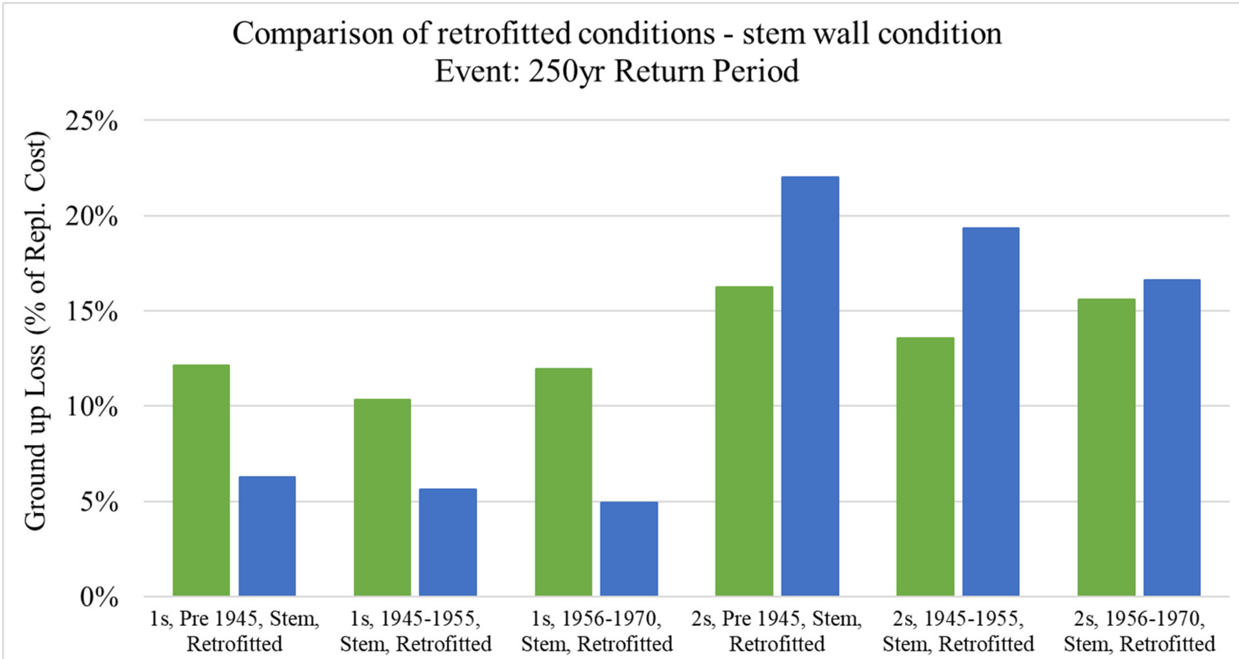


Figure 6.7 **Comparison of retrofitted conditions: stem-wall conditions @ 250-year return period.**

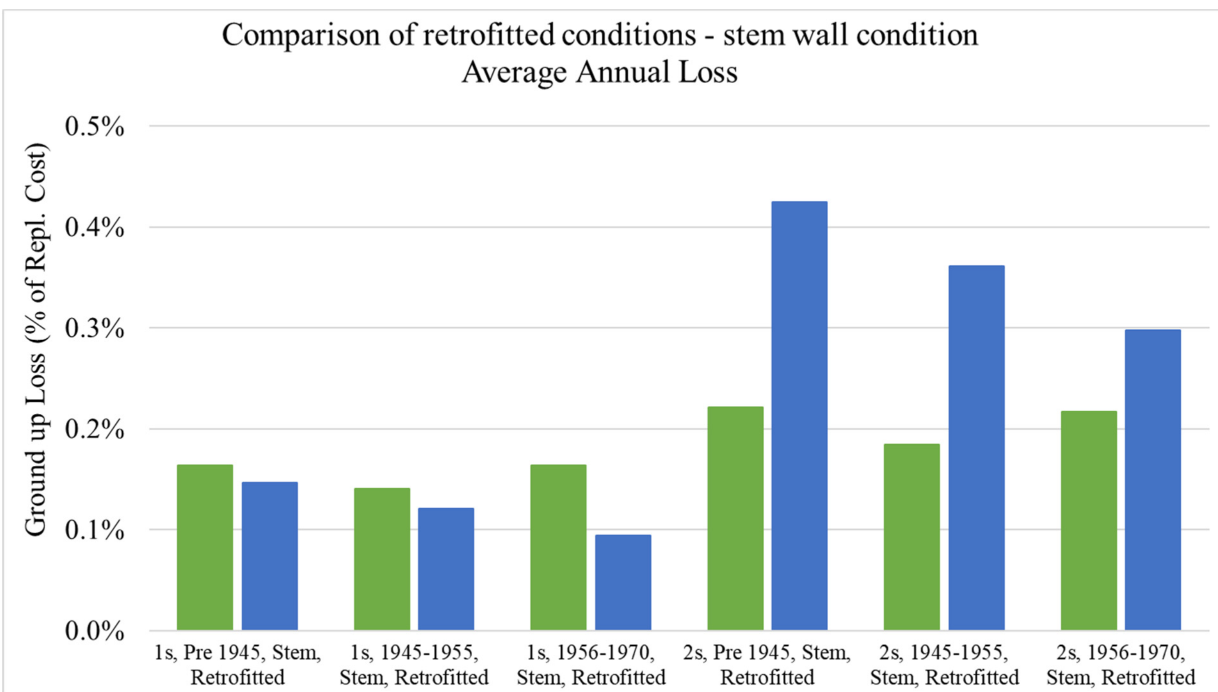


Figure 6.8 **Comparison of retrofitted conditions: stem-wall condition, average annual loss.**

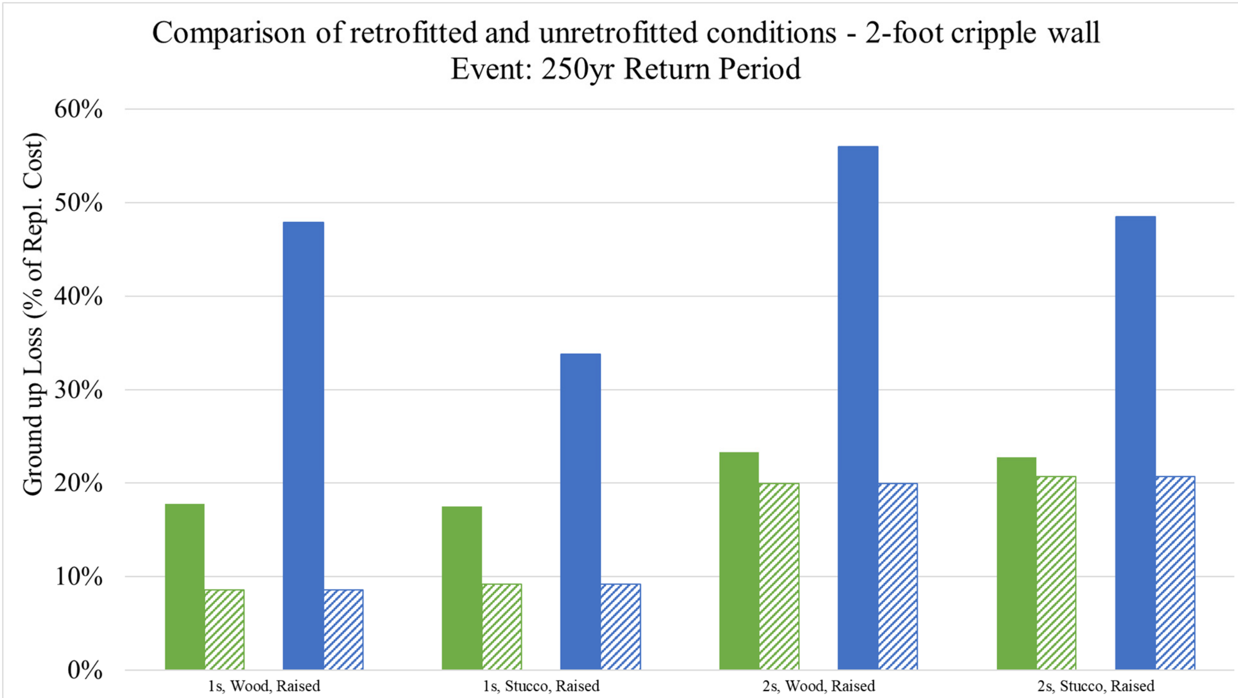


Figure 6.9 **Comparison of unretrofitted and retrofitted conditions: 2-ft-tall cripple wall @ 250-year return period.**

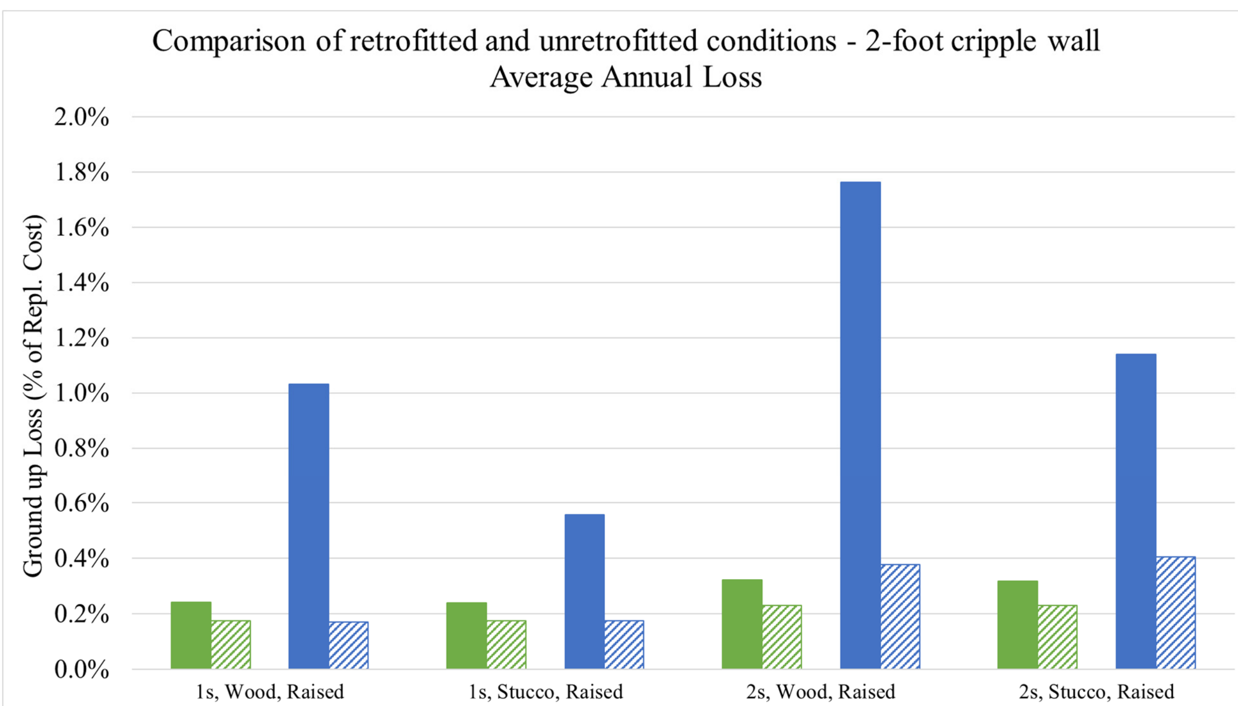


Figure 6.10 **Comparison of unretrofitted and retrofitted conditions: 2-ft-tall cripple wall, average annual loss.**

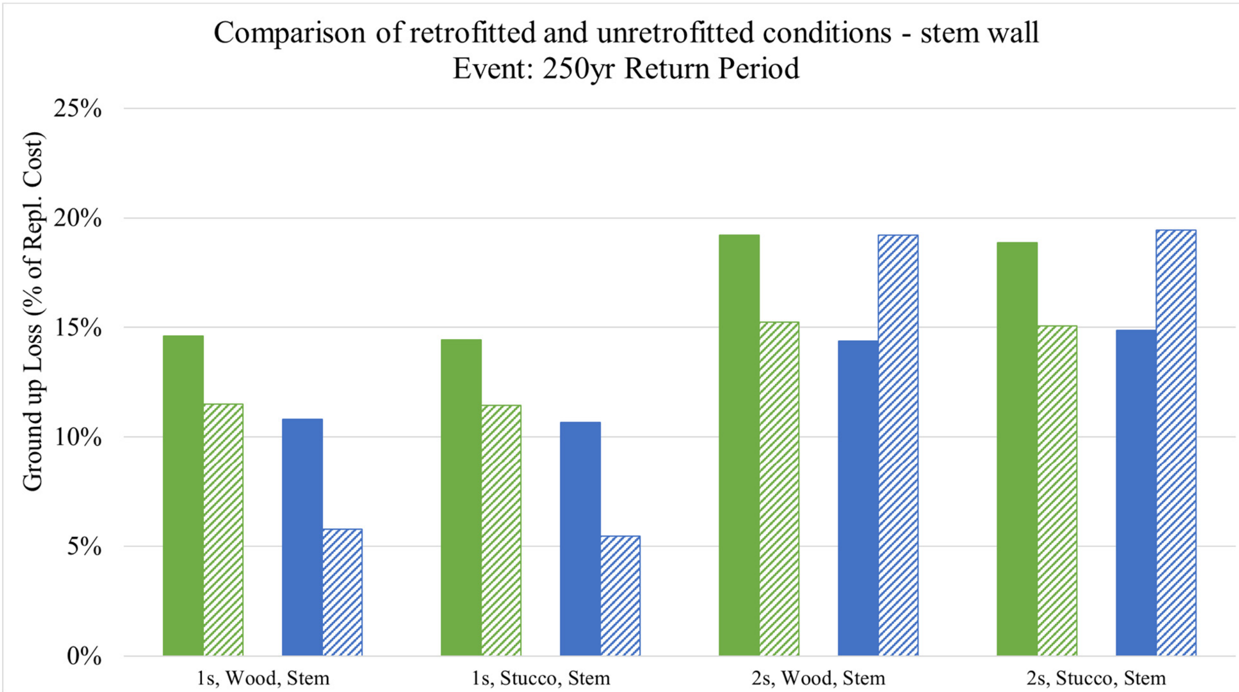


Figure 6.11 **Comparison of unretrofitted and retrofitted conditions: stem wall @ 250-year return period.**

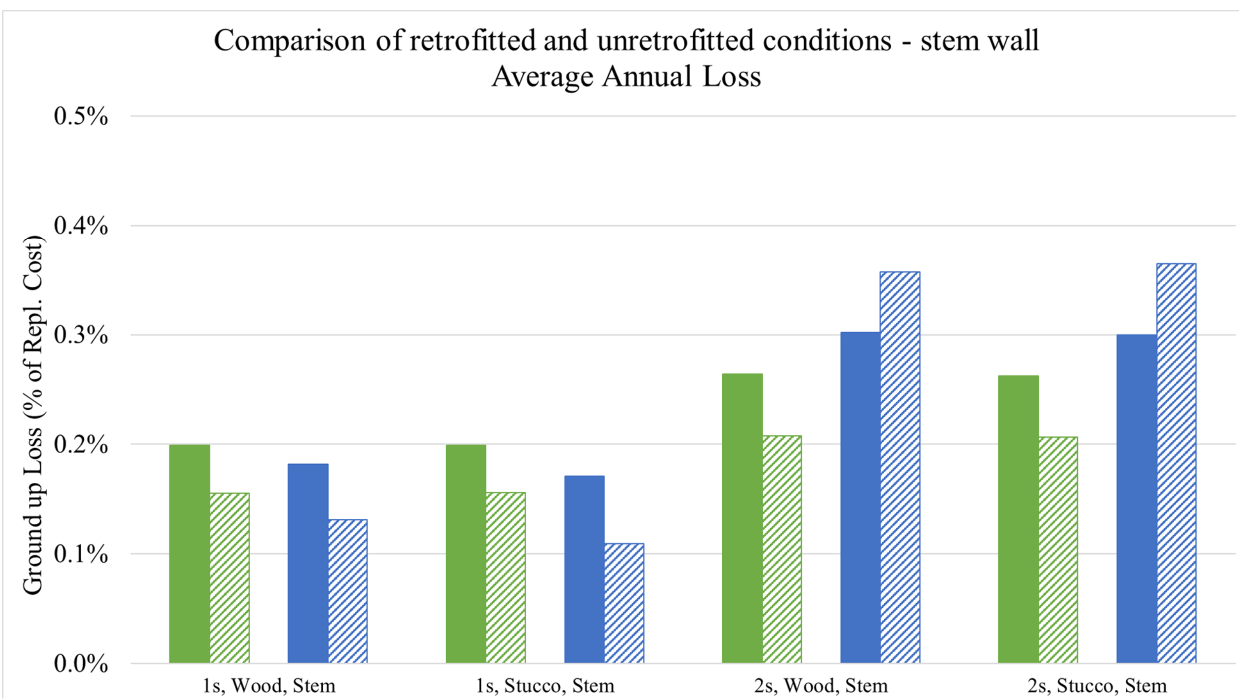


Figure 6.12 **Comparison of unretrofitted and retrofitted conditions: stem wall, average annual loss.**

Legend for Figure 6.13 through Figure 6.60.

(blue)	PEER-CEA Project Results
(gray)	Modelers

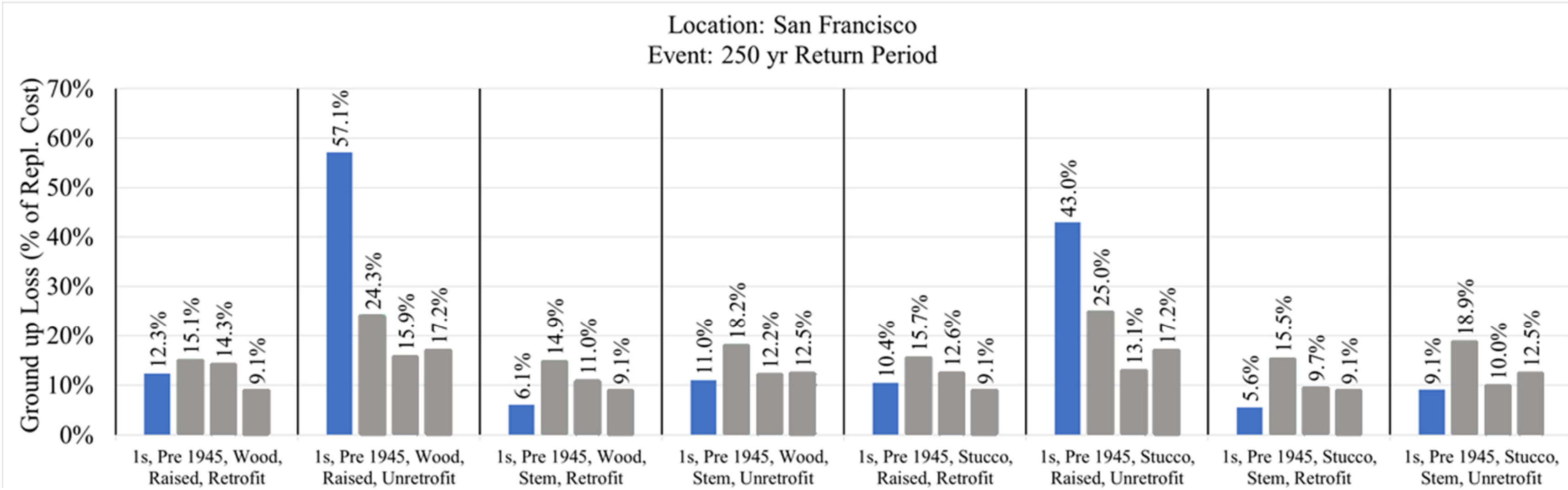


Figure 6.13 San Francisco: loss comparisons by location, one-story home built pre-1945, 250-year return period.

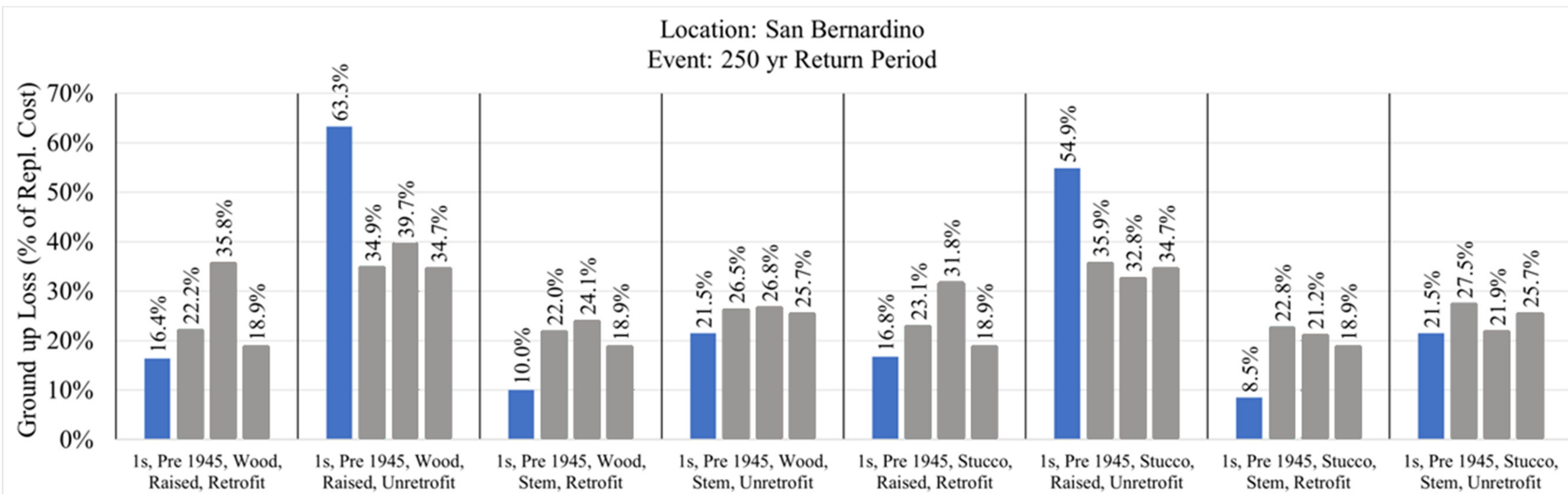


Figure 6.14 San Bernardino: loss comparisons by location, one-story home built pre-1945, 250-year return period.

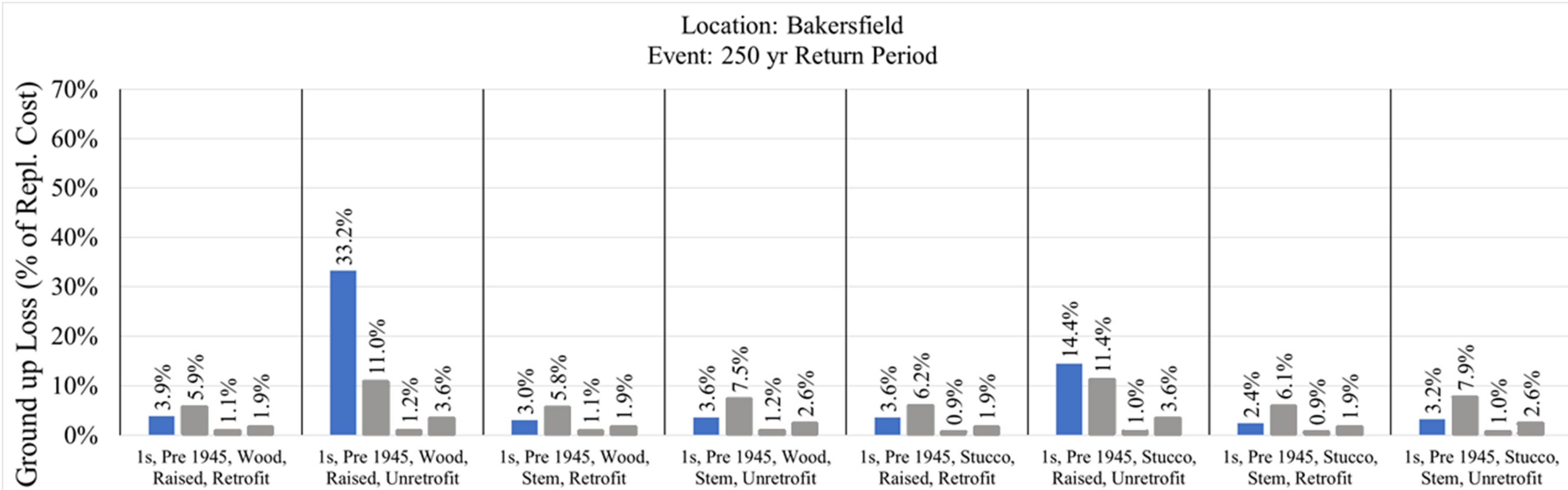
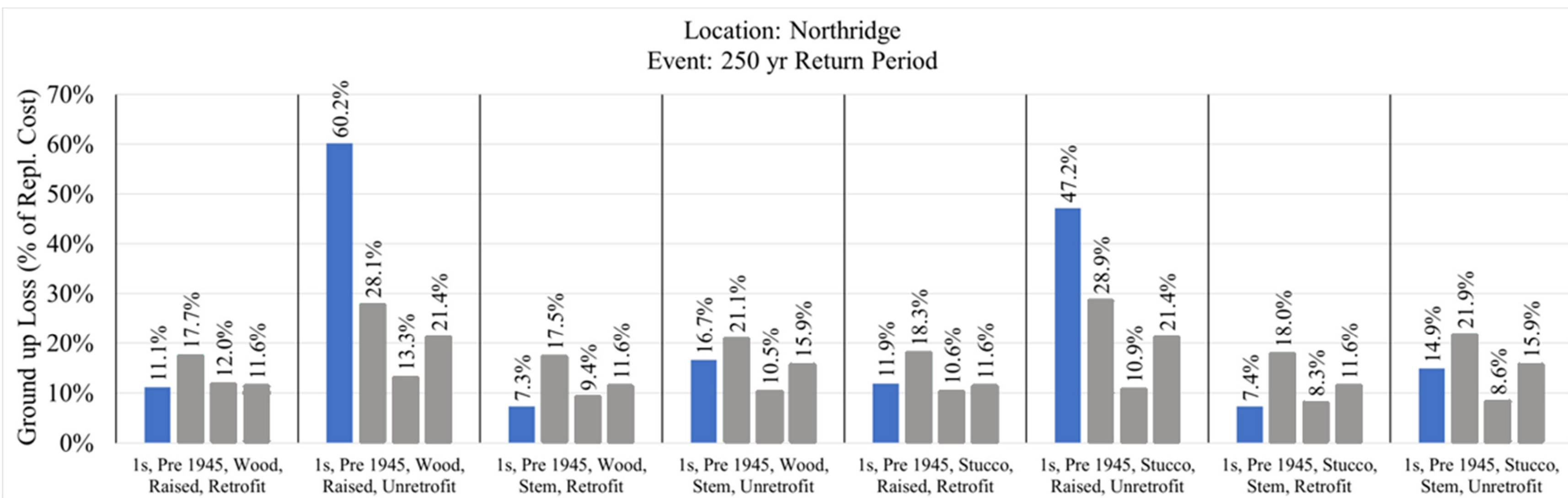


Figure 6.15 Bakersfield: loss comparisons by location, one-story home built pre-1945, 250-year return period.



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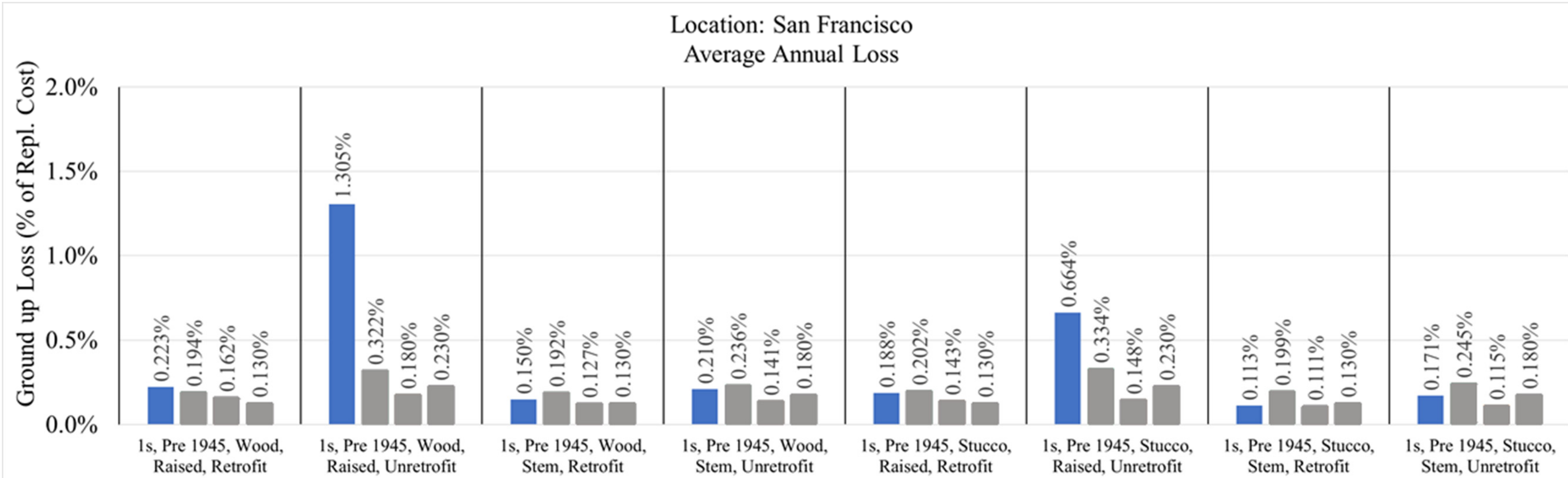

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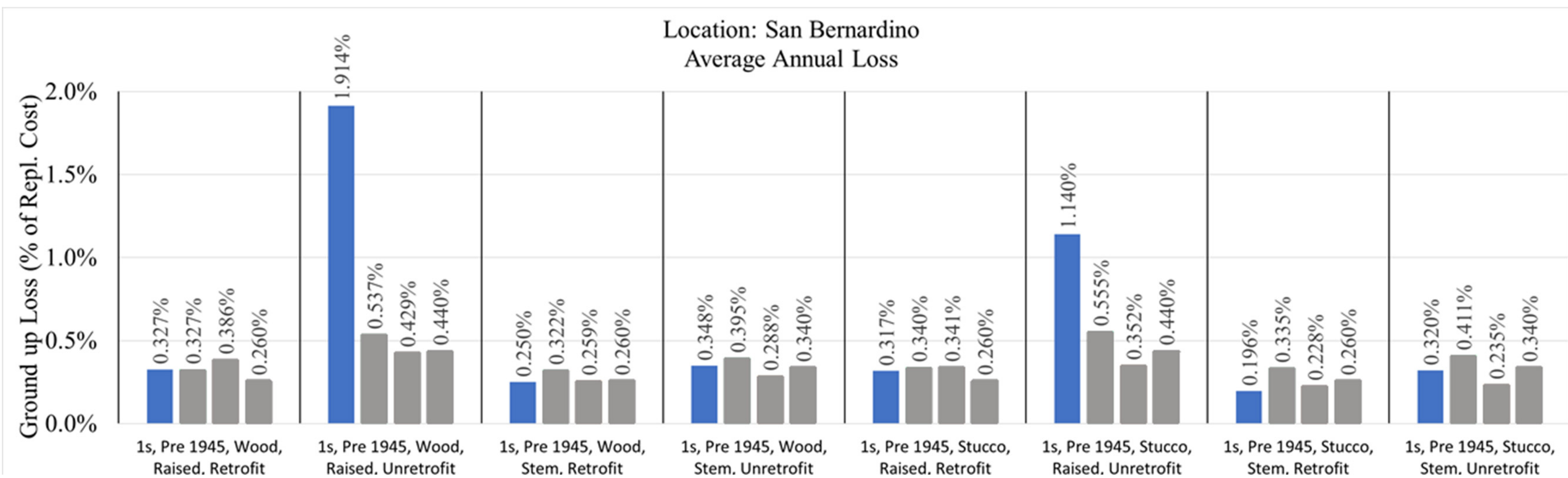

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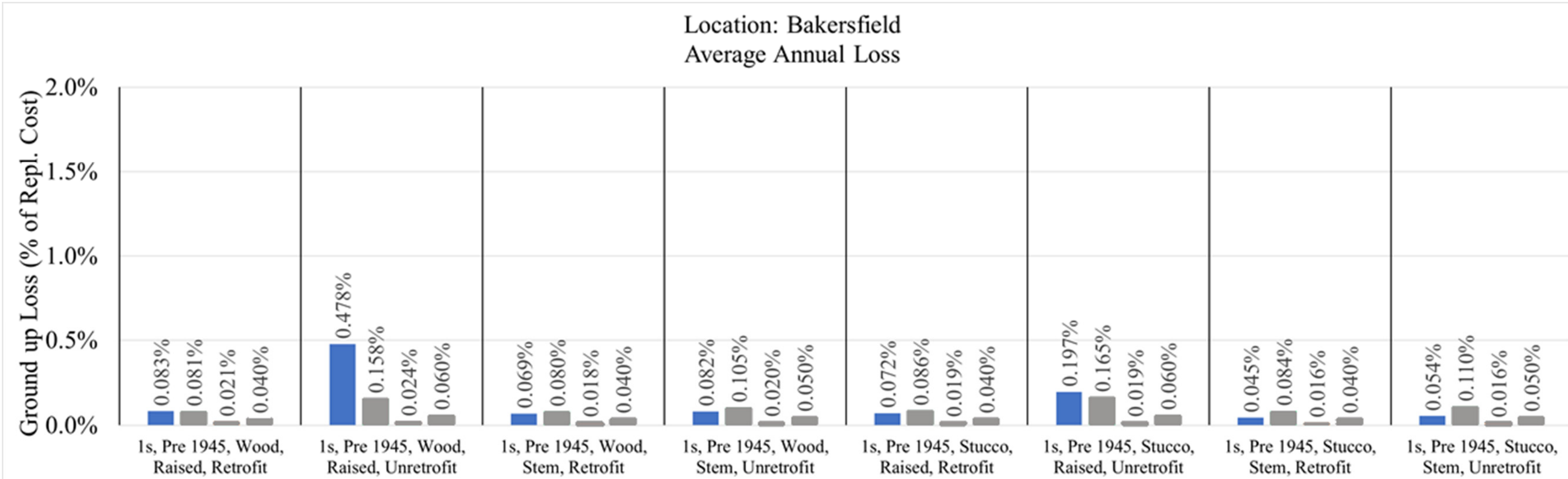

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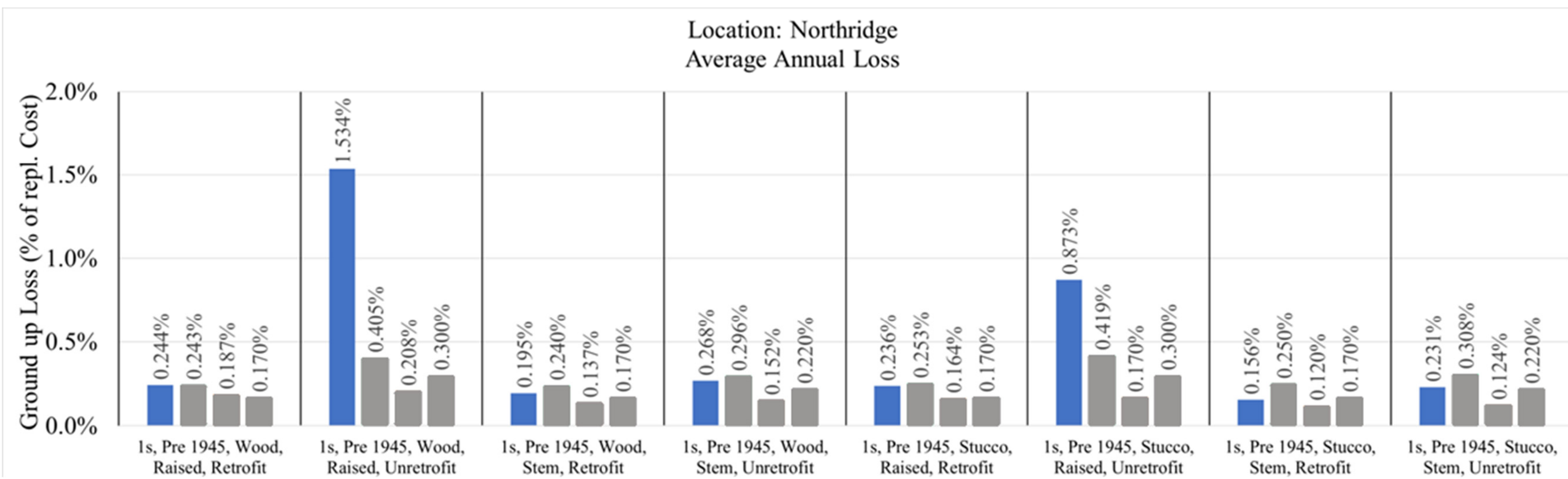

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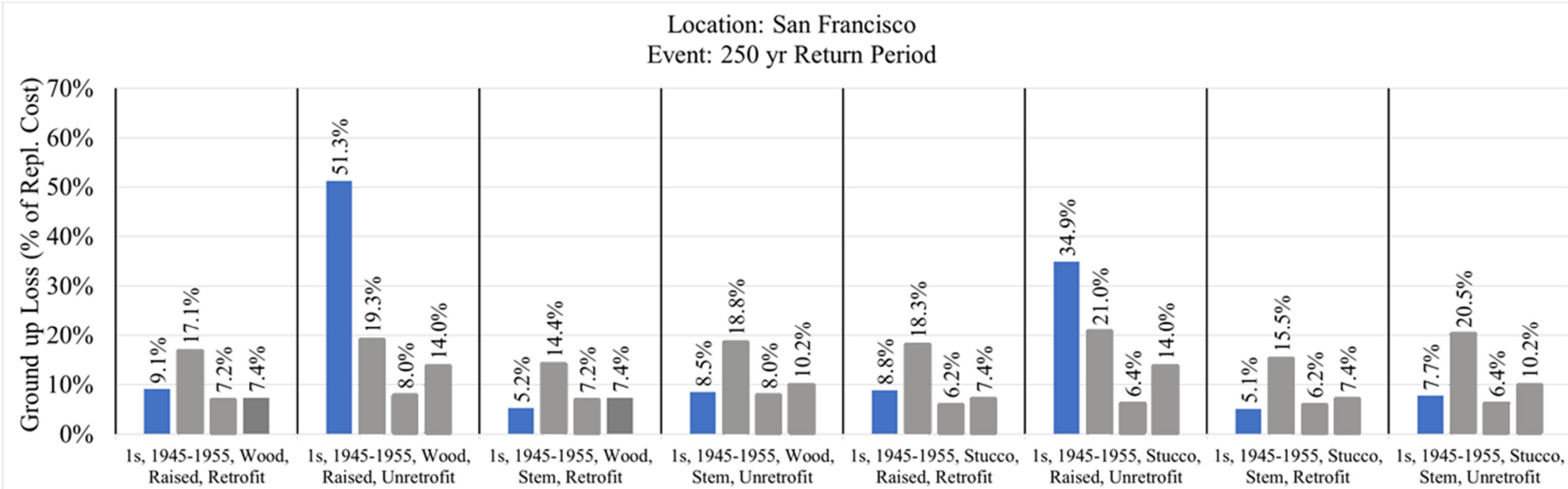
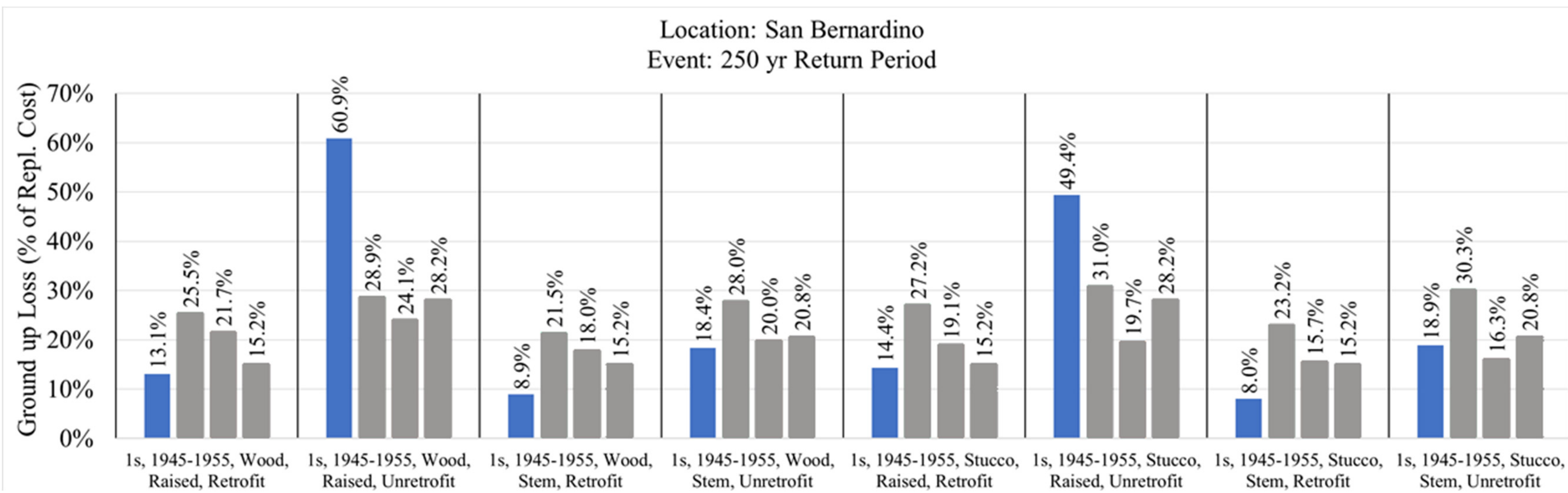


Figure 6.21 San Francisco: loss comparisons by location, one-story home built between 1945–1955, 250-year return period.



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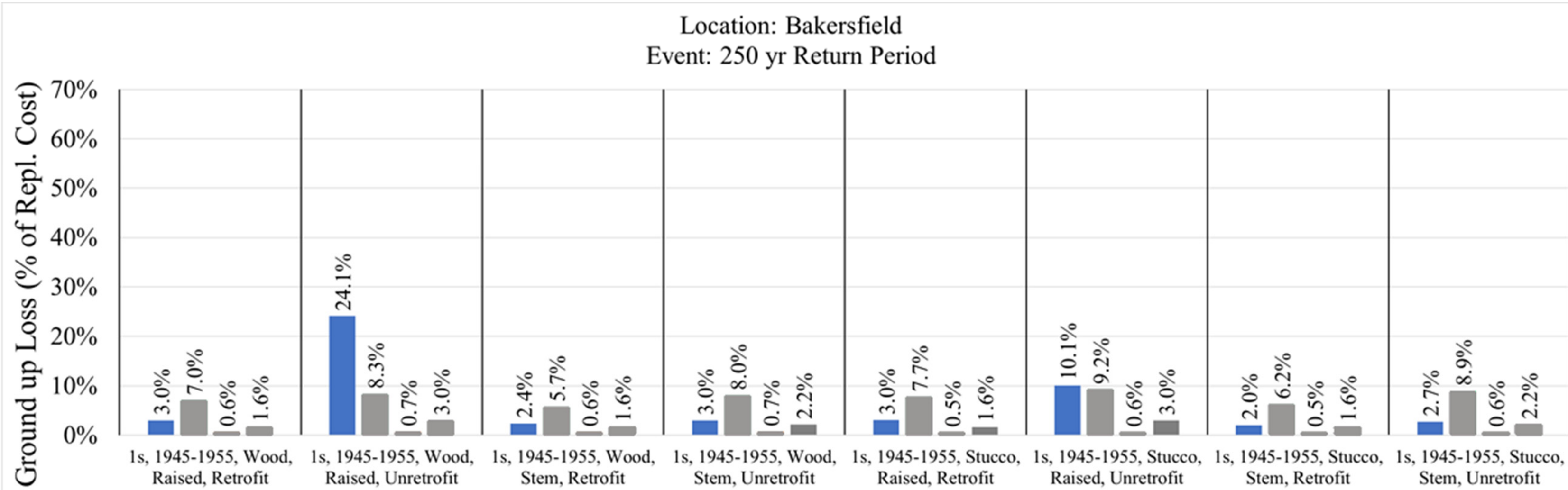

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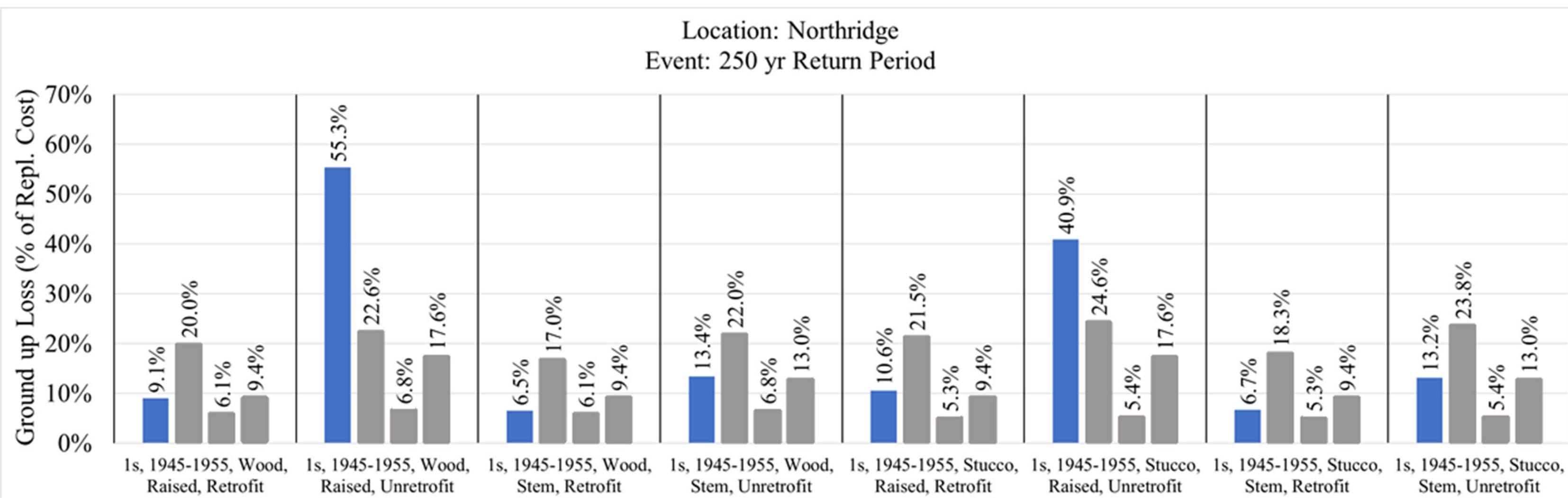

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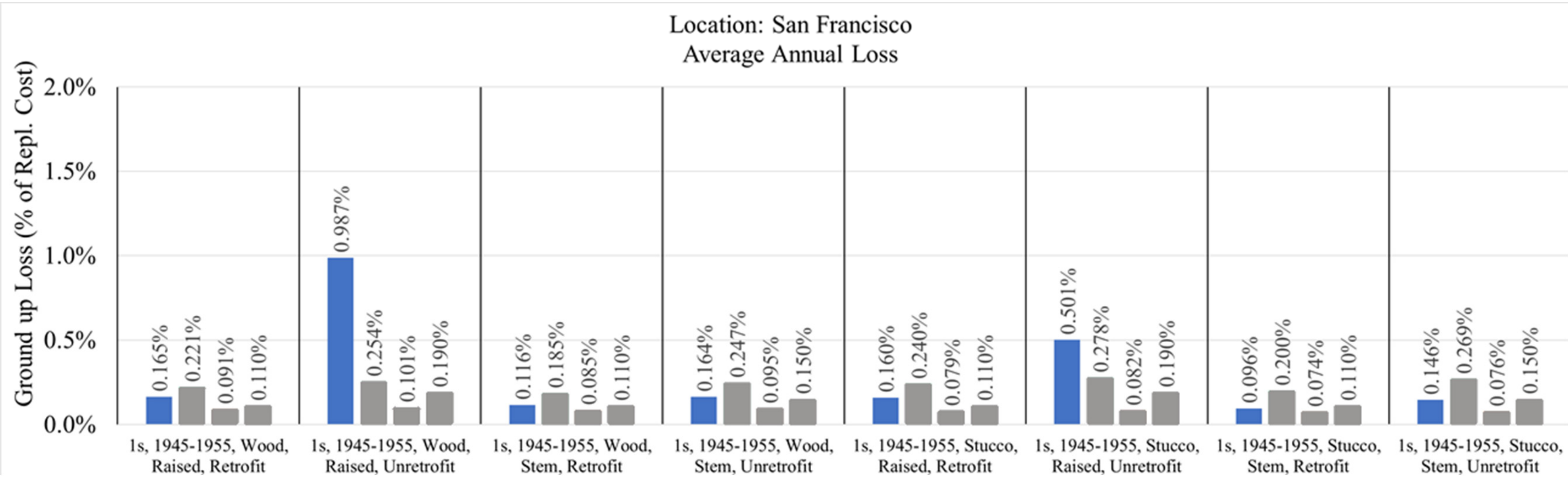

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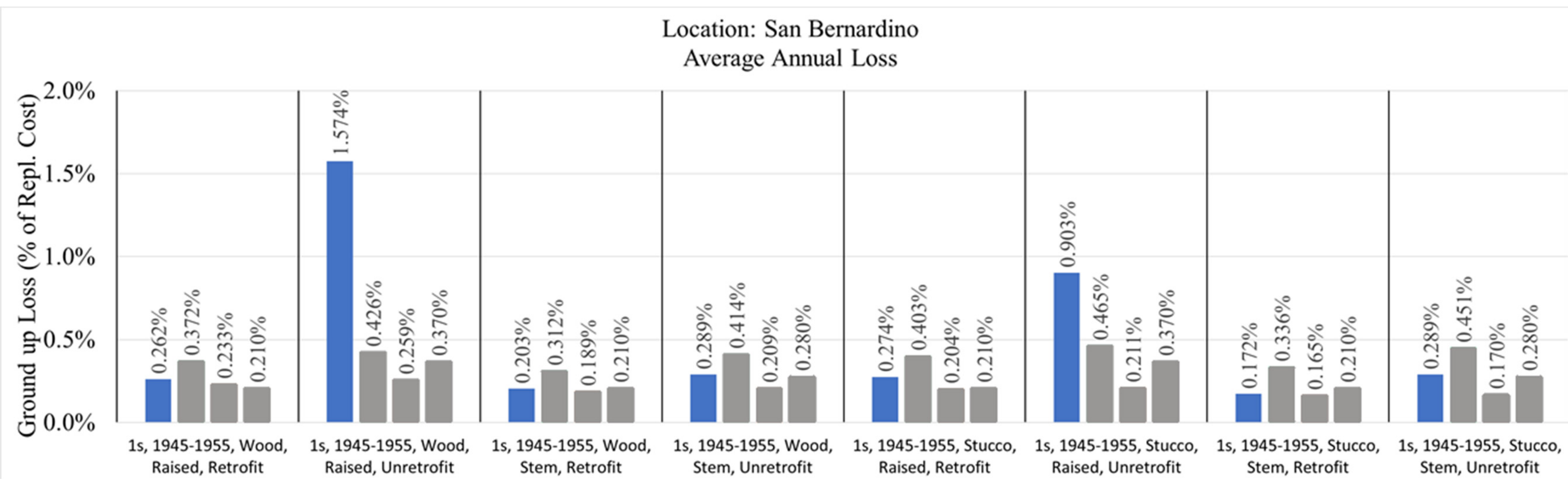

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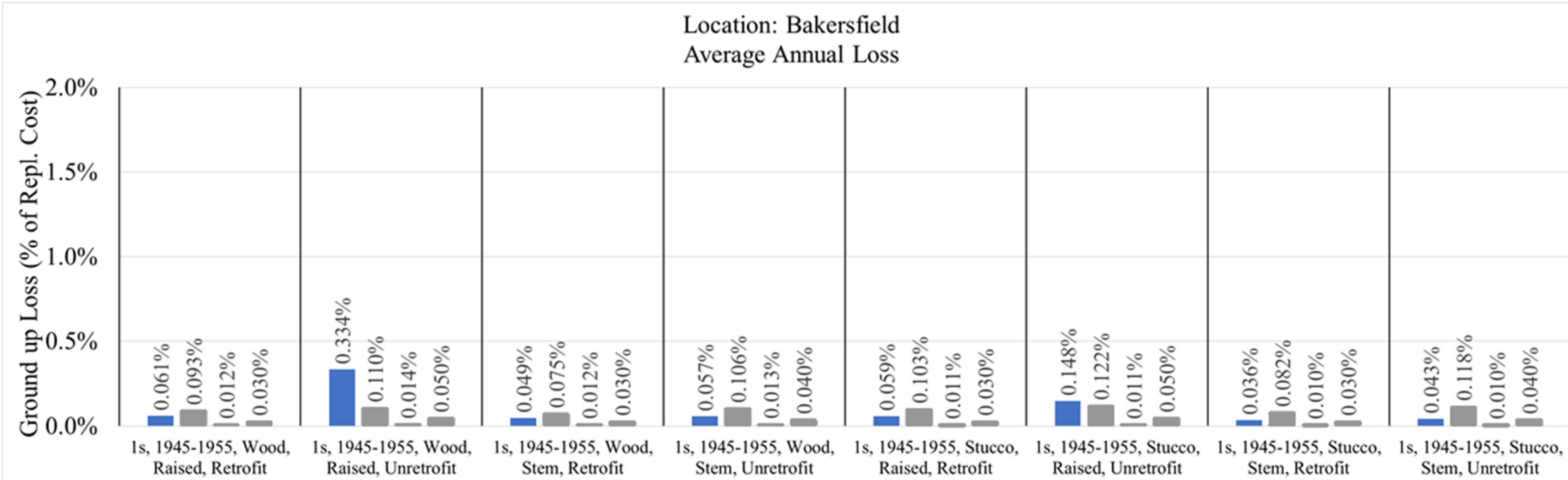

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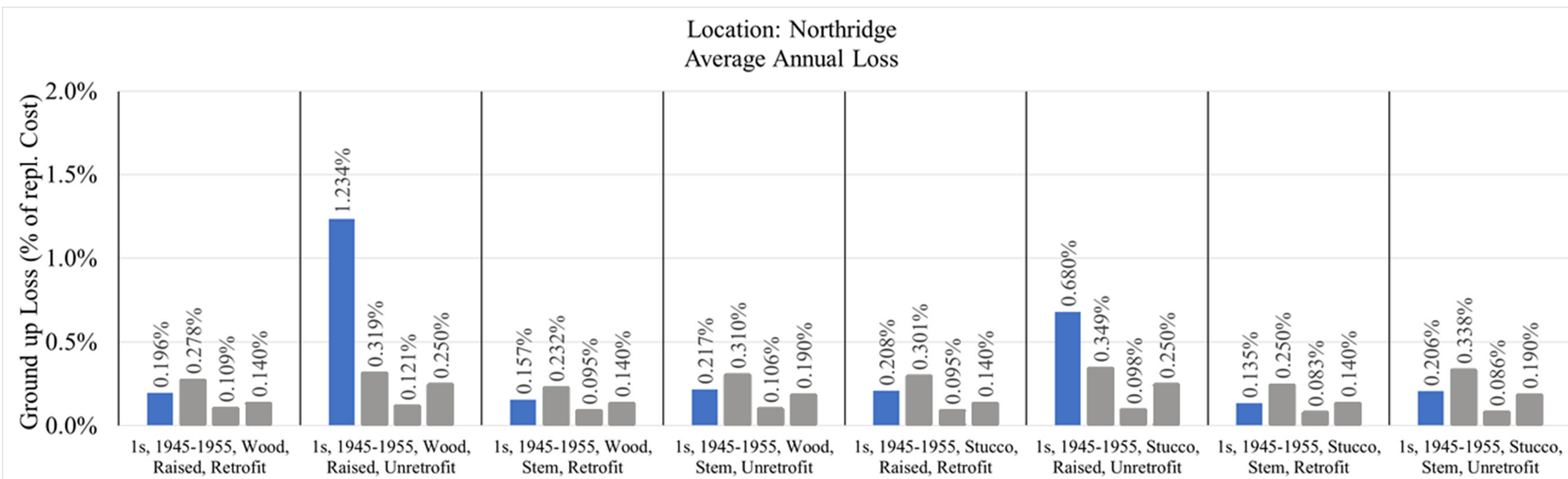

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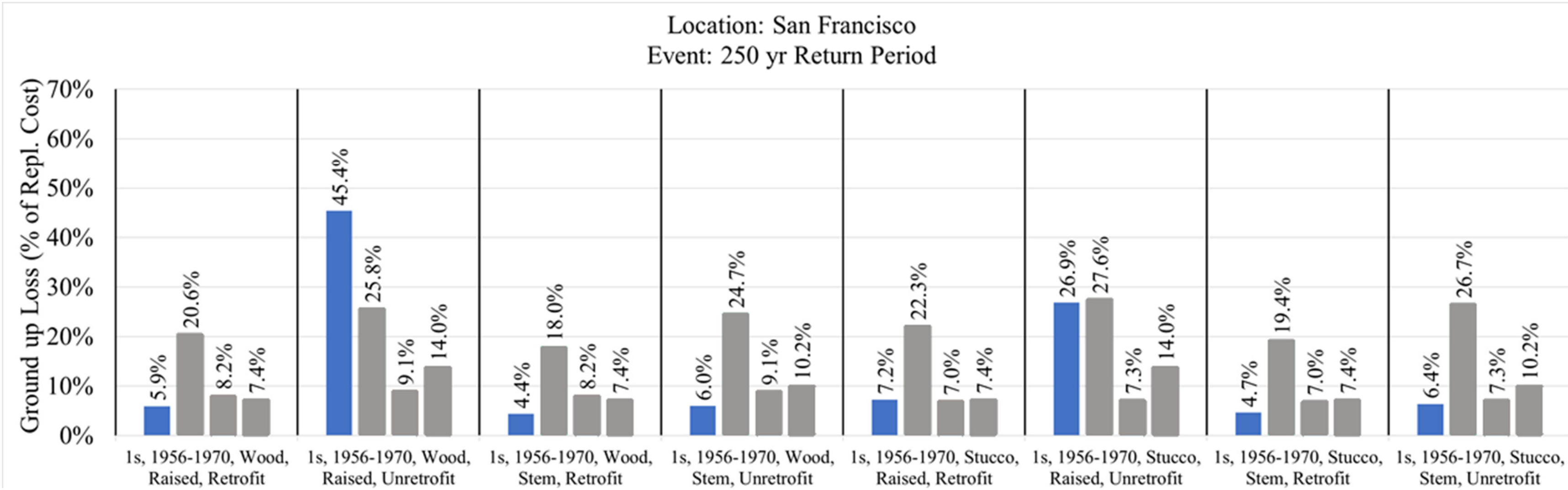


Figure 6.29 **San Francisco: loss comparisons by location, one-story home built between 1956–1970, 250-year return period.**

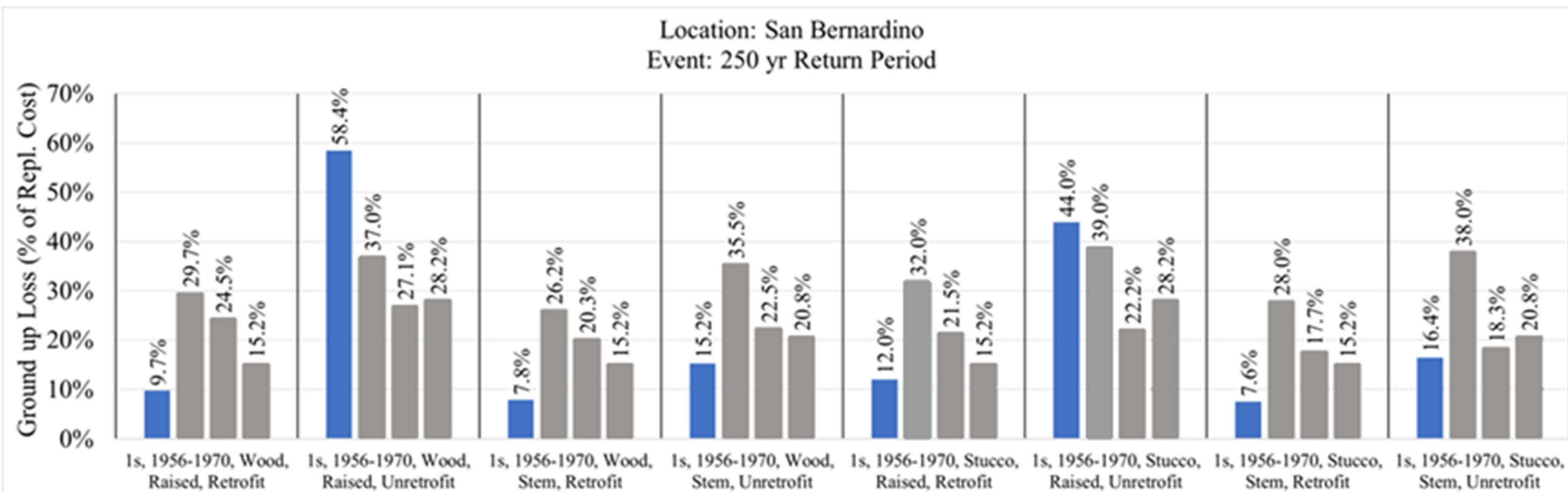
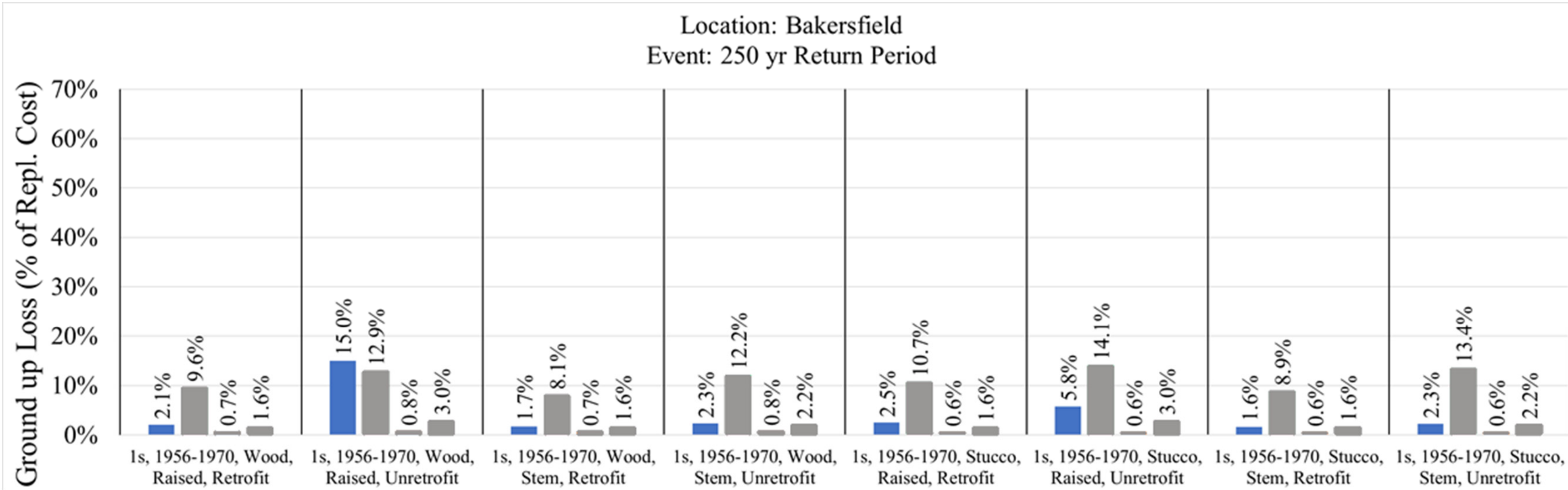


Figure 6.30 **San Bernardino: loss comparisons by location, one-story home built between 1956–1970, 250-year return period.**



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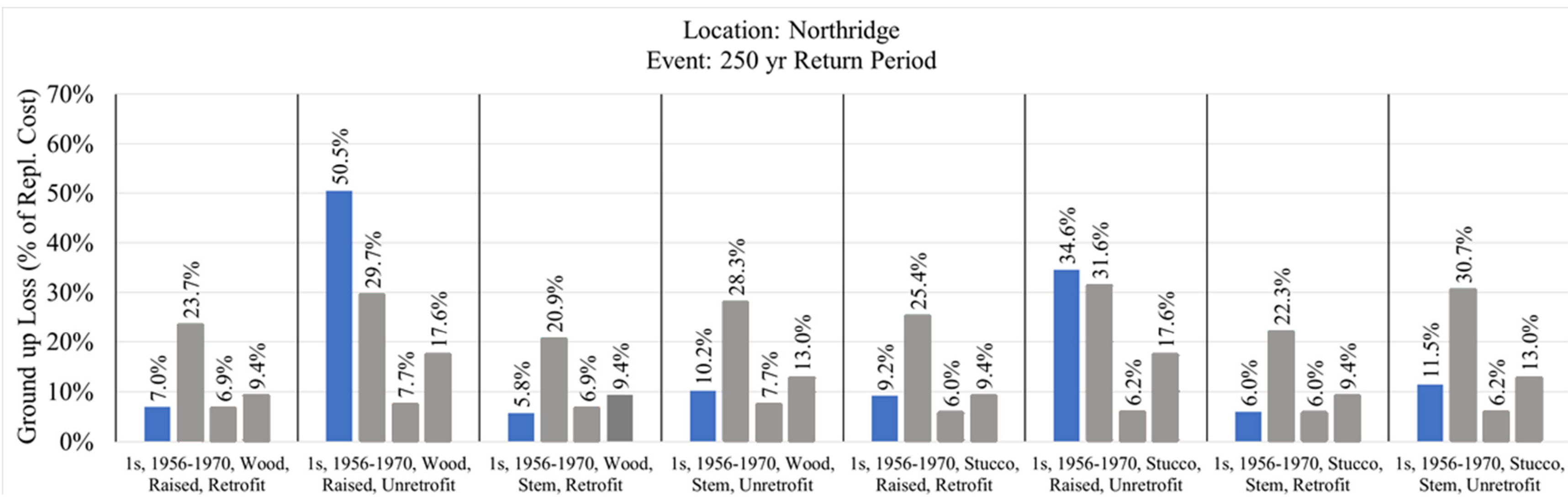


Figure 6.32 Northridge: loss comparisons by location, one-story home built between 1956–1970, 250-year return period.

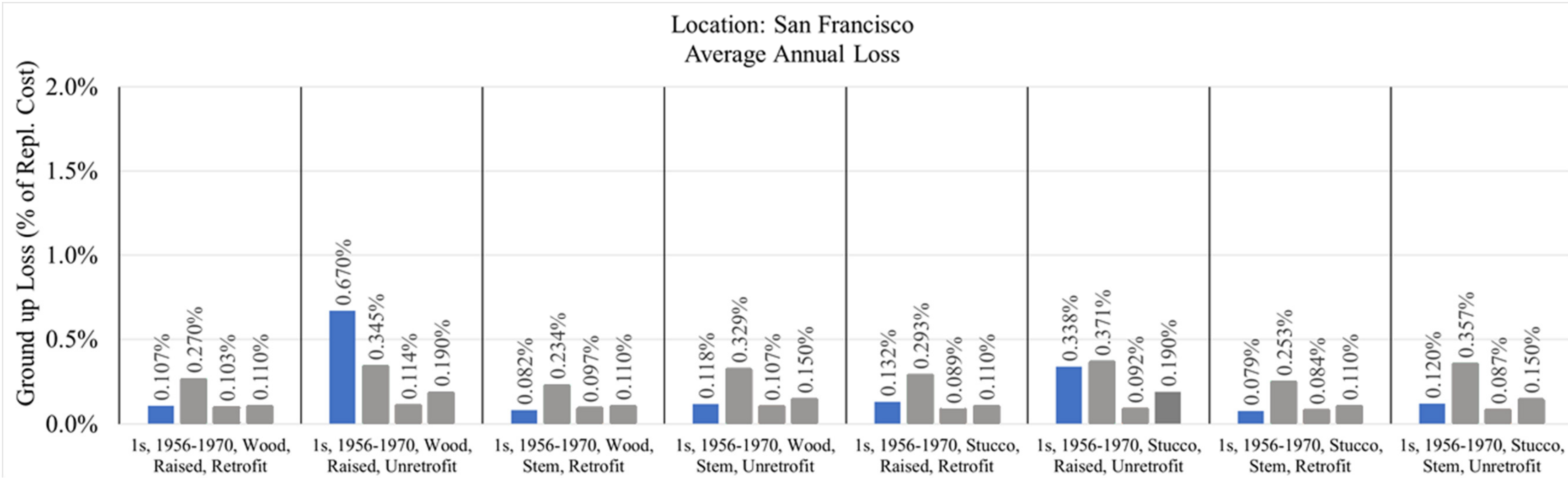


Figure 6.33 San Francisco: loss comparisons by location, one-story home built between 1956–1970, average annual loss.

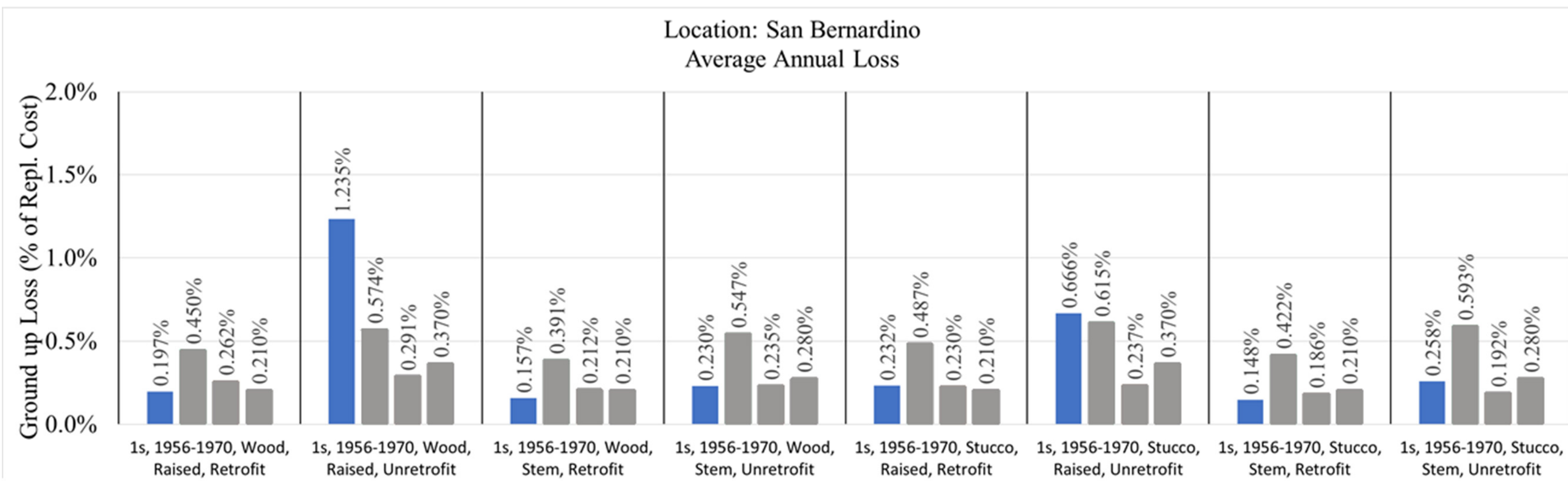
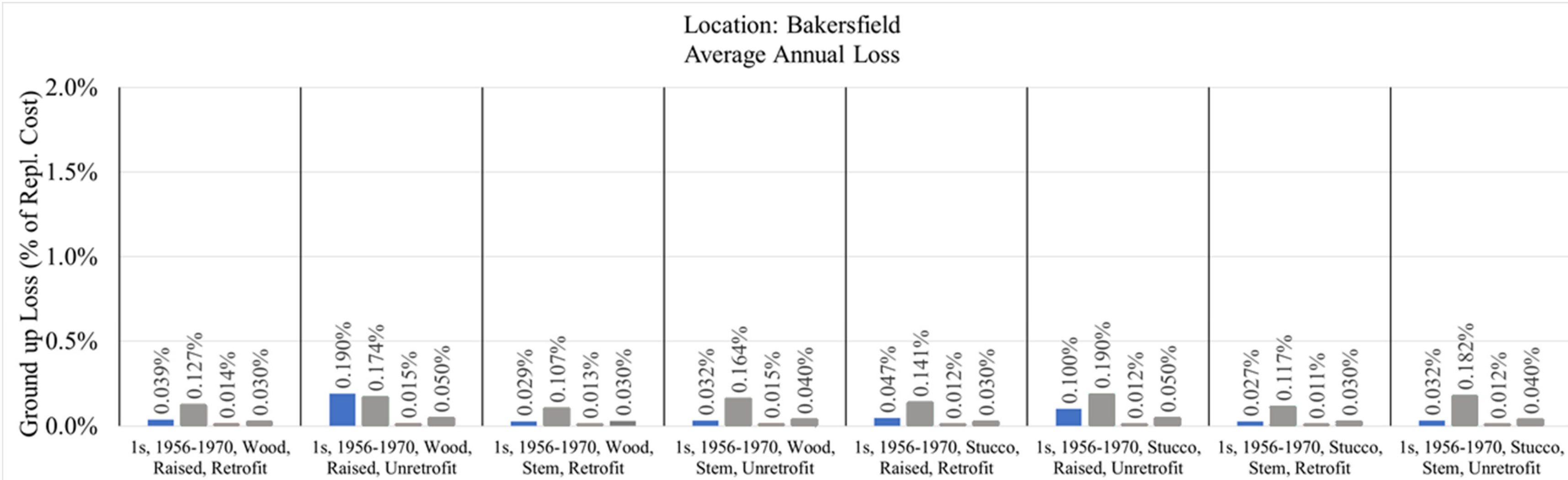


Figure 6.34 San Bernardino: loss comparisons by location, one-story home built between 1956–1970, average annual loss.



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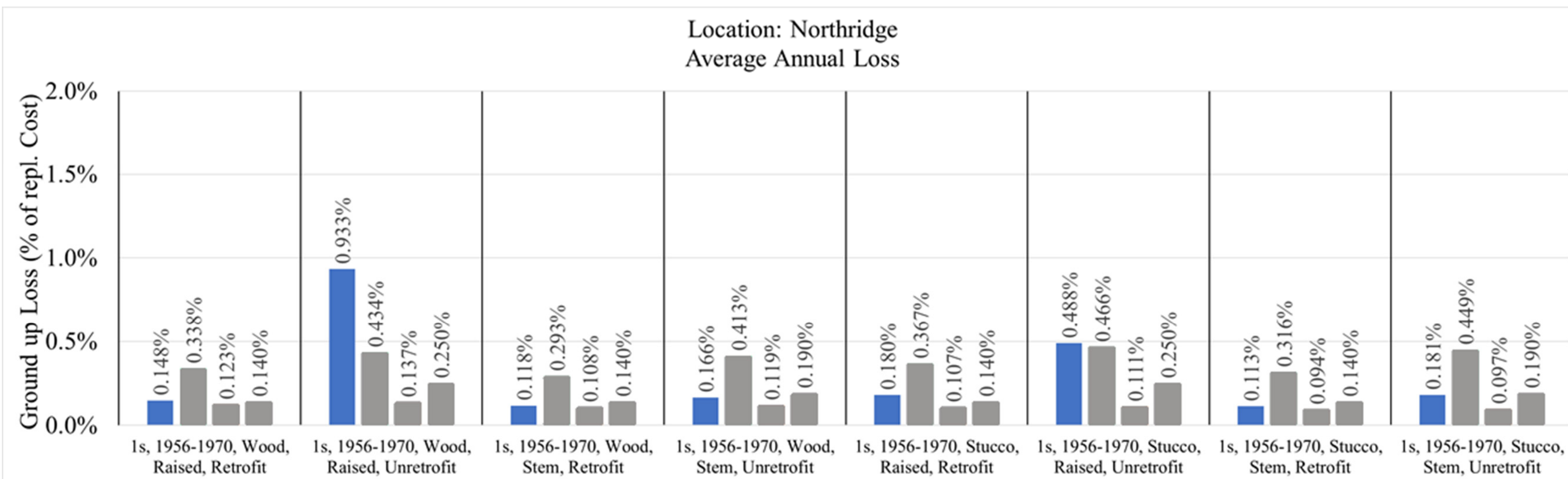


Figure 6.36 Northridge: loss comparisons by location, one-story home built between 1956–1970, average annual loss.

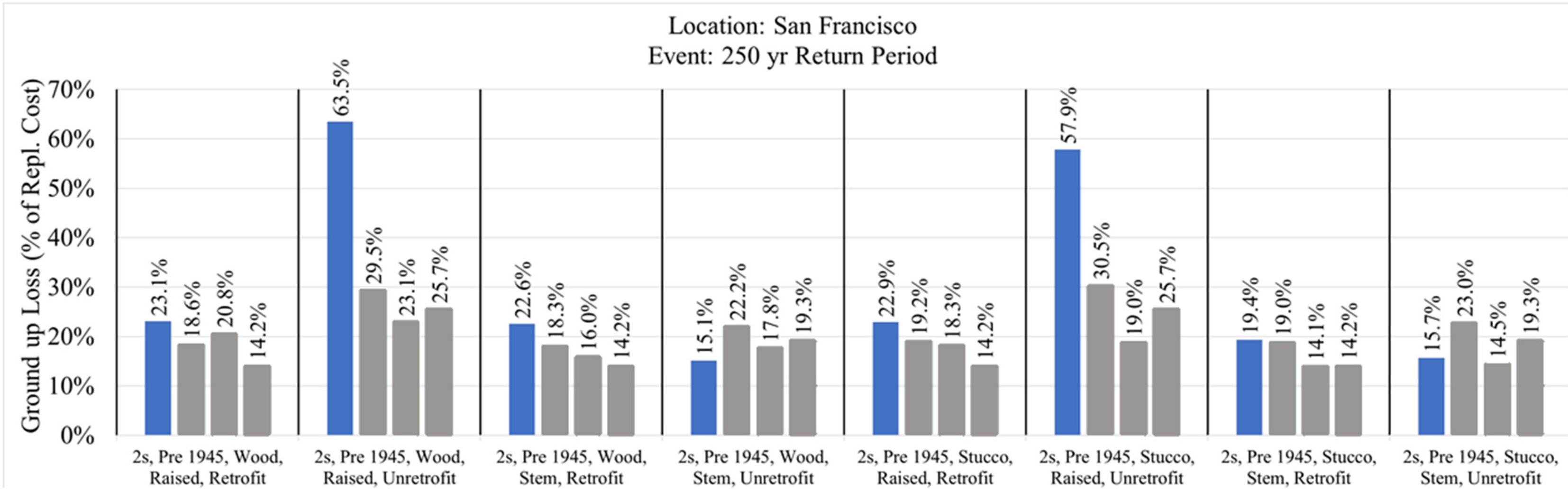


Figure 6.37 San Francisco: loss comparisons by location, two-story home built pre-1945, 250-year return period.

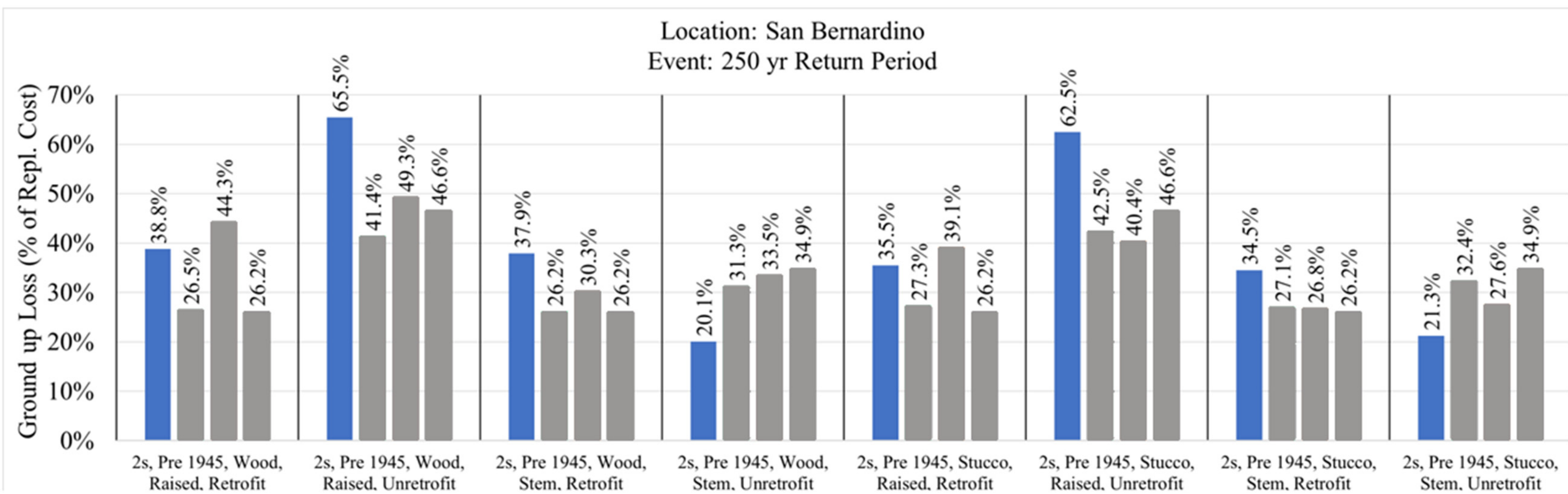
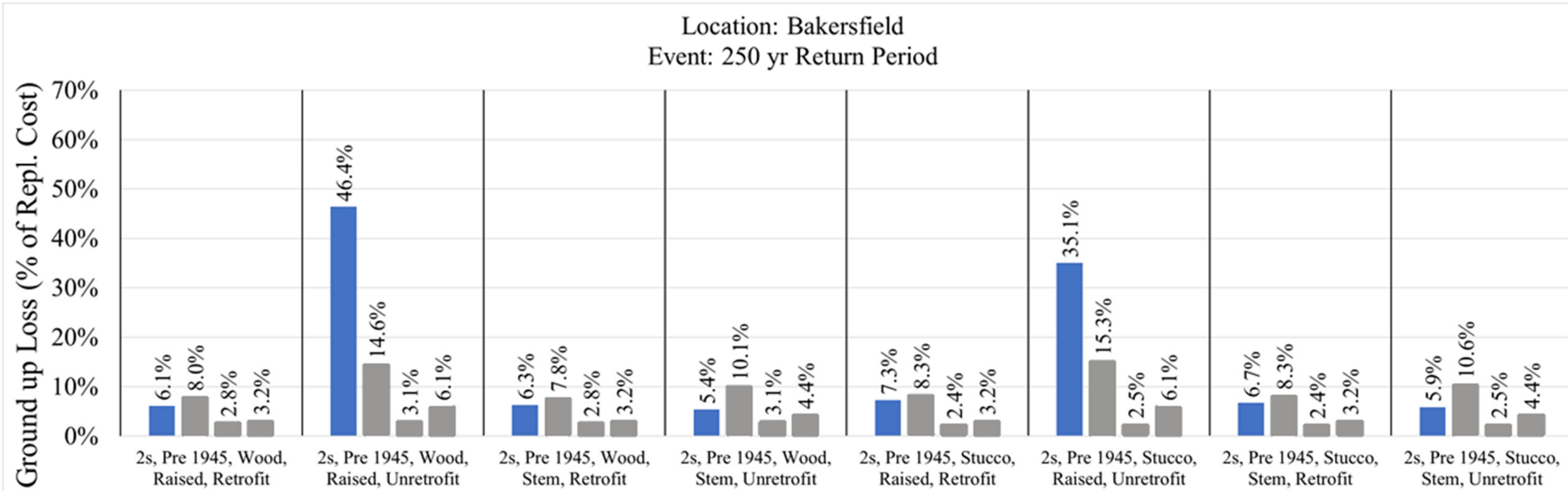


Figure 6.38 San Bernardino: loss comparisons by location, two-story home built pre-1945, 250-year return period.



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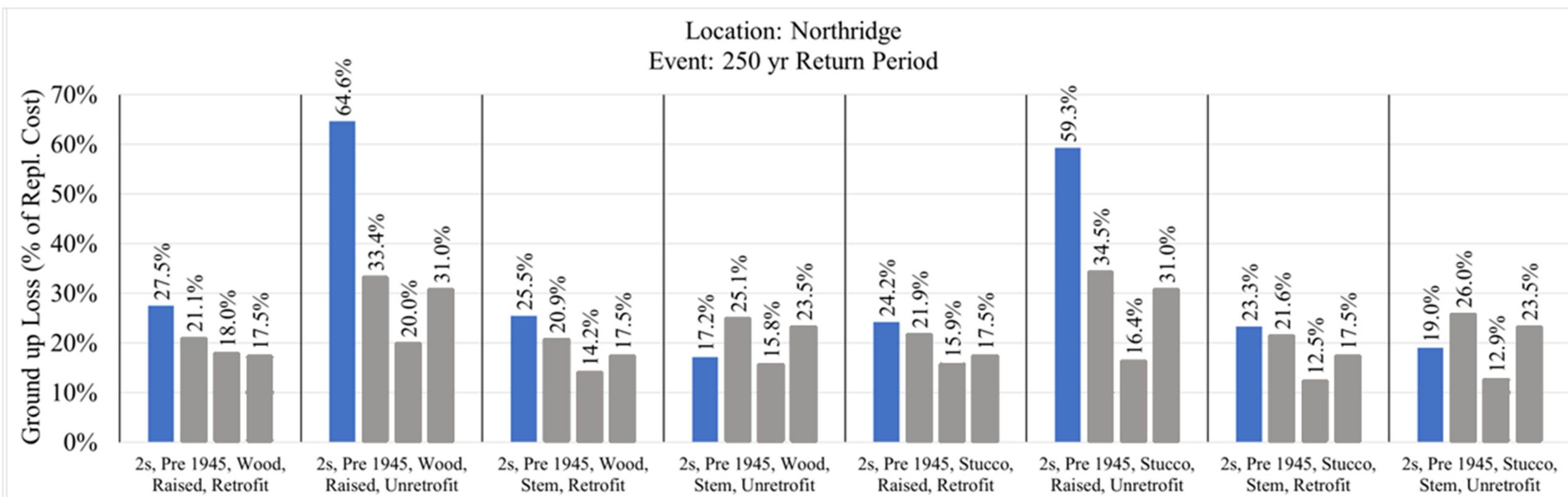


Figure 6.40 Northridge: loss comparisons by location, two-story home built pre-1945, 250-year return period.

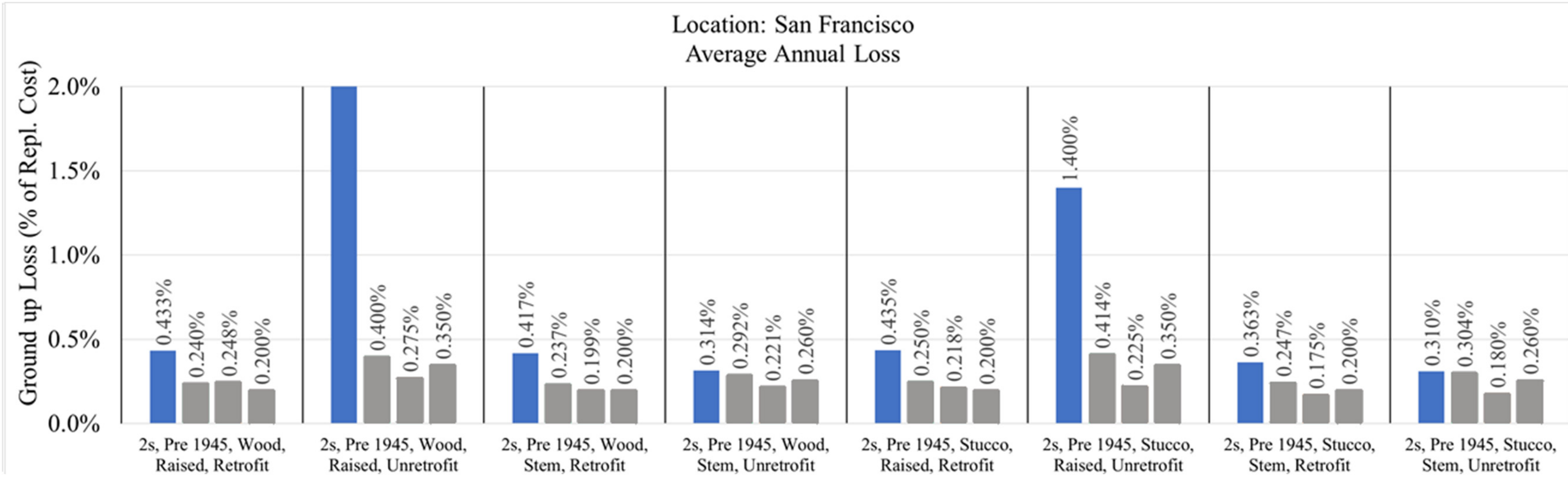


Figure 6.41 San Francisco: loss comparisons by location, two-story home built pre-1945, average annual loss.

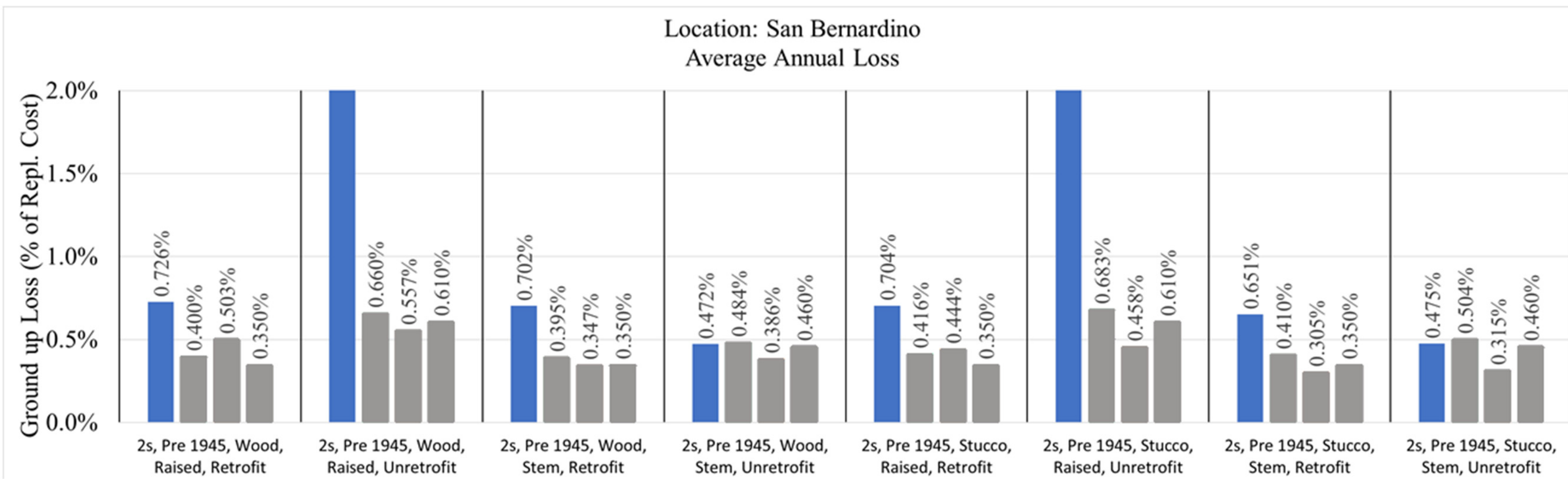


Figure 6.42 San Bernardino: loss comparisons by location, two-story home built pre-1945, average annual loss.

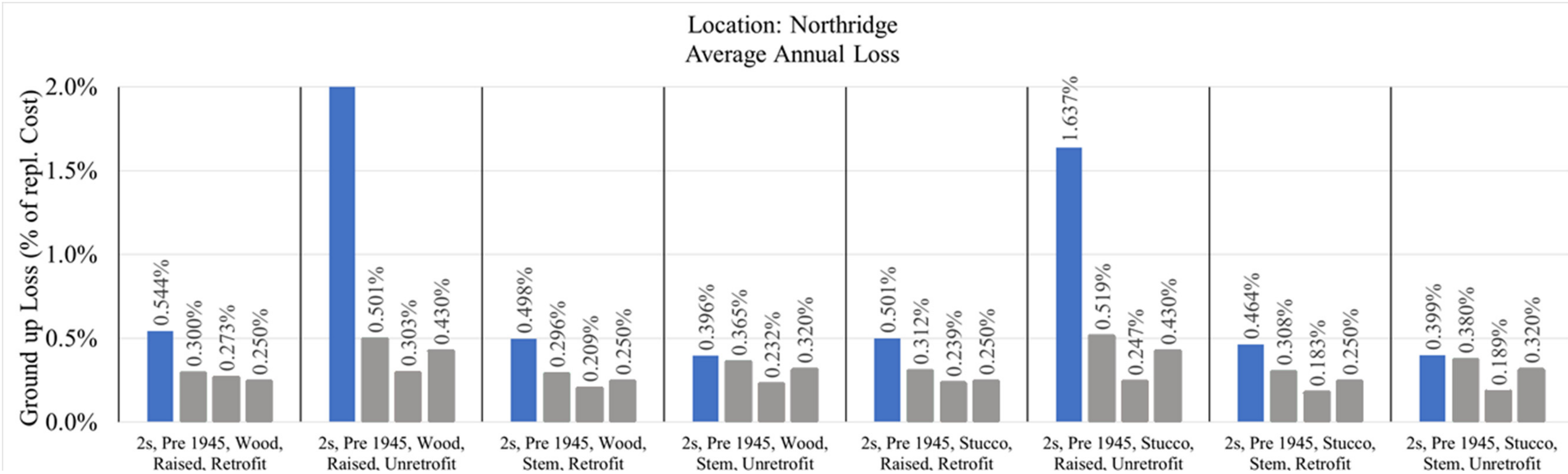


Figure 6.43 Bakersfield: loss comparisons by location, two-story home built pre-1945, average annual loss.

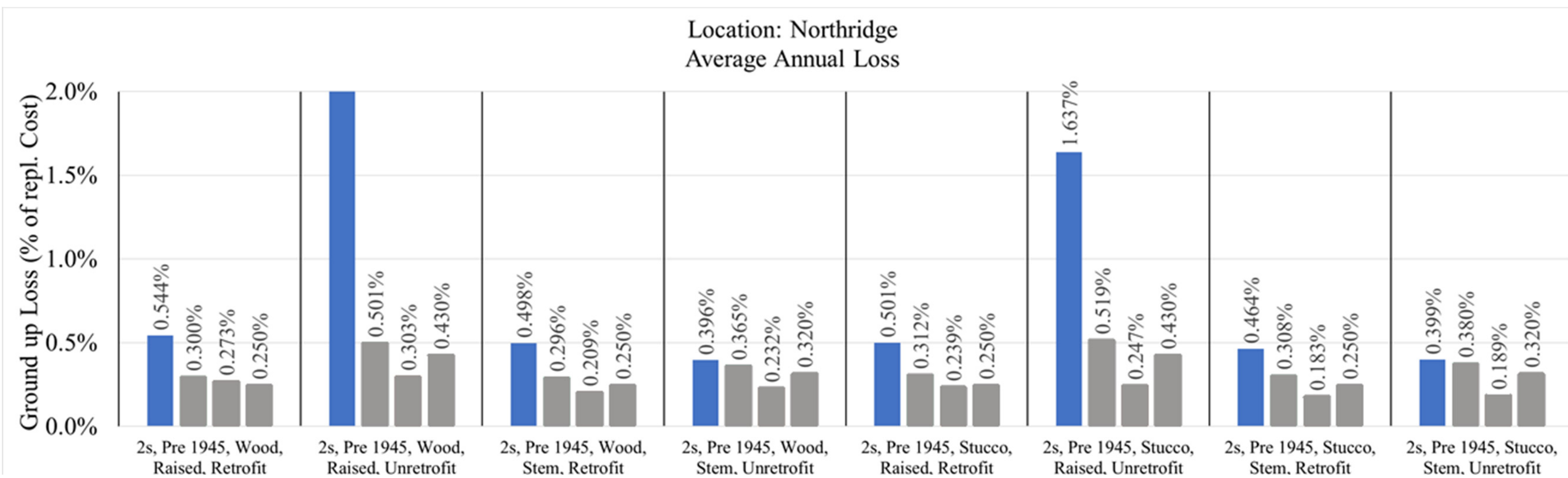


Figure 6.44 Northridge: loss comparisons by location, two-story home built pre-1945, average annual loss.

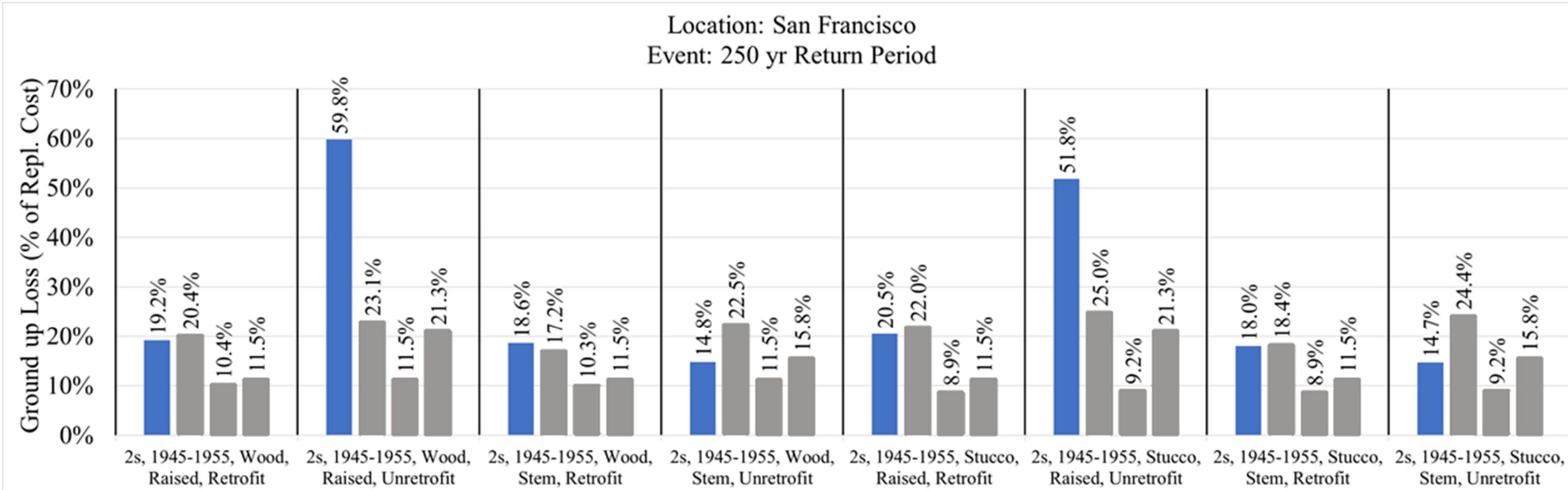


Figure 6.45 San Francisco: loss comparisons by location, two-story home built between 1945–1955, 250-year return period.

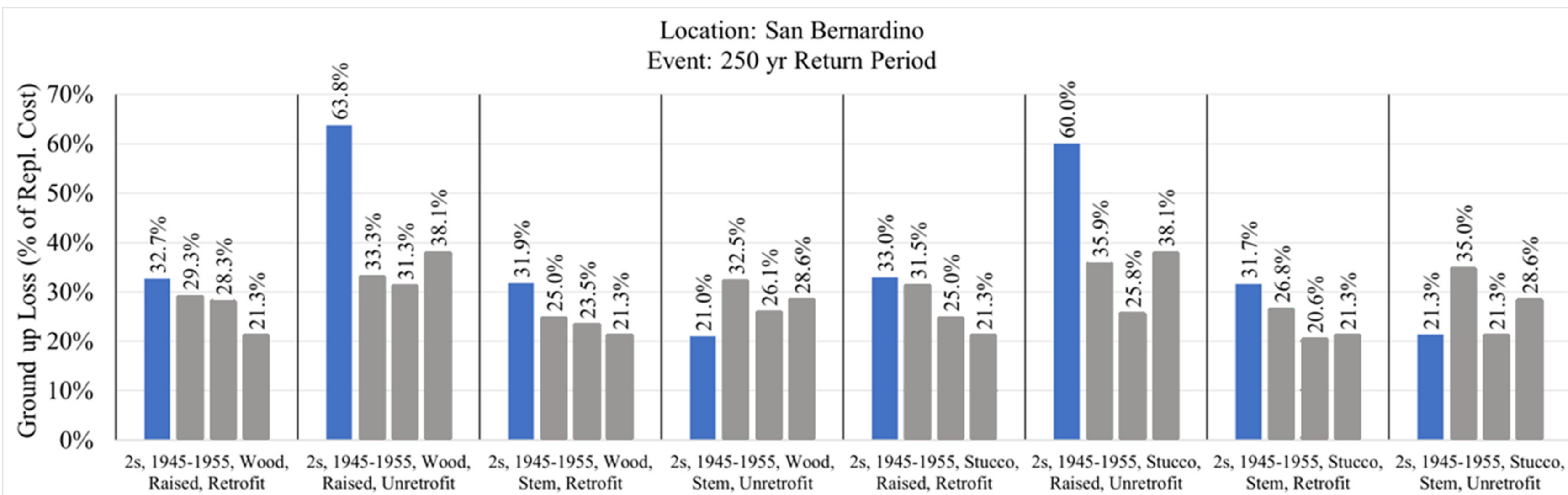


Figure 6.46 San Bernardino: loss comparisons by location, two-story home built between 1945–1955, 250-year return period.

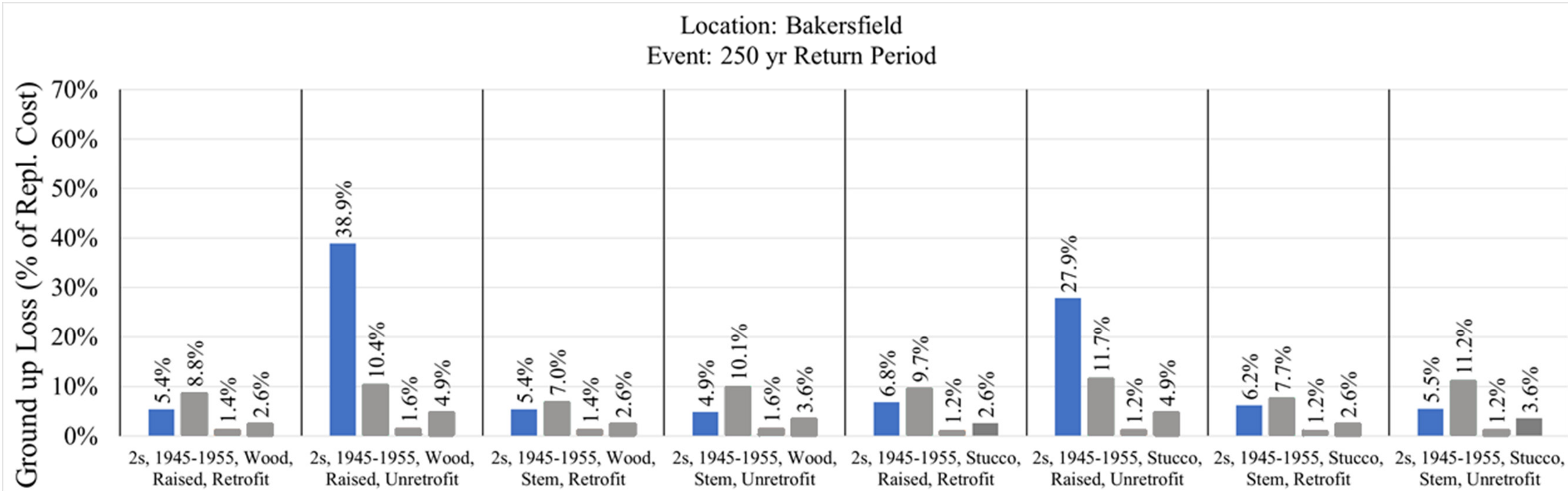


Figure 6.47 Bakersfield: loss comparisons by location, two-story home built between 1945–1955, 250-year return period.

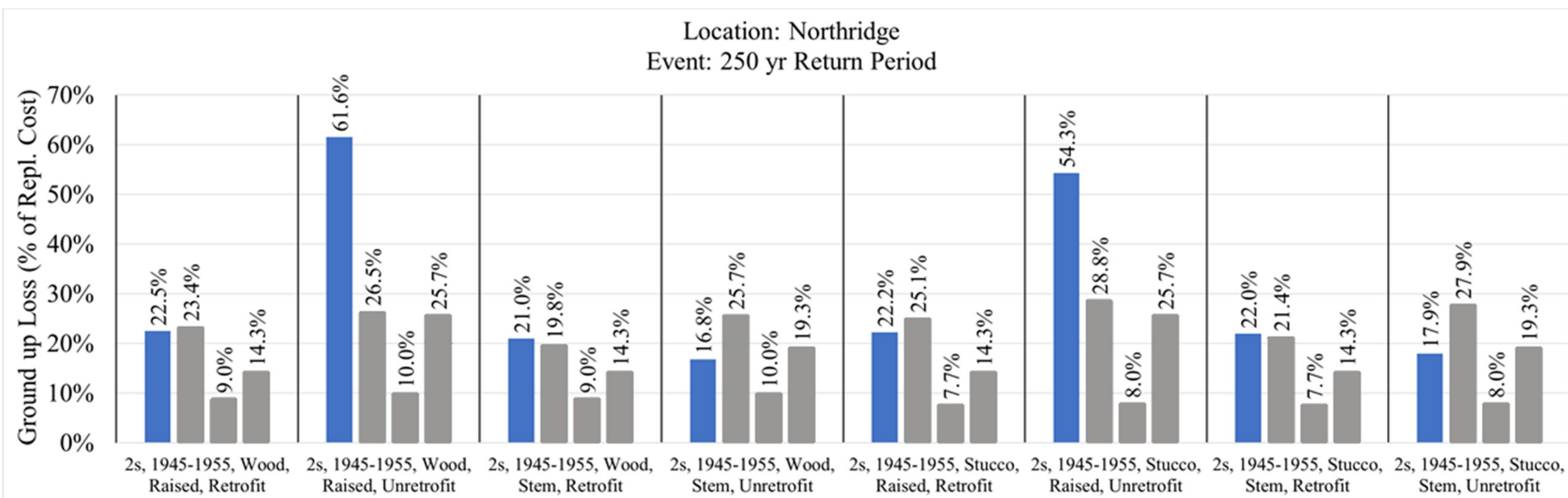


Figure 6.48 Northridge: loss comparisons by location, two-story home built between 1945–1955, 250-year return period.

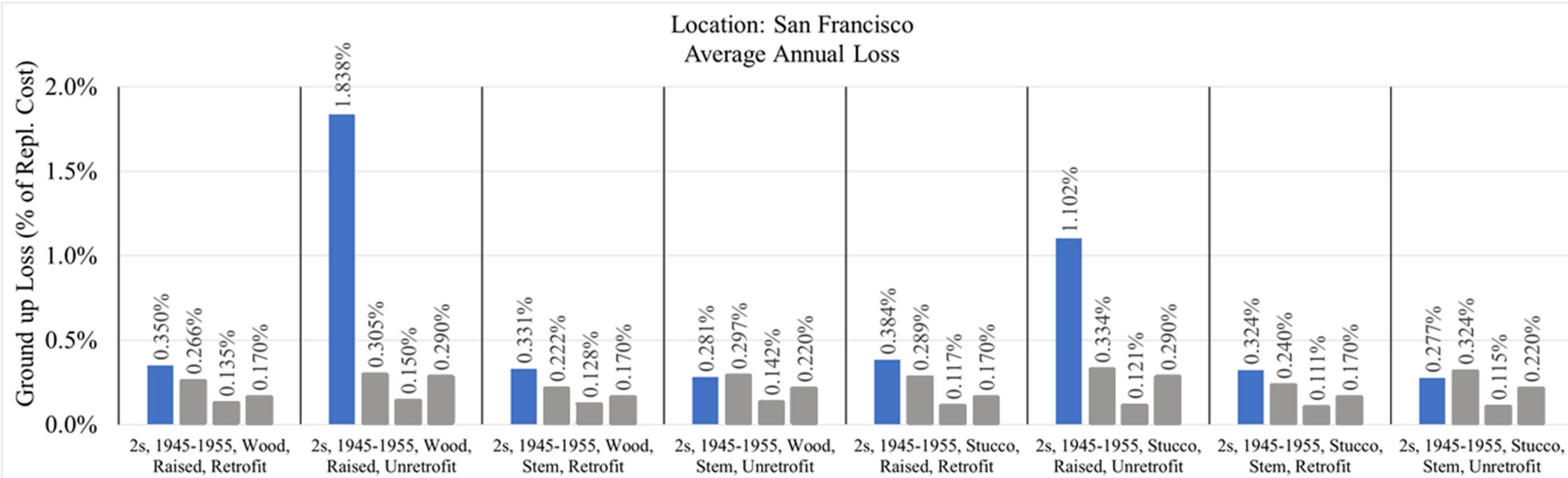


Figure 6.49 San Francisco: loss comparisons by location, two-story home built between 1945–1955, average annual loss.

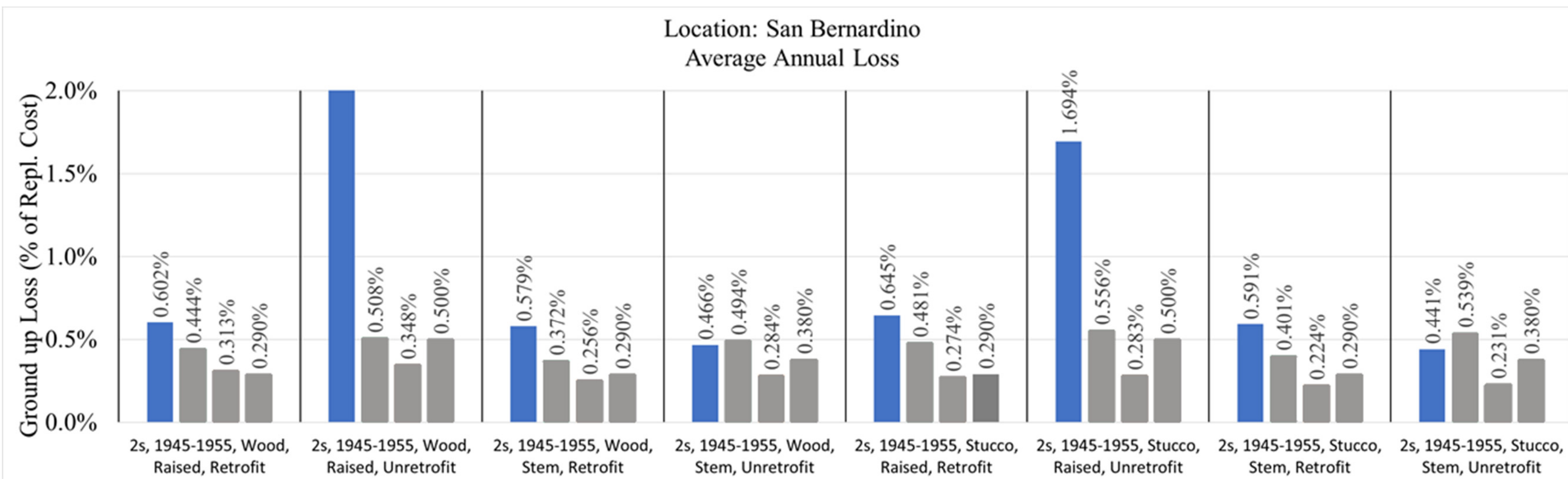
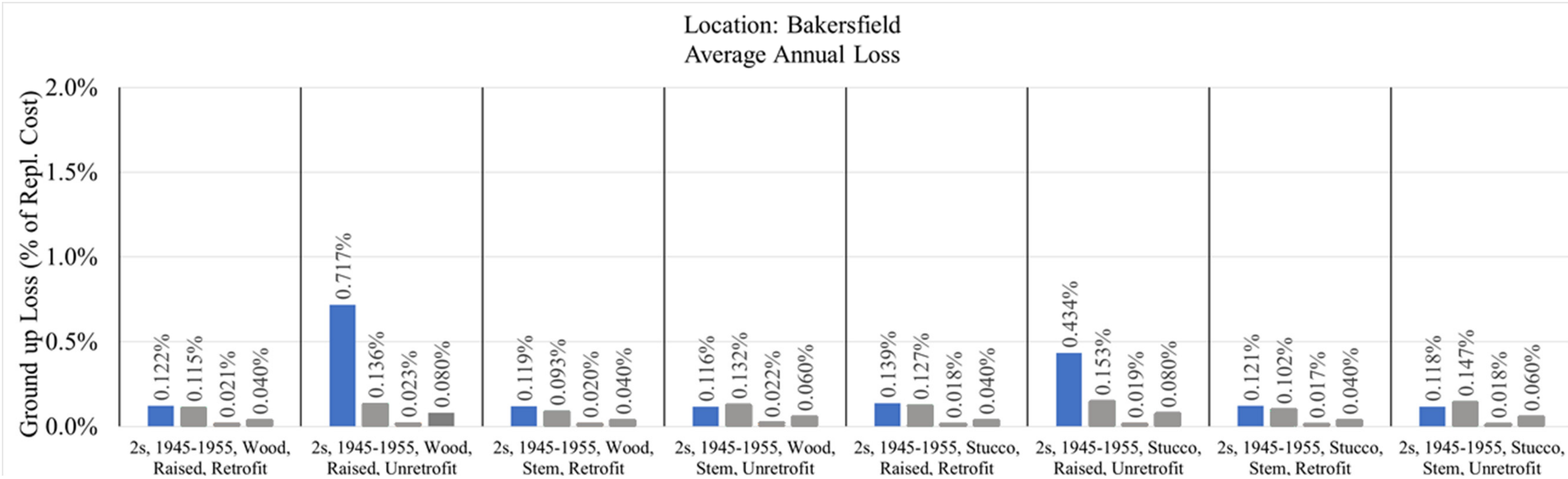


Figure 6.50 San Bernardino: loss comparisons by location, two-story home built between 1945–1955, average annual loss.



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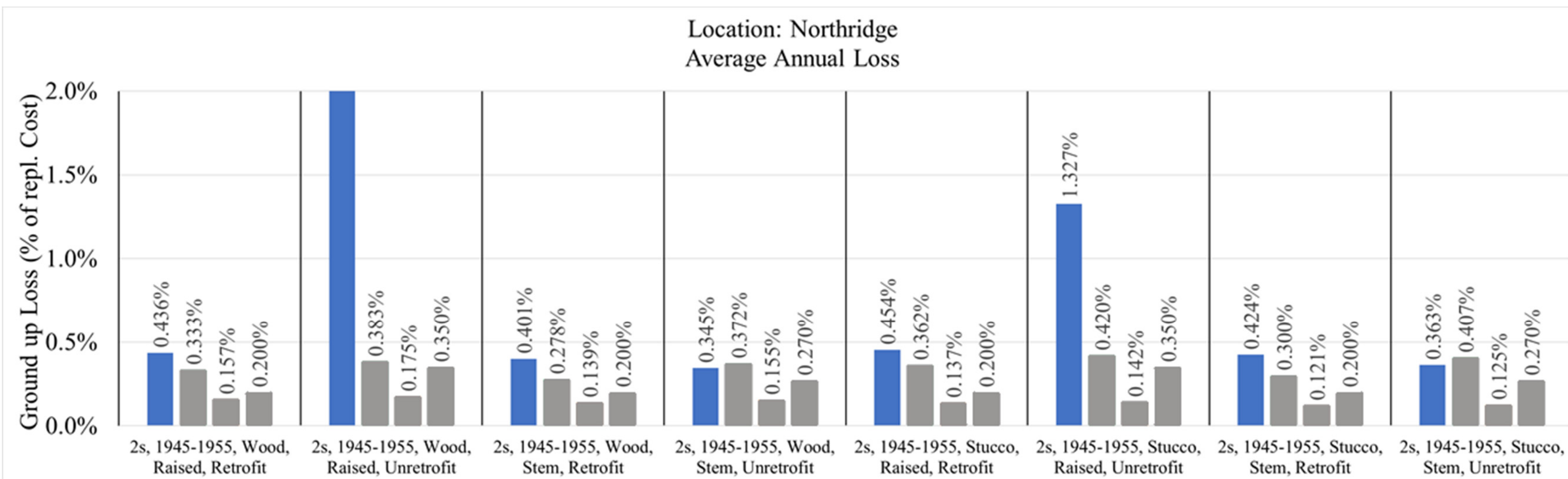


Figure 6.52 San Northridge: loss comparisons by location, two-story home built between 1945–1955, average annual loss.

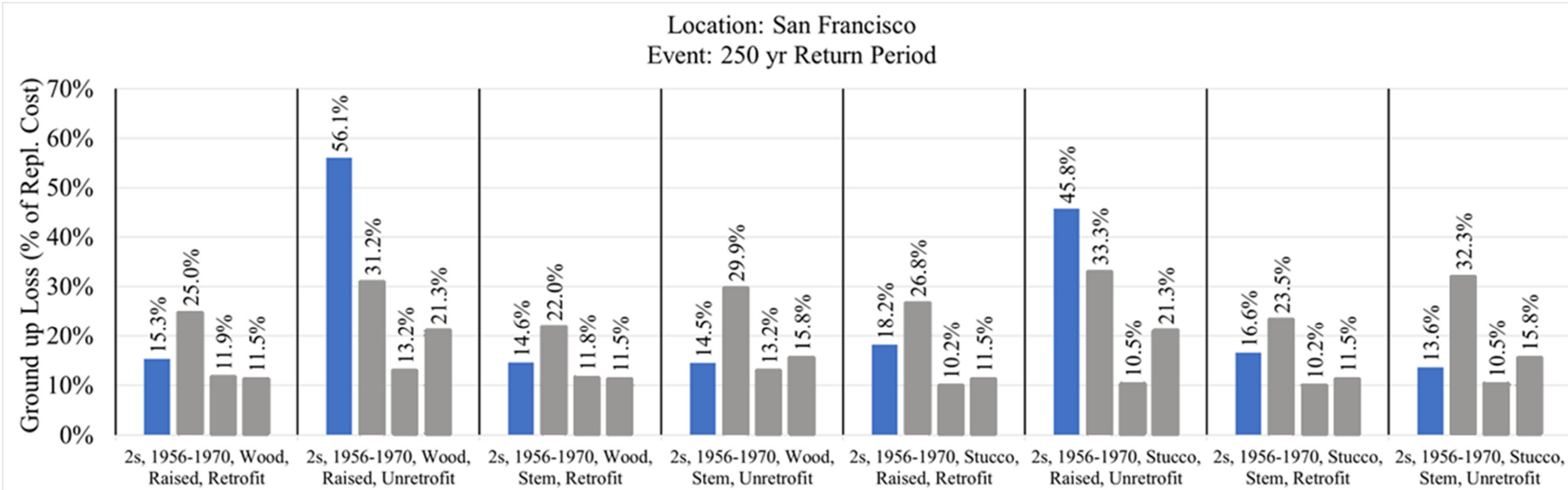
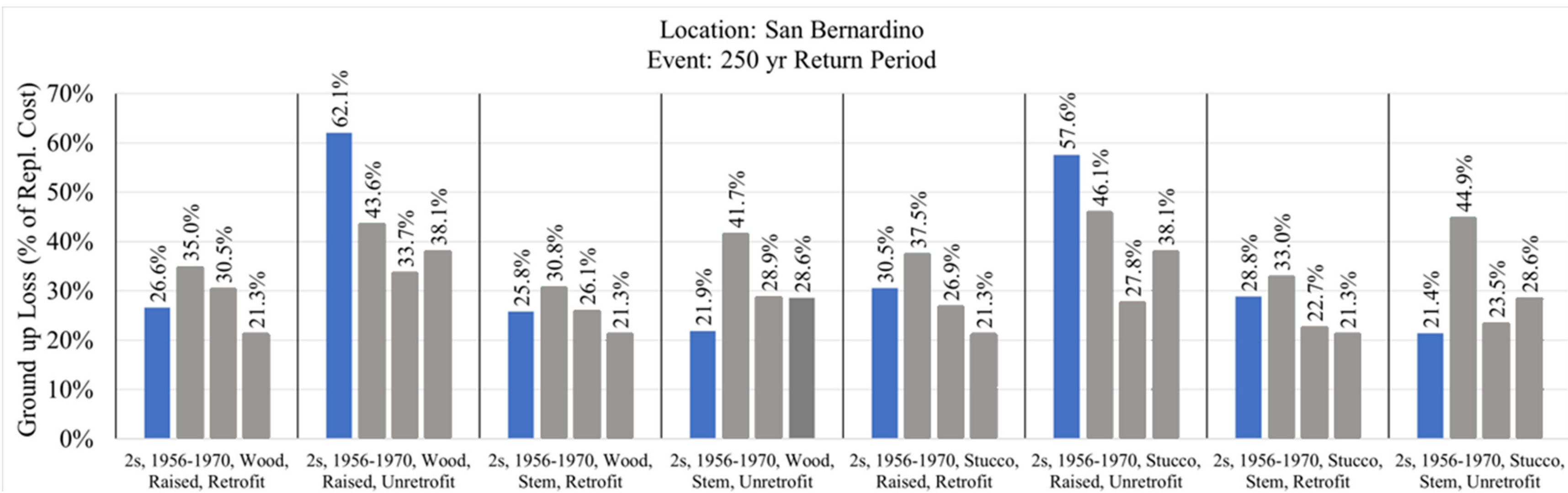


Figure 6.53 San Francisco: loss comparisons by location, two-story home built between 1956–1970, 250-year return period.



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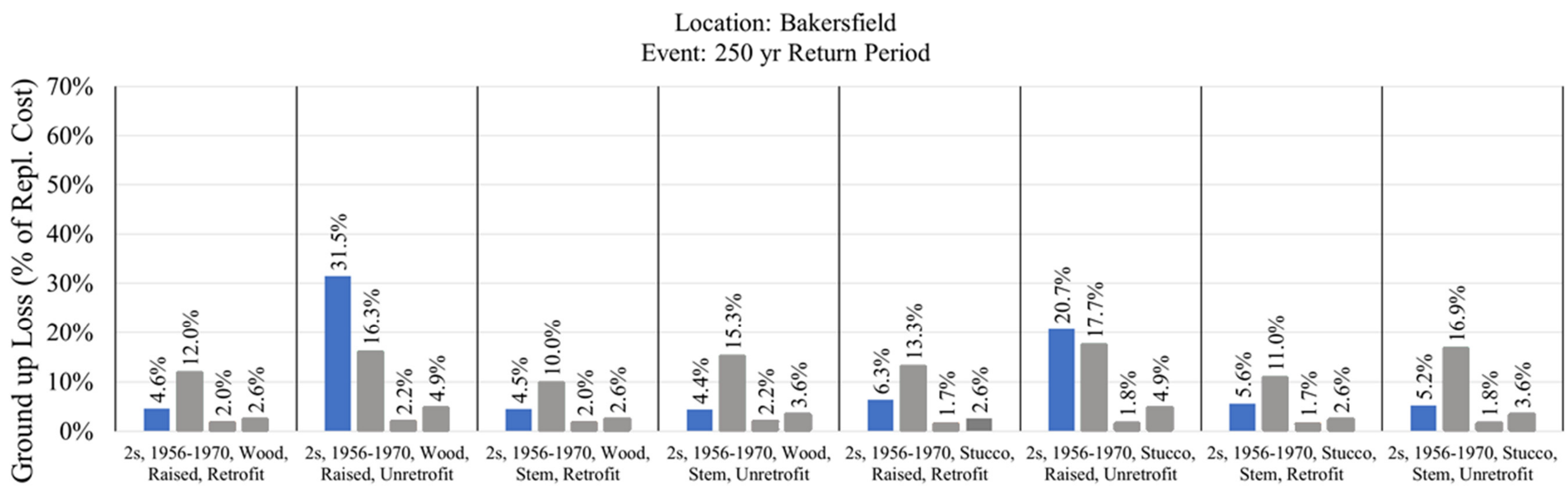

Figure 6.55 Bakersfield: loss comparisons by location, two-story home built between 1956–1970, 250-year return period.

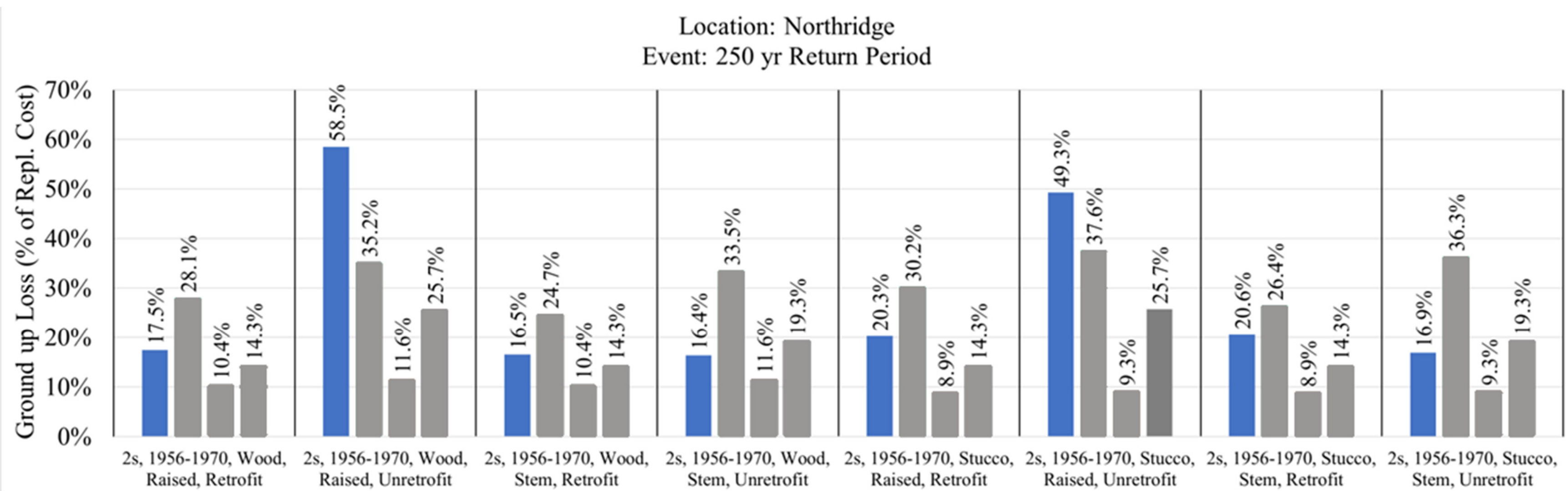

Figure 6.56 Northridge: loss comparisons by location, two-story home built between 1956–1970, 250-year return period.

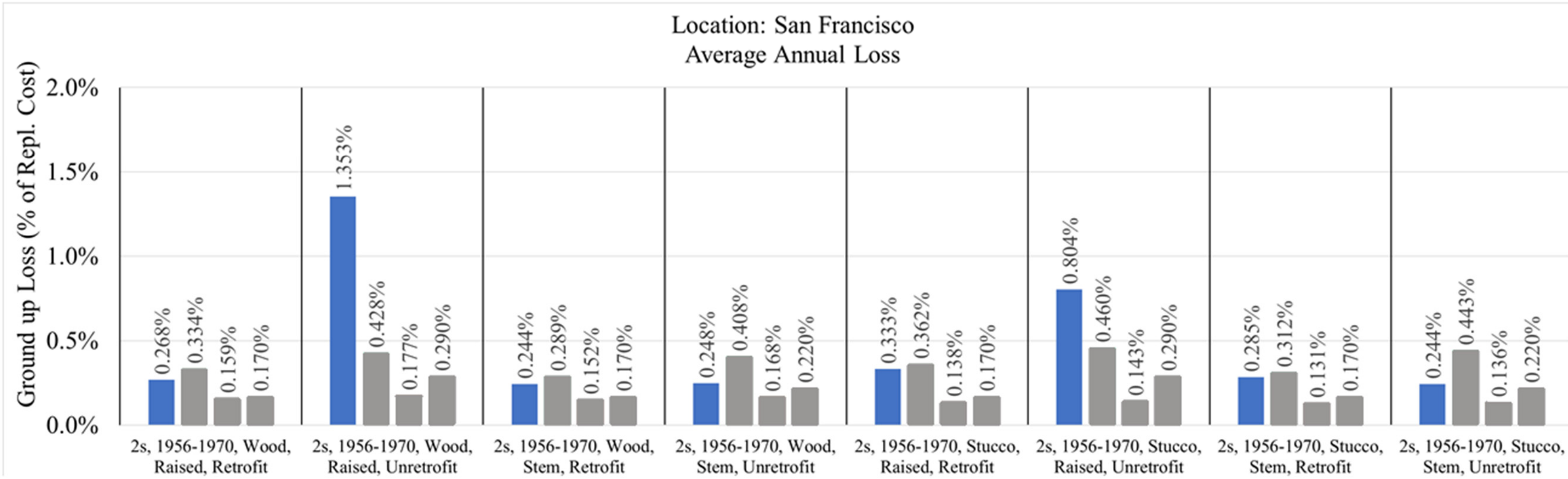

Figure 6.57 San Francisco: loss comparisons by location, two-story home built between 1956–1970, average annual loss.

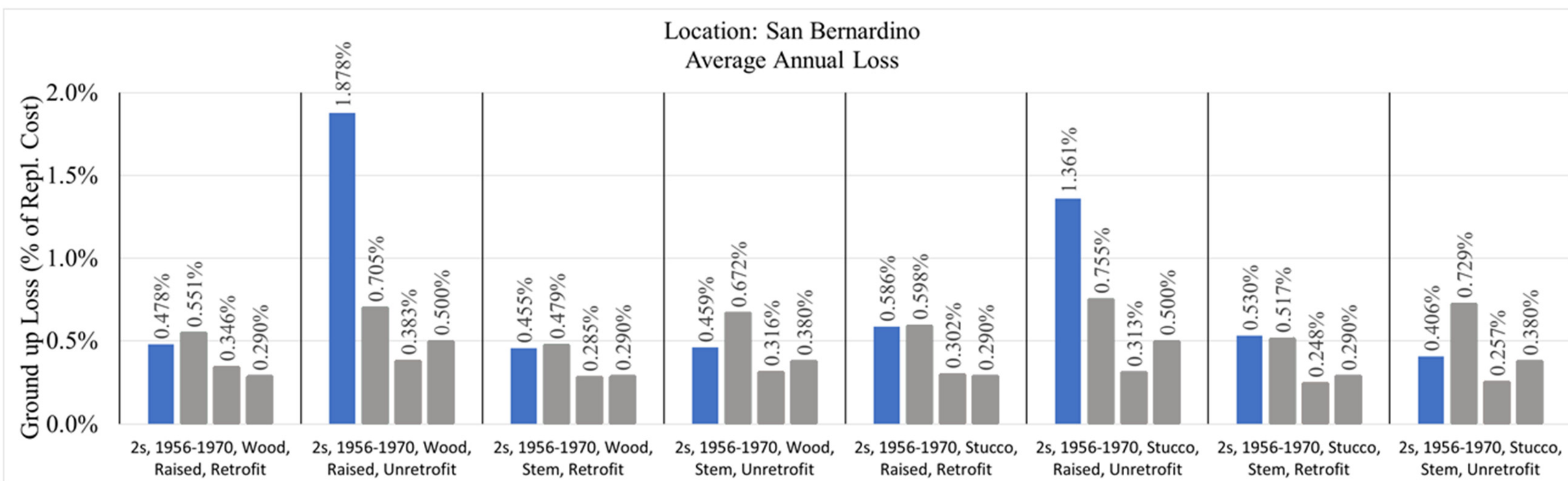

Figure 6.58 San Bernardino: loss comparisons by location, two-story home built between 1956–1970, average annual loss.

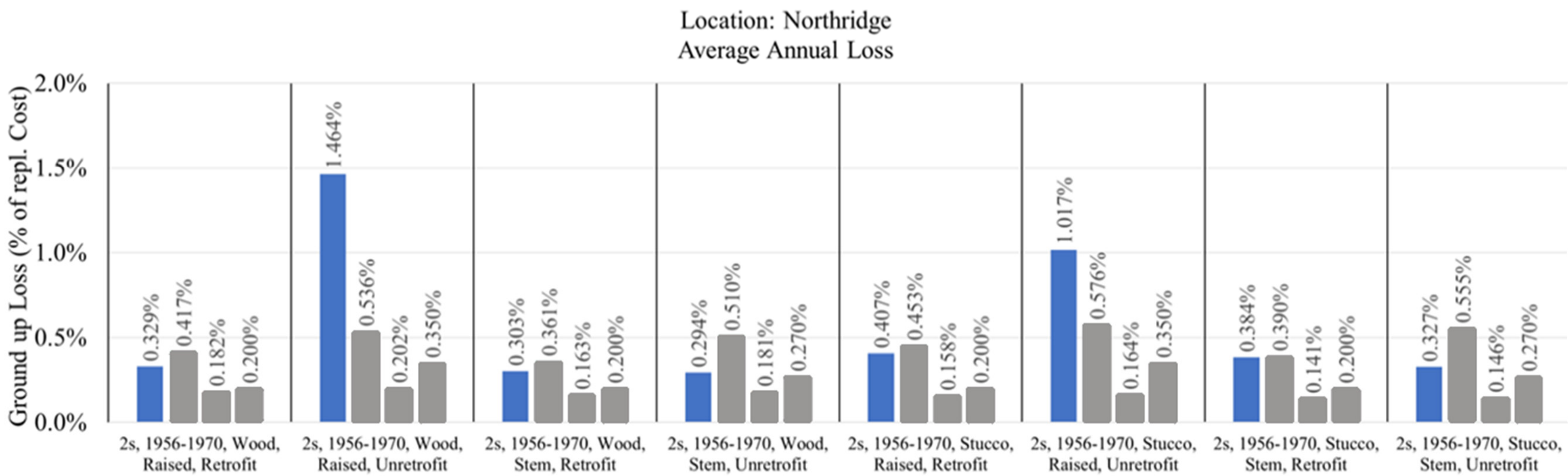

Figure 6.59 Bakersfield: loss comparisons by location, two-story home built between 1956–1970, average annual loss.

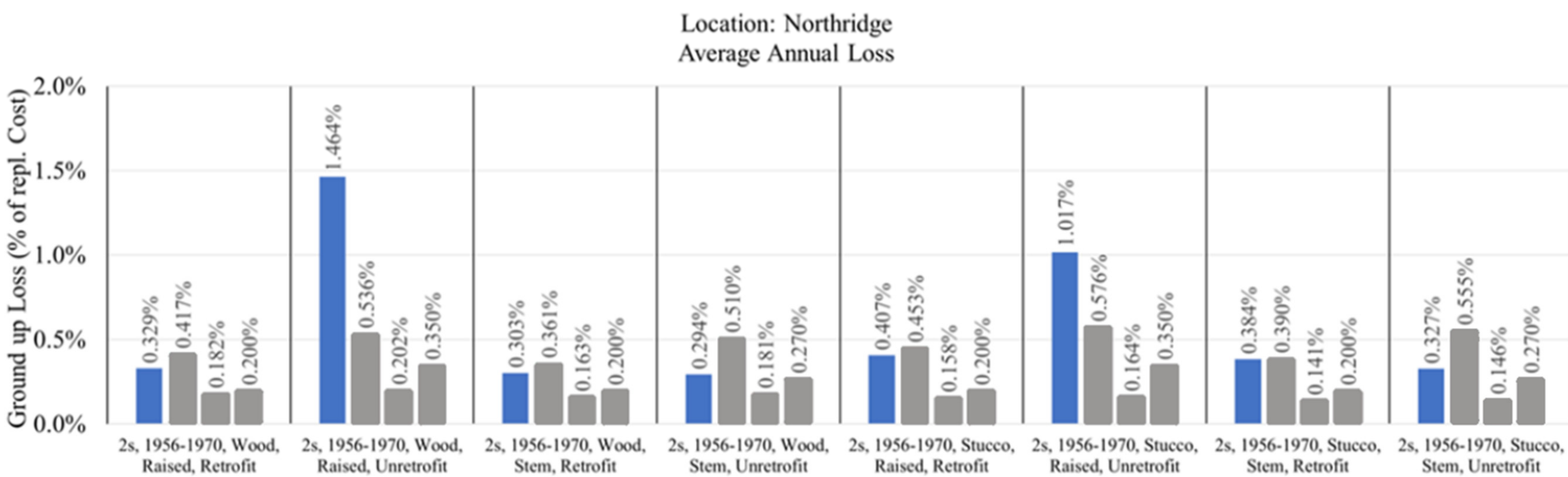

Figure 6.60 Northridge: loss comparisons by location, two-story home built between 1956–1970, average annual loss.

7 Key Findings

The PEER–CEA Project Team in conjunction with the Project Working Group reports will post links on the PEER website to the raw data accumulated through the project for widespread use by the research community and by the Modelers as they consider incorporating the information into their catastrophe models. In this section the Project Team presents a summary of its own conclusions about how the result of its study compare with those provided by the Modelers.

Key finding #1 – For unretrofitted raised (2-ft-tall) cripple wall conditions, the Modelers consistently estimated lower damage than did the project team, for both the AAL and the 250-year return period across all age groups, heights, and locations. The PEER–CEA Project models for the 250-year return-period values are on the order of 200% to 250% larger than the Modelers' reported values, and AAL values are on the order of 400% to 700% larger. The PEER–CEA Project models, confirmed by the test results, prove that raised cripple walls were a significant weak link in the performance of all houses.

Key finding #2 – Both the Modelers and PEER–CEA Project predicted greater damage for two-story, raised cripple wall houses versus one-story homes, but the difference is more significant in the PEER–CEA Project models. PEER–CEA Project's AAL values for two-story homes are on the order of 200% of the one-story values, whereas the ratio for the Modelers is closer to 150%. The added weight of the second story added significant seismic inertial force at the cripple wall. Because the typical historical design of the unretrofitted cripple wall is typically independent of the number of stories, more damage would be predicted.

Key finding #3 - For unretrofitted stem-wall conditions, the Modelers consistently estimated higher damage at the 250-year return period with respect to the PEER–CEA Project model across all age groups, heights, and locations, on the order of 33% to 50%. On the other hand, the AAL values compared quite well, on the order of within 10% to 25% of the PEER–CEA Project values. All three of the Modelers indicated to the Project Team that the quality of their claims-inventory data is poor insofar as it does not distinguish raised versus stem-wall conditions, and that the differences in performance between the two results stems primarily from expert opinion within the modeling companies.

Key finding #4 – For retrofitted conditions, the PEER–CEA Project and Modelers' results compare significantly better for unretrofitted conditions, particularly for single-story construction; the values for both AAL and 250-year RP for both raised and stem-wall conditions were generally within 10% to 25% of each other. For two-story homes, the Modelers consistently underestimated damage with respect to the PEER–CEA Project results by 10% to 40% for the 250-year return period and 30% to 100% for AAL.

Key finding #5 – The PEER–CEA Project results that show improved performance with age, regardless of location, number of stories, and exterior siding material is consistent over the period considered. This is unsurprising as the only difference within the PEER–CEA Project models for each age category was the weight of the interior finish material. Lath and plaster, which is representative of older construction methods, is heavier than gypsum wallboard, adding considerable mass and seismic demand but contributes relatively little additional strength.

The Modelers do not consider interior finish material as an explicit variable. The Modelers results show improved performance with age that is consistent over the 1945–1955 age band over the pre-1945 age band. This performance begins to deteriorate when comparing the 1955–1970 age band over the 1945–1955 age band. The Project Team believes that the Modelers' results reflect what is known in the industry and reflected empirically in insurance claims: that the quality of single-family housing decreased in the 1960s and 1970s due to a range of factors, including larger interior open spaces in homes and the decline in union labor in California. The Project Team could find no explicit way to model these conditions.

Key finding #6 – The Modelers' results show virtually no difference in performance between stucco and wood siding for any of the conditions considered. The PEER–CEA Project models show distinctly better performance for stucco over wood siding in the unretrofitted condition with a raised cripple wall in both the one- and two-story conditions. The particular weakness of the horizontal siding cripple wall when compared with stucco is clearly demonstrated in the PEER–CEA Project models. This difference mostly disappeared in the stem-wall condition, where the stucco and wood-sided houses performed similarly.

Key finding #7 – The PEER–CEA Project results show that retrofitting a two-story stem-wall house using the ATC-110 plan set resulted in slightly poorer performance. Although counterintuitive, it can be explained thusly. The failure mode for the stem-wall condition, as described in the WG5 report [Welch and Deierlein 2020], is the separation of the first-floor joists from the sill plate, which remains attached to the concrete foundation. Once this separation occurs, the superstructure is somewhat isolated from the foundation and the earthquake ground motions. The models show that the amount of slippage of the first-floor joists relative to the sill plate is low—less than an inch—for return periods up to more than 250 years. The repair of this condition would typically be to push the house back to its original position, reattach the joists to the sill plate, and repair damaged stucco or siding up to about two feet above the sill plate. Overall, this is not a particularly expensive repair job. When the house is retrofitted, by solidly attaching the first-floor joists to the sill plate in conformance to the ATC-110 plan set, the isolation effect is lost, and ground motion is transmitted into the superstructure. As a two-story home is heavier than a one-story home, the damage tends to concentrate in the first story, exceeding the repair costs associated with the first floor sliding on the sill plate in the unretrofitted condition. The Modelers results show no such increase in damage in the retrofitted stem wall condition.

The significance of this finding should not be overstated. There are many conditions that could lead to poorer performance of unretrofitted two-story stem-wall houses that were not fully evaluated in this limited study. These may include homes where: (1) the existing sill plate connection is weaker than assumed due to deterioration or lack of nailing; (2) the first-story walls are stronger than assumed; (3) the existing sill plate is narrower than assumed; (4) the floor plan or foundations have irregular configurations; and/or (5) the flexibility of the first-floor diaphragm can lead to localized areas of increased deformation and increased risk of separation of the floor from the stem wall. There could also be considerable variability in the repair cost of a stem-wall house that does slide partially off its foundation sill plate. Given these and other uncertainties in a study of this scope, retrofitting stem-wall houses according to the ATC-110 plan set remains the preferred engineering recommendation.

An important consideration when comparing the results of the PEER–CEA Project and the Modelers is the deaggregation of building characteristics within the Modelers' damage functions. The comparison study was crafted explicitly to consider primary and secondary modifiers—age, stories, siding, cripple walls, retrofit condition, etc.—that are available inputs in the Modelers' models. All of the Modelers stressed that the differentiation in their damage models is not entirely based on empirical claims data. Much of the claims data incorporated into their models does not contain complete descriptions of the buildings, nor does it identify the primary and secondary modifiers. Thus, the Modelers must also use expert judgement in assigning damage function adjustment factors to account for the individual building characteristics.

An example is the presence of a raised cripple wall itself. As described in Section 8, the Project Team identified a single report from the Department of Housing and Urban Development [1994] that attempted to quantify damage to single-family houses in the 1994 Northridge, California, earthquake. Samplings of 341 structures were surveyed. Of those 341 structures, only 3% were raised cripple wall houses, with the remainder being slabs-on-grade or stem-wall foundations.

A study in 2004 by Wesson et al. developed a damage function for single-family homes using zip-code level insurance-claims data from the 1994 earthquake. Assuming that the deaggregation across building characteristics of the Wesson data would be similar to the HUD study inventory, the damage functions would therefore mostly reflect homes without raised cripple walls. Furthermore, assuming that the claims data used by the Modelers in the development of their own damage functions would also be heavily influenced by the Northridge insurance data (which comprises a large share of the available empirical data over the past fifty years), it would also be credible to conclude that the Modeler functions are heavily weighted toward slab or stem-wall conditions. Thus, the justification for the significant difference in the AAL and losses at the 250-year return period between the Modelers and the PEER–CEA Project results for raised cripple wall homes can quite possibly be explained by the implicit weighting of the former toward non-cripple wall structures.

Similarly, the HUD inventory identified that 79% of the homes surveyed were single story. Again, if this percentage reflects the insurance data ultimately used by the Modelers, then the damage functions could also be heavily weighted toward single-story homes. The large difference in predicted performance between the PEER–CEA Project and the Modelers for two-story homes could also reflect the judgment factors the Modelers may have used to adjust damage functions based on number of stories.

Similar conclusions could be made for retrofitted versus unretrofitted conditions. It would be uncommon for underwriters or claims adjustors to crawl under homes—especially damaged ones—to make a determination as to whether the house had been seismically retrofitted, and certainly not to what extent relative to the ATC-110 plan set completed in 2019. Therefore, considerable judgment would have been used by the Modelers to adjust damage functions to account for any retrofit strategies employed, whereas the PEER–CEA Project considered retrofit explicitly in the modeling and testing.

These key findings suggest that loss modeling would benefit greatly from requiring that empirical claims data gathered in future earthquakes contains more detailed information on building characteristics. Damage estimates will be improved by including the following additional required information in the underwriting data collection process and the Modelers' catastrophe software:

- The ability to distinguish between a raised cripple wall and a stem wall;
- The ability to distinguish between interior finishes of lath and plaster, and those of gypsum wallboard; and
- The ability to distinguish between unretrofitted and retrofitted conditions.

Furthermore, if engineers and the scientific community are to continue to improve methods of credibly estimating building performance in earthquakes and other hazards, it is essential that their collaboration with insurers should include access to the underwriting and claims inventory at a granular level. Sharing this valuable information, while finding ways to preserve anonymity and proprietary advantage, would be extremely beneficial to the effort of improving insurance pricing for earthquakes and other natural hazards.

8 HAZUS Damage Function Comparison

The PEER–CEA Project scope of work includes a comparison between the results obtained through this study with damage functions developed for FEMA's HAZUS® [FEMA 2014] software. HAZUS was developed as a tool for jurisdictions to estimate the impacts of earthquakes at a regional level, i.e., cities, counties, and states. Damage functions were developed for classes of buildings (wood, steel, concrete, and masonry) as a function of age, code level, and height, which was based primarily on expert opinion. Although a broad study was conducted to compare regional aggregated losses from several earthquakes, with estimates produced by modeling the events in HAZUS, direct testing, analytical modeling, or empirical data were not typically used by the developers of HAZUS to establish these functions.

Following the release of HAZUS, researchers developed tools by which individual buildings could be modeled based on their unique characteristics, using the building class damage functions as a guide. One such effort, led by Dr. Charles Kircher, a member of the PEER–CEA PRP, developed damage functions for light wood-frame structures with and without "irregularities," which were defined as plan related, i.e., torsional irregularities commonly found in houses non-rectangular in shape. The damage functions did not include evaluation of cripple wall configurations or consider conditions with and without bracing and bolting. Therefore, the comparisons in this section between the damage functions developed by Kircher versus the damage functions of the Project Team is not an "apples to apples" comparison. Rather, the Kircher functions should be considered as providing a range of damage functions that may reflect the diversity of housing construction that includes cripple wall and stem-wall configurations, various siding characteristics, and braced/bolted and unbraced/unbolted conditions.

Kircher also compared damage functions developed in 2004 by Wesson et al. as part of a study that aggregated empirical data from the 1994 Northridge, California, earthquake for light wood-frame structures. The Wesson et al. study indicates that data was provided by the Department of Insurance and aggregated by zip code, with no differentiation for building characteristics.

Figures 8.1 and 8.2 compare the one- and two-story PEER–CEA Project damage function results with the Kircher (HAZUS) and Wesson functions at a *Sa* of 0.3 sec. Because neither the Kircher nor Wesson functions are disaggregated by number of stories, the functions are identical in both figures.

A legend for the PEER–CEA Project damage functions is shown in Table 8.1.

Table 8.1 PEER–CEA Project vs. HAZUS comparison, graph legend.

Wood siding	Blue lines
Stucco siding	Green lines
Unbolted/unbraced	Dashed lines
Bolted/braced	Solid lines
Two-ft crawl space	Smooth lines
Stem wall	Lines with symbols
HAZUS no deficiencies	Solid black line
HAZUS with plan deficiencies	Dashed black line
Wesson's Northridge data	Red line

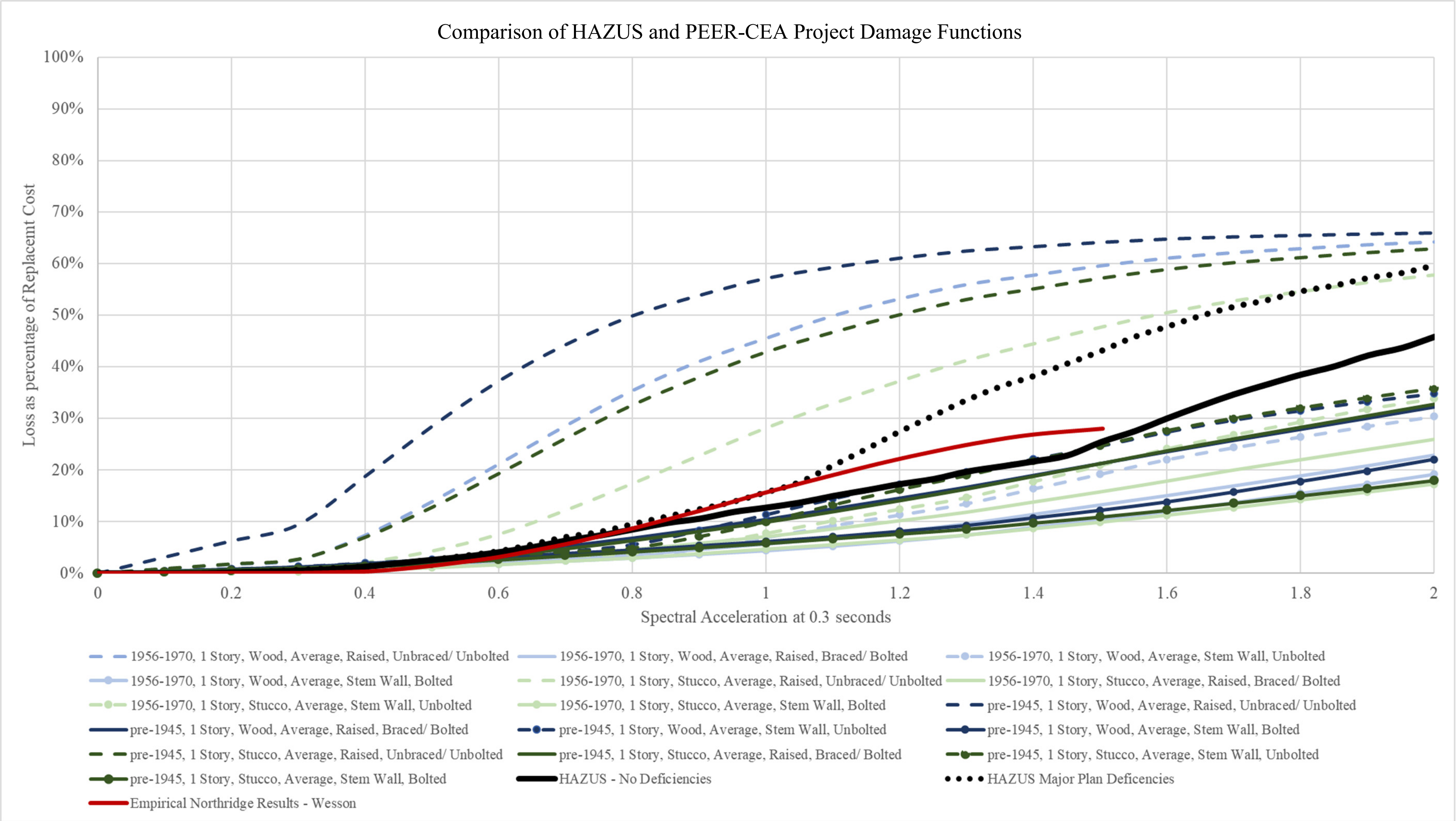

Figure 8.1 Damage function comparisons: HAZUS and Wesson vs PEER–CEA Project, one-story, average of San Francisco, San Bernardino, and Northridge sites [Wesson et al. 2004; Kircher 2018].

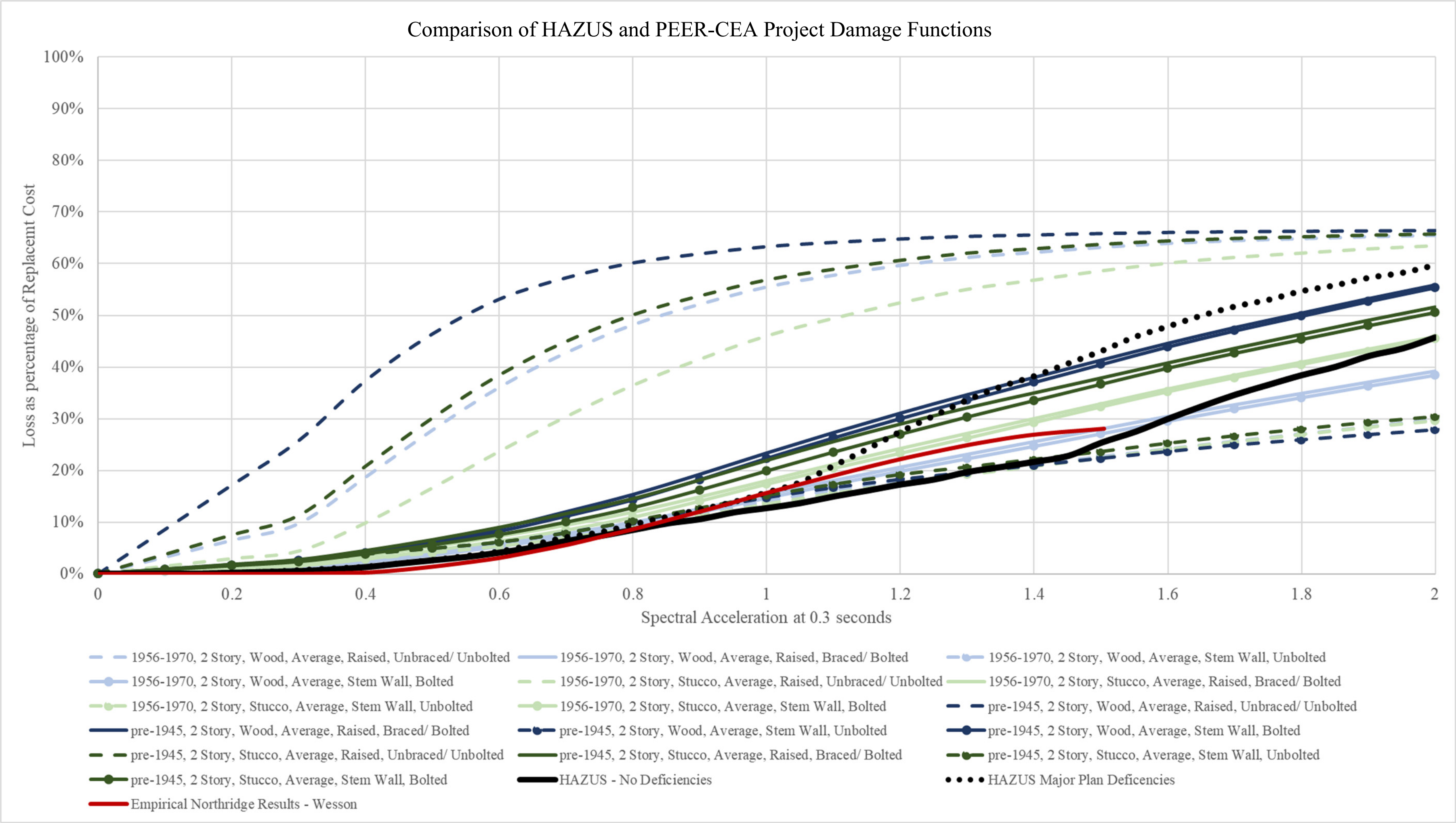

Figure 8.2 **Damage function comparisons: HAZUS and Wesson et al. vs PEER–CEA Project, two-story, average of San Francisco, San Bernardino, and Northridge sites [Wesson et al. 2004; Kircher 2018].**

A comparison of the damage functions yields the following observations:

- The PEER–CEA Project consistently predicts significantly more damage to unretrofitted, raised cripple wall homes for both one- and two-story structures with wood and stucco siding compared to the aggregate HAZUS and the Wesson results.
- The PEER–CEA Project predicts less damage than HAZUS for one-story stem-wall homes or those one-story homes retrofitted with raised crawl spaces.
- The PEER–CEA Project predicts generally similar damage as HAZUS for two-story stem-wall homes or those two-story homes retrofitted with raised crawl spaces.

The Project Team was able to identify a single report from the U.S. Department of Housing and Urban Development (HUD) [1994] that attempted to quantify damage to single-family houses in the 1994 Northridge, California, earthquake. A sample of 341 structures were surveyed. A breakdown of the characteristics of the sample are shown in Table 8.2.

This table was aggregated from individual surveys completed on a FEMA-developed form. The Project Team was not able to obtain the individual forms; therefore, the Project Team could not directly weight the damage functions based on their assumed percentage of the population of houses in Southern California. Nevertheless, some interesting conclusions can be made:

- Only 3% of the surveyed homes had raised cripple walls. It is not clear, nor is it explained in the HUD report, why the *Foundation* category does not sum to 100% whereas the other categories do. Perhaps this was a typographical error, and the stem wall or slab percentages are mistakenly over presented by 10%. Still, more than 90% of homes surveyed have no cripple wall. This would indicate that while the comparative results between the Wesson et al. study (which also represents actual Northridge data) and the PEER–CEA Project show that the Project estimates much higher losses for homes with cripple walls. If homes with cripple walls represent only a small fraction of the data gathered by HUD and Wesson et al., then this difference may be easily explained in the implicit weighting of the Wesson et al. results;
- Nearly 80% of the homes HUD surveyed were single-story homes. The Wesson et al. damage function compares better with the Project functions for two-story homes as opposed to one-story homes. If the construction characteristics of the Wesson et al. data are similar to the HUD inventory, then this would seem to be counterintuitive;
- Ninety-five percent of the HUD houses had stucco siding. The Project results indicate that stucco-clad houses performed better than wood-sided houses, which might mitigate some of the large difference with the Wesson et al. results when compared against the Project wood-siding conditions for cripple wall configurations; and
- Twelve percent of the homes in the HUD study were constructed after 1970. The Project only considered homes built before 1970. If homes in Southern California built after 1970 more commonly employed plywood sheathing or T1-

11 siding, then the Wesson et al. results are reflective of the HUD inventory and would predict a lower aggregate damage function compared to the PEER–CEA Project, which only considered homes without plywood.

Table 8.2 HUD earthquake study housing characteristics [1994].

Sample: 341 homes at 75 sites		
Year Built	1970 or before	88%
	1971 or later	12%
Stories	One	79%
	Two	18%
	One-and-a-half	1%
	Three or more	2%
Shape	Rectangular	41%
	Irregular	59%
Attachments (may be more than one type per home)	Garage	64%
	Porch	20%
	Addition	11%
	Other	3%
Exterior finish	Stucco mix	50%
	Stucco only	45%
	Wood Siding	5%
Interior finish	Plaster	60%
	Gypsum Board	26%
	Other	1%
	Unknown	13%
Exterior framing	Wood	99%
	Other	1%
Wall sheathing	None	80%
	Plywood	7%
	Unknown	13%
Roof framing	Wood Rafter	87%
	Wood Truss	5%
	Other	5%
	Unknown	3%
Roof sheathing	Board	69%
	Panel - Ply or OSB	16%
	Other	3%
	Unknown	12%
Foundation	Crawlspace—stem wall	68%
	Crawlspace—cripple wall	3%
	Slab-on-Grade	34%
	Other	5%

Until a deaggregation of the Wesson et al. [2004] and Kircher [2018] (HAZUS) damage functions can be made by the number of stories, cripple wall configuration, retrofit condition, and siding characteristics, the Project Team does not believe there is justification to modify the damage functions developed in this study. In particular, the largest differences regarding raised cripple wall configurations can be rationalized because only 3% of the HUD inventory [1994] were cripple wall homes, and it is assumed that the Wesson et al. inventory was similar. In Figures 8.3 and 8.4, cripple wall structures have been removed from the graph. In general, the Project, HAZUS, and Wesson et al. damage functions are reasonably comparable.

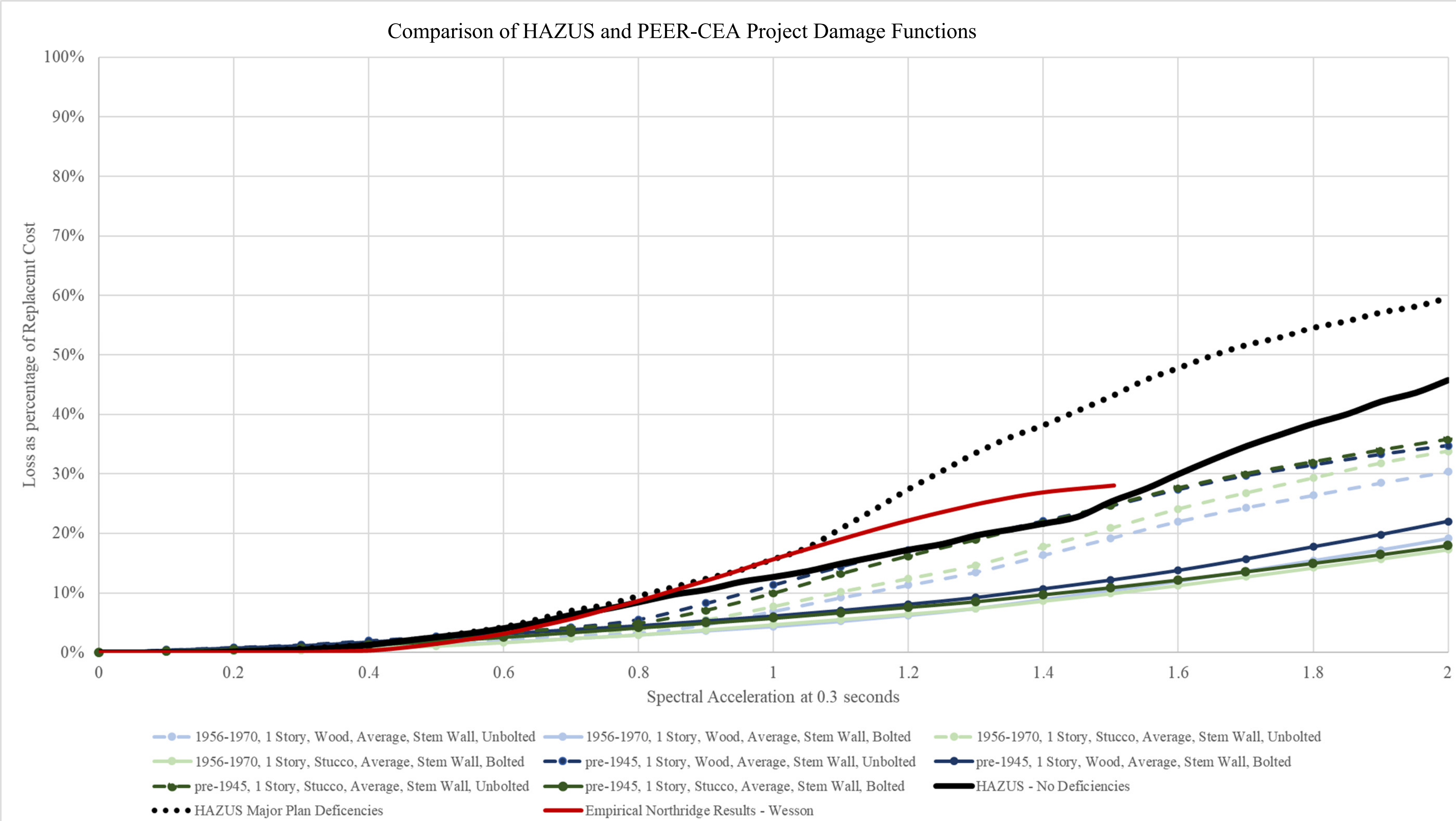

Figure 8.3 **Damage function comparisons: HAZUS and Wesson vs. PEER–CEA Project, one-story, *stem wall configurations only*, average of San Francisco, San Bernardino, and Northridge sites [Wesson et al. 2004; Kircher 2018].**

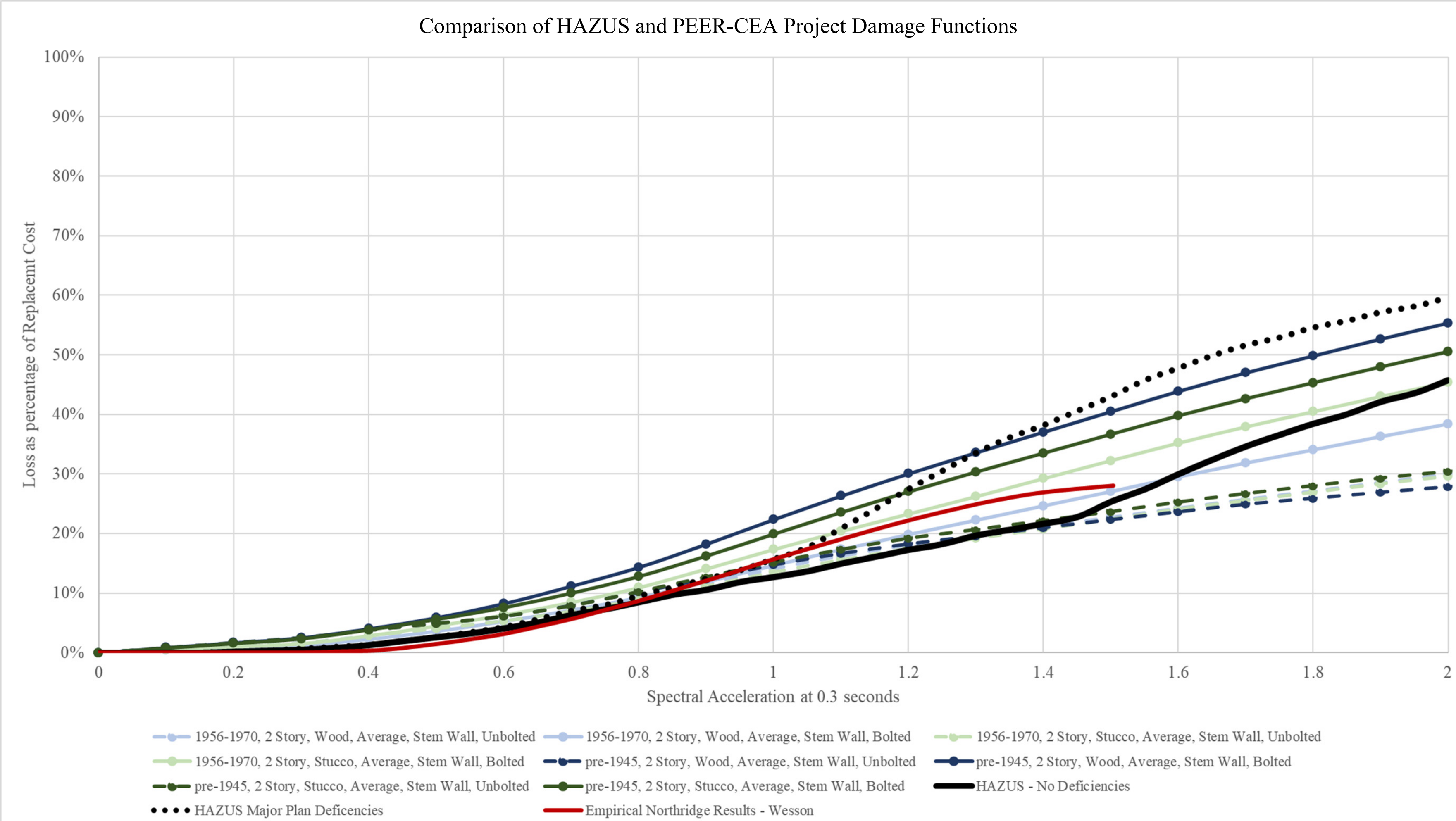

Figure 8.4 **Damage function comparisons: HAZUS and Wesson vs. PEER–CEA Project, two story, *stem wall configurations only*, average of San Francisco, San Bernardino, and Northridge sites [Wesson et al. 2004; Kircher 2018].**

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ISSN 2770-8314
https://doi.org/10.55461/QMBU3779