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QUANTIFYING THE BENEFIT OF RETROFITTING UNBRACED CRIPPLE WALLS IN SINGLE-FAMILY WOOD-FRAME DWELLINGS

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Abstract

A major contributor to earthquake damage to older wood-frame houses is the failure of unbraced cripple walls and inadequate foundation sill anchorage. To reduce risk of earthquake damage and loss, and thereby promote post-earthquake recovery, the California Earthquake Authority (CEA) seeks to incentivize retrofit of unbraced cripple walls through insurance pricing adjustments and retrofit grant programs. This includes the retrofitting of single-family dwellings using the recently developed FEMA P-1100 guidelines. To support its efforts, the CEA engaged the Pacific Earthquake Engineering Research (PEER) center to develop loss functions that more accurately quantify the reduction in losses by retrofitting of unbraced cripple walls in one- and two-story wood-frame houses.

Using the FEMA P-58 building-specific loss assessment framework as a basis, existing and retrofit cripple wall conditions are evaluated for a series of archetype houses with a range of common configurations, interior and exterior wall finishes, cripple wall geometries, and other variants. The archetype house responses are simulated using nonlinear dynamic analysis models, which are calibrated to previously published tests of structural wall assemblies, combined with tests of cripple walls and superstructure materials conducted as part of the PEER-CEA Wood-frame project. FEMA P-58 damage and loss functions for wood-frame houses are refined based on lab tests, expert opinions from insurance adjustors and parametric studies. Refinements include adjusted damage fragility and loss functions for older construction materials (e.g., plaster on wood lath interior), and considerations for the difference between full-height and cripple wall sub-assemblies.

The analysis results demonstrate a significant range in the reduction in damage and repair costs from retrofit of cripple walls, depending on the house configurations, construction materials and site hazard. Consistent with post-event reconnaissance observations, the analyses demonstrate that older houses with wood siding are considerably more vulnerable to cripple wall failure than houses with stucco exteriors, and two-story configurations are more vulnerable than single-story houses. The benefits of cripple wall retrofit follow accordingly, ranging from substantial reductions in expected annual loss ratios for the most vulnerable two-story wood siding cases to a more modest reduction for the one-story stucco cases. Select sub-sets of archetypes are illustrated to highlight key findings and trends including the influence of existing material condition and the impact of assumed economic consequences for cripple wall failure.

Keywords: building-specific loss estimation; wood-frame; cripple wall; seismic retrofit; nonlinear dynamic analysis

1. Introduction

The vulnerability of unbraced cripple walls in older wood-frame dwellings has been observed following numerous seismic events over the last 60 years in the United States. This susceptibility to failure is rooted in the construction practice of propping residential structures up on perimeter framing and interior posts in order to create a crawlspace for access, storage and in some cases flood protection. The exterior material used to clad the home or provide architectural finish is the only source of lateral resistance of the cripple wall, thus creating a soft-story condition compared to occupied stories above. Examples of cripple wall failures from previous seismic events in California are shown in Fig. 1.

a) b) c) d)

Fig. 1 – Examples of unbraced cripple wall failures following earthquakes: a) 1987 Whittier (Photo: Whittier Museum), b) 1989 Loma Prieta (Photo: USGS), c) 1994 Northridge, d) 2014 South Napa (Photo: LA Times)

The need for improved standards and procedures for seismic retrofitting of single-family dwellings with unbraced cripple walls was addressed within the recent FEMA and California Earthquake Authority (CEA) funded ATC-110 project that resulted in the FEMA P-1100 guidelines [1] for assessment and retrofit of wood-frame houses with known seismic vulnerabilities. The key concept behind an effective cripple wall retrofit is allowing for lateral forces developed by earthquakes to be transferred from the superstructure (source of mass) into the sub-flooring, cripple wall and into the underlying foundation. This is achieved through the installation of additional clips, wood structural panel sheathing and anchor bolts. An illustration of the key elements of a typical cripple wall retrofit is shown in Fig. 2.

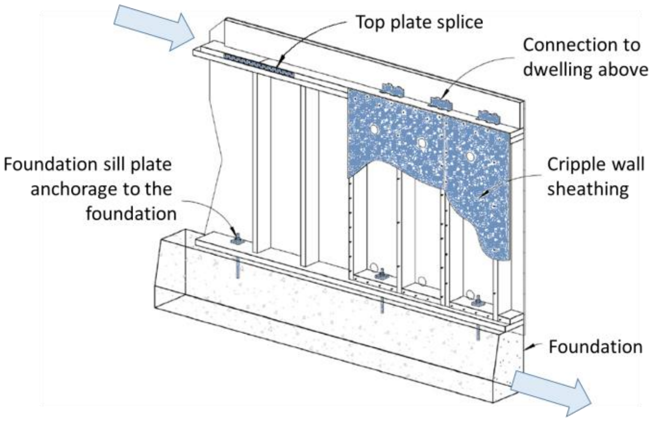

Fig. 2 – Elements of a typical cripple wall retrofit showing seismic force transfer (Image adapted from [1])

The CEA's continuing mission is to reduce risk of seismic damage and loss, thereby promoting rapid recovery and increased community resilience. This includes creating incentive programs to retrofit unbraced cripple wall dwellings through insurance pricing adjustments and retrofit grant programs. To support its efforts, the CEA engaged the Pacific Earthquake Engineering Research (PEER) center to develop loss functions to quantify the change in expected loss due to retrofitting unbraced cripple wall dwellings. With the FEMA P-1100 guidelines serving as the recipe for retrofit, the PEER-CEA Wood-frame project aims to answer the key research questions shown in Fig. 3.

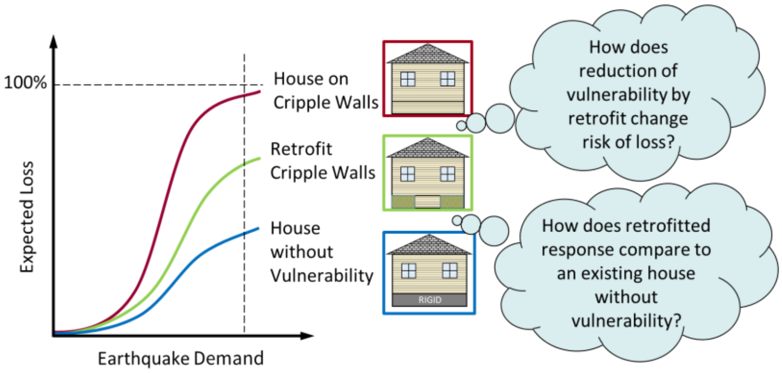

Fig. 3 – Key research questions for the PEER-CEA Wood-frame Project

The PEER group is assembled into seven distinct working groups (see Fig. 4) in order to properly investigate the numerous factors involved with conducting seismic loss assessment. The various working groups contribute to the necessary steps in order to estimate seismic performance using the building-specific FEMA P-58 framework [2]. The framework is both multi-staged and multi-disciplinary, beginning with the definition of a facility or archetype, followed by hazard analysis, structural analysis, damage analysis, and consequence (loss) estimation. The various stages of the process are reflected in the ordering of working groups shown in Fig. 4, with the multi-disciplinary nature of the process shown by the different interactions between working groups in order to reach project goals.

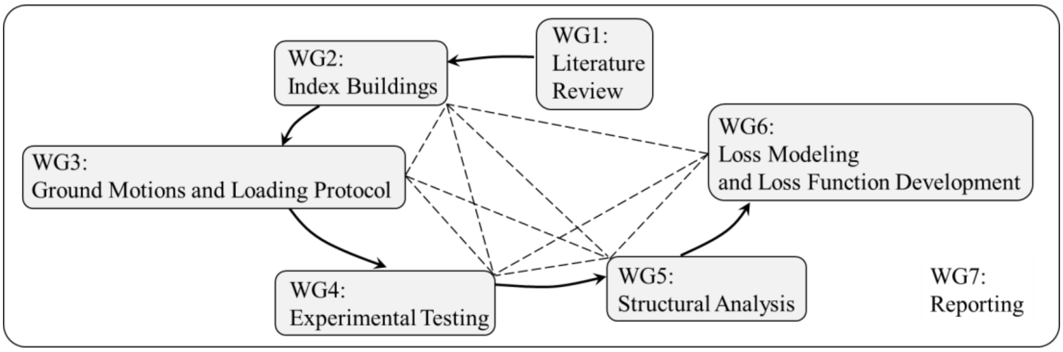

Fig. 4 – Project working groups (WG) illustrating logical ordering of tasks (solid arrows) and interactions between working groups (dashed lines)

The remainder of this paper illustrates some of the key contributions made by various working groups involved on the project and a brief overview of important results and observations from the study. Section 2 discusses the efforts made to define what building variants should be analyzed as well as an overview of new information gained from experimental testing. Section 3 provides an overview of how building variants are analyzed using the FEMA P-58 framework, highlighting some important modifications specific to cripple wall dwellings. Section 4 presents a subset of building variants in order to illustrate some of the key findings of the study followed by concluding remarks provided in Section 5.

Technical reports covering various topics and working group tasks (e.g., ground motion selection, experimental testing, and structural modeling) performed for the project will be issued as PEER reports in the coming year. PEER reports are posted at the PEER website (https://www.peer.berkeley.edu) under “Publications and Products”. Notification of PEER reports can be obtained by subscribing to the PEER News Digest, and the link is on the PEER website.

2. Scope Development and Data Collection for Analysis of Cripple Wall Dwellings

2.1 Identification of Building Variants for Analysis and Testing

The development of the building variant scope for numerical analysis considered available information within the literature regarding residential inventory and construction trends in California, as well as typical considerations within the insurance industry. The initial collection of possible variants focused on having a significant impact on seismic damage and, more importantly, having the differential in seismic losses due to retrofitting be affected by the presence of the variant. Preliminary variants included both primary and secondary modifiers applicable to the insurance industry.

Primary variants include easily accessible and documented information for residential homes such as the number of stories and era of construction. Secondary variants can be observable, such as the exterior material of the home, or unobservable such as the presence of horizontal or diagonal wood sheathing beneath the exterior finish. Initial development of the building variant list also drove the scope for experimental testing, with subsequent test data and accompanying numerical studies informing decisions on important variants to maintain throughout the course of the project. A sample of the building variants considered for numerical analysis is shown in Fig. 5. The project considers three eras of construction ranging from pre-1940 to 1956-1970. The main distinction for construction era is the interior material, with the earliest era assuming lath and plaster interior and the later assuming gypsum wallboard. The intermediate era represents the transition period where both materials were commonly used. The different cripple wall heights range from 2-foot and 6-foot cripple walls to a “zero-height” condition, including cases with vulnerable anchorage between the superstructure and a perimeter stem wall.

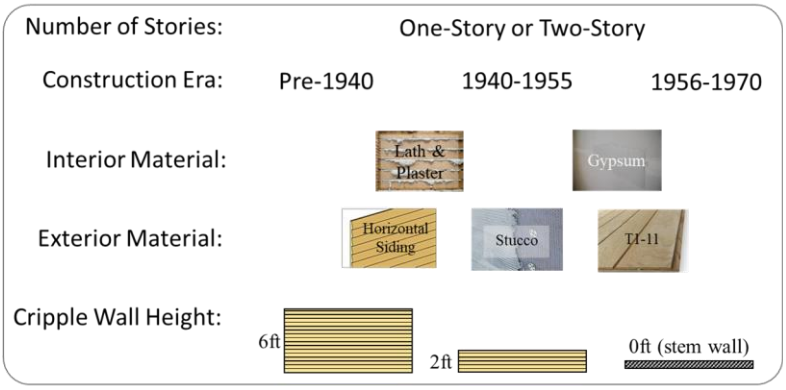

Fig. 5 – Sample of building variants considered for analysis (not exhaustive)

In addition to assumed materials and cripple wall details, the configuration and layout of the variant dwellings is also important. Consistent with the ATC-110 project, the current project targeted a moderate-sized plan area of 1200 ft^2 with an aspect ratio of 0.75 (i.e., 40 ft by 30 ft). Geometrical data from the ATC-110 project was collected for a number of one- and two-story homes from archived housing catalogs ranging in construction era from 1900 to 1969 (data available in Part 6 of [3]). This data was used in order to maintain realistic interior and exterior wall densities as well as relative wall densities from first to second stories of two-story dwellings. Baseline configurations were selected and developed using this information. Configurations were also used to inform the experimental testing group of target dwelling sizes in order to design and construct the most appropriate retrofit specimens that would be used in numerical analysis.

2.3 Experimental Testing Campaign

The PEER-CEA Wood-frame project includes an extensive experimental component (Working Group 4) to improve the current level of knowledge and provide data to calibrate numerical models for the assessment of cripple wall dwellings. The scope of the testing campaign adds to existing experimental information on wood-frame structures, such as that produced within the CUREE-Caltech Wood-frame Project (https://www.curee.org/publications/woodframe_project.html). The amount of information produced by the experimental group easily merits a standalone paper, yet a brief overview is provided.

The experimental testing portion of the project is split between small and large component testing. Small component testing, conducted at the University of California, San Diego (UCSD), consisted of 28 cripple wall sub-assemblies (12 feet in length). These tests investigated the effects of different existing cripple wall variants including exterior material (e.g., stucco, wood siding, panelized T1-11 siding), presence of underlying sheathing (e.g., none, horizontal, diagonal), cripple wall height, and boundary conditions, in addition to testing equivalent FEMA P-1100 retrofit cases. A sample set of existing and retrofit 2-foot tall cripple wall small component specimens is shown in Fig. 6a.

Large component testing, conducted at the University of California, Berkeley (UC Berkeley), examined specimens with a 20-foot long by 4-foot wide footprint that considered two parallel walls with continuous end walls. A total of five large component tests were conducted. The first two investigated the influence of stucco continuity across the diaphragm level for existing and retrofit 2-foot tall cripple walls. Two other tests investigated different combinations of occupied story materials to provide cyclic data for materials lacking existing test information (i.e., plaster on wood lath and T1-11 panelized siding). The final large component test investigated the capability of load path connections above and below the cripple wall to develop the full capacity of wood structural panel sheathing. Notably, tests were conducted using a cyclic displacement protocol developed as part of the project using similar techniques to those used in the CUREE-Caltech Wood-frame Project. An example of a large component test is shown in Fig. 6b.

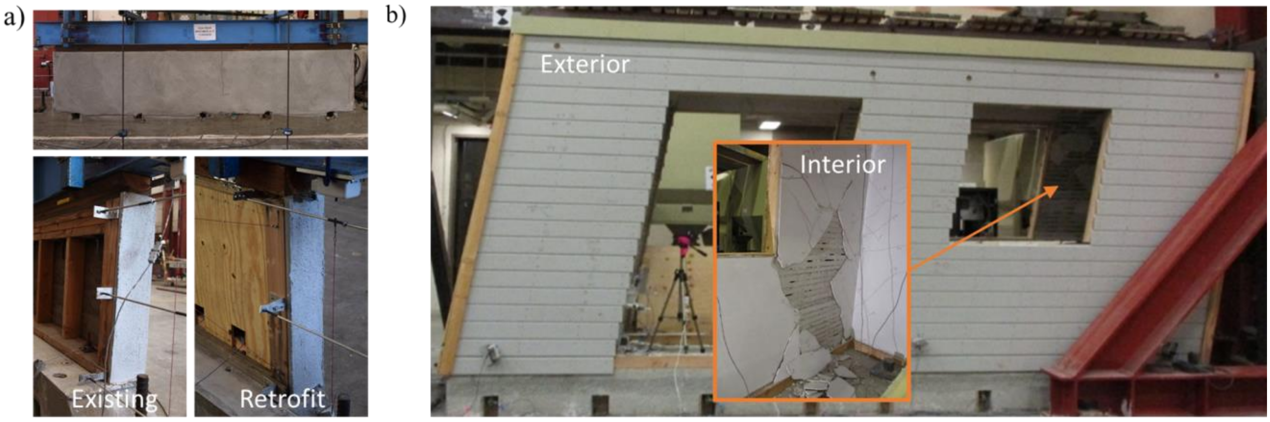

Fig. 6 – Experimental tests: a) Small component specimens (Photos: Tara Hutchinson and Brandon Schiller – WG4), b) Large component specimen (Photos: Kelly Cobeen and Vahid Mahdavifar – WG4)

3. Analysis of Building Variants

3.1 Treatment of Site Hazard and Ground Motion Selection

The ground motion working group (WG3) performed probabilistic seismic hazard analysis (PSHA) for a total of ten sites in Northern and Southern California. Site hazard considered the UCERF3 rupture model [4] and used the NGA-West2 ground motion prediction equations (GMPEs) [5]. This initial list of ten sites was reduced to four in order to limit analysis demands while including the design intensity levels covered by the FEMA P-1100 plan sets [1] with short period design spectral accelerations (S_{DS}) values of 1.0g (seismic), 1.2g (high seismic) and 1.5g (very high seismic). The important distinction between sites, aside from varying seismic demands, is the detailing of the seismic retrofit, where details such as the length of required cripple wall bracing is governed by the controlling plan set sheet. An illustration of this relationship is shown with the four selected sites in Fig. 7. Notably all considered sites assume a $V_{S,30}$ of 270 m/s (NEHRP Soil D).

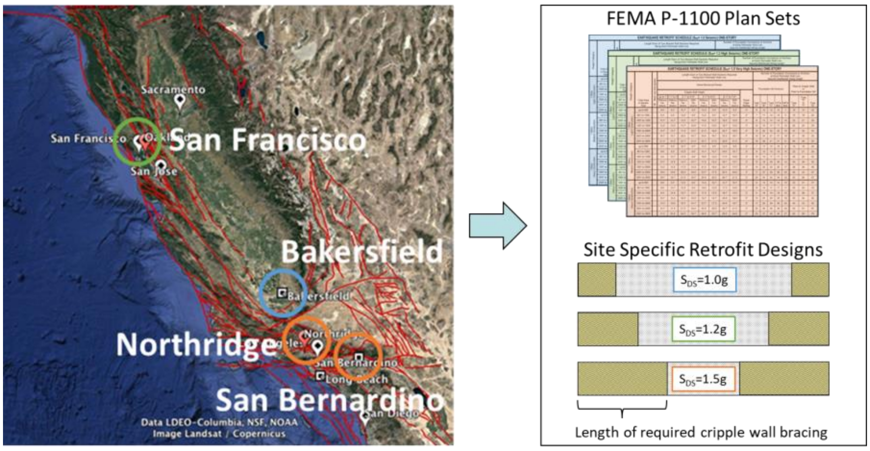

Fig. 7 – Baseline sites selected to cover a range of seismicity covered by the FEMA P-1100 plan sets for retrofit design (Site map provided by Silvia Mazzoni – Working Group 3)

The target hazard for ground motion selection was a conditional spectrum [6] with a conditioning period (T*) of 0.25s. Individual suites of 45 ground motions (2 horizontal components each) were selected for ten different return periods (15-year to 2500-year) that provide a range of intensities suitable for estimating annualized losses at each site. The selection process used a modified version of the tool developed by [7] in order to match the conditional mean spectra (mean) and conditional spectra (variance) for each return period. An example of the target hazard and ground motion spectra for the San Francisco site are provided in Fig. 8.

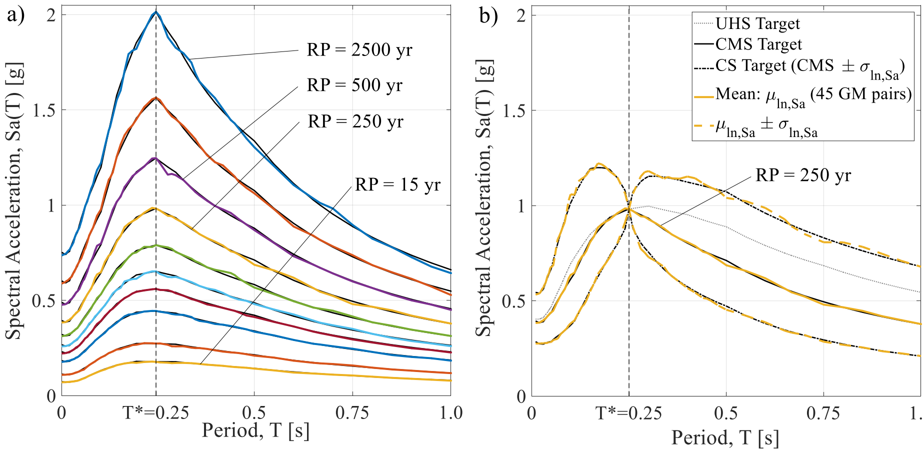

Fig. 8 – Ground motion spectra for the San Francisco site ($V_{S,30}$=270 m/s, RotD50, ξ=5%): a) Conditional mean spectra (CMS) conditioned on T*=0.25s, b) Conditional spectra (CS) for the 250 year return period

3.2 Structural Analysis Approach

Case study structures within the project assume a 40 ft by 30 ft plan dimension. Superstructure (occupied stories) story heights are assumed as 9 ft. Roof weights consider an eave overhang of 18 in and a hip roof with a pitch of 6:12. One-story cases have a total floor area of 1200 ft^2 while two-story cases are 2400 ft^2. Cripple wall geometry and material unit weights depend on the variant under consideration.

The structural modeling of cripple wall dwellings uses a three-dimensional macro-element approach using the *OpenSEES v2.5.0* analysis program [8]. The modeling concept is illustrated in Fig. 9. The geometrical considerations are included in the model by creating rigid diaphragms for the floor and roof levels that are supported by elastic co-rotational truss elements that are applied vertical gravity loads in order to capture second order (P-delta) effects. The strength and stiffness of the structure is captured by nonlinear shear spring elements that represent the location, material and effective length of walls located within the structure. The nonlinear shear springs use the *Pinching4* material in *OpenSEES* [8] to represent the hysteretic behavior of materials. A two-spring in parallel approach (adopted from [9]) is implemented for each wall material in order to capture the difference in cyclic behavior of materials under small displacements (onset of damage) and large displacements (collapse). Interpretation of available testing required careful attention to capturing initial stiffness behavior and close interaction between the experimental testing and analysis groups to understand the influence of different boundary conditions and specimen details.

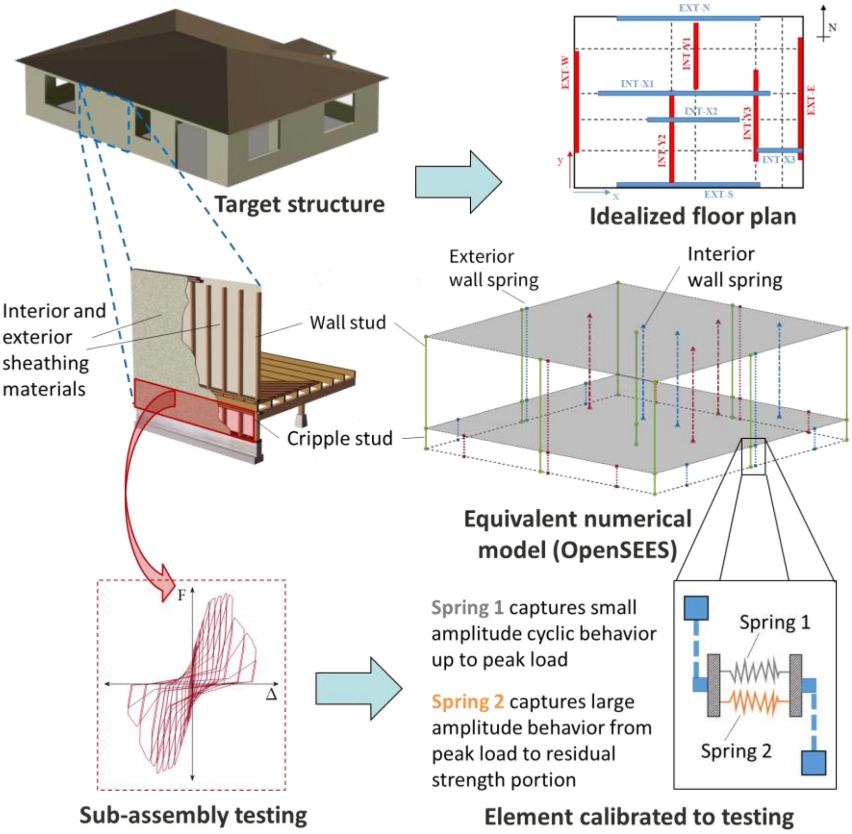

Fig. 9 – Structural analysis approach for creating numerical models of cripple wall dwellings

The structural analysis collects relevant Engineering Demand Parameters (EDPs) such as story drift ratios and peak floor accelerations to obtain response statistics to estimate structural and nonstructural damage. An estimate of the collapse fragility of the structure must also be estimated. Global collapse is defined in the project as a very large drift ratio (e.g., > 20%) that exceeds the abilities of the wood framing to withstand P-delta collapse, yet allows for the analyses to be terminated for computational efficiency. Collapse fragilities are created using the maximum likelihood approach [10] for multiple stripe analysis [11]. Both the collapse fragilities and EDPs conditioned on no-collapse include an additional modeling uncertainty of 0.35 (β_{mod}) using an SRSS combination with the record-to-record variability (β_{RTR}). Notably, residual drifts are recorded as part of the project, yet are not currently included in the performance assessment of cripple wall dwellings.

3.3 Component Damage Fragility and Repair Cost Considerations

An important investigative effort was conducted to review available damage fragility information for wood-frame construction in order to determine appropriate adjustments for older cripple wall dwellings. Although all materials used within the analysis scope were reviewed, only two proposed adjustments are mentioned here for brevity, noting that both were supported by observations from recent testing. One assumption within the project was the use of a height-dependent relationship to relate the damage fragility of full-height stucco walls to that of shorter cripple walls in terms of drift ratio (Fig. 10a). Another key adjustment is revised interior finish fragilities that capture the more brittle nature of older plaster on wood lath when compared to modern gypsum wallboard (Fig. 10b).

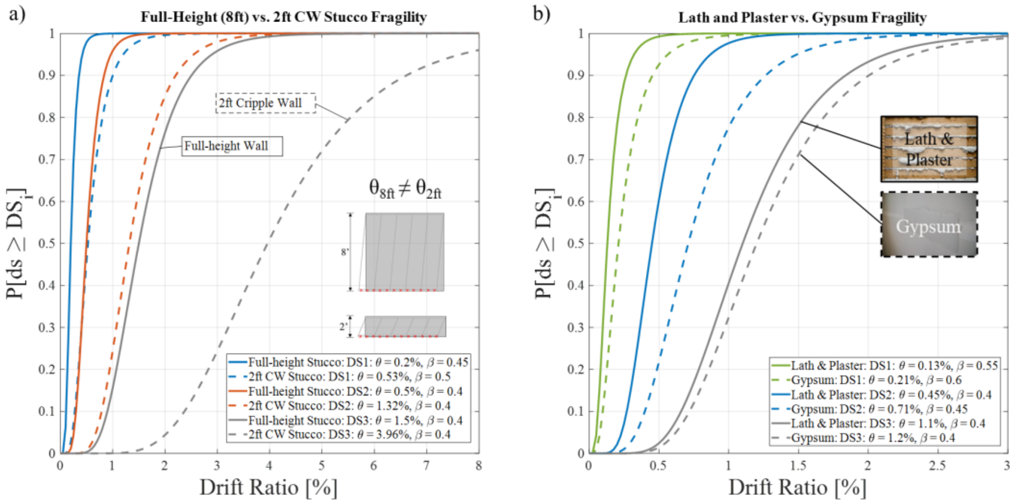

Fig. 10 – Damage fragility adjustments from the FEMA P-58 database: a) height-dependent relationship for the drift ratios triggering different damage states for exterior stucco, b) revised lath and plaster fragilities

To gain a better understanding of repair costs, a claims adjuster damage workshop was organized to collect feedback from experts with experience in assessing damage costs following earthquakes within the insurance industry. Damage description packages were developed for three case study buildings that provided photographs, drawings and textual descriptions of different materials and sub-assemblies at various damage states within a home. Case study buildings were purposefully devised to provide comparisons to available FEMA P-58 materials (e.g., exterior stucco, gypsum wallboard) as well as gain much needed information on the repair costs for sheathing materials that are not included in the P-58 fragility database (e.g., plaster on wood lath). The results of the damage workshop allowed for cross-comparison with existing P-58 functions as well as expanding the range of damage and loss functions for older wood-frame dwellings.

An important consideration for the assessment of cripple wall dwellings is the treatment of economic collapse consequences due to cripple wall failure. Supported by reconnaissance reports following earthquakes, the economic consequences due to cripple wall failure can vary widely. In the best case scenario, the cripple wall fails without significantly damaging the flooring or occupied stories, requiring that the structure be raised and the cripple wall or foundation be rebuilt. In other cases, the failing cripple wall causes significant damage to interior flooring and finishes and can result in a total loss. Based on previous studies [12], practitioner surveys [13], and reconnaissance review, this cost can range from approximately 33% to 100% (total loss) of building replacement cost. The project has assumed that cripple wall failure incurs 67% of replacement cost to reflect the large uncertainty due to cripple wall failure for interpretation of results. However, the ability to vary this assumption and investigate the sensitivity to other loss ratios is maintained within project documentation.

4. Discussion of Key Results

A small subset of building variants is selected for presentation of key observations from the study. The variants presented are four post-1955 era dwellings with gypsum wallboard interior and asphalt shingle roof. Exterior materials are horizontal wood siding and stucco. One- and two-story variants are considered, both assumed to be on 2-foot tall level cripple walls located in San Francisco. Each variant has its own existing and retrofit pair, with a spectral intensity of S_{DS}=1.2g controlling retrofit design according to FEMA P-1100. Notably, retrofit designs are similar for both exterior material types (light classification) with cripple wall braces of 8 ft and 12 ft required in each corner (2 per side) for one- and two-story cases, respectively. All materials are representing best estimate values. Damageable assemblies include exterior walls, interior walls and interior finish (e.g., tile). The building replacement values are assumed to be \$200/ft^2 (2019 USD), applied to the total plan areas of 1200 ft^2 and 2400 ft^2 for one- and two-story configurations, respectively. Cripple wall collapse assumes 67% of replacement cost for the results presented. Performance calculations were conducted using *SP3* (HBRisk) [14] and *pelicun* (NHERI-SimCenter) [15] at different stages of the project. Computational workflows, combining the nonlinear *OpenSees* [8] analyses with the *pelicun* [16] performance calculations on a high-performance computing cluster, were essential to complete the simulations of multiple variants within the project timeline.

The performance results for the one-story variants are shown in Fig. 11 with the corresponding results for two-story variants shown in Fig. 12. The figures illustrate the three key outputs for the project, namely i) mean loss versus intensity, ii) expected annual loss (time-based) and iii) the mean loss at a return period (RP) of 250 years (intensity-based). Notably, the 250 year return period corresponds to a spectral intensity Sa(0.25s) of approximately 1.0g for the San Francisco site. A summary of the loss metrics comparing existing and retrofit cases is provided in Table 1. In general, the addition of cripple wall retrofit is shown to drastically improve the seismic performance. However, there are key differences between variants that will be discussed.

Beginning with one-story cases, a key observation is the influence of the existing material strength of the cripple wall. The solid lines and bars in Fig. 11 represent the existing condition for one-story cases where the stronger and stiffer stucco material has more resistance to failure than the weaker horizontal wood siding. This is reflected in the loss curves and metrics in Fig. 11. The one-story retrofit cases (dashed lines in Fig. 11) show a significant reduction in losses compared to the corresponding existing case. However, the stucco retrofits perform slightly worse than wood siding retrofits; opposite of the existing trend. This is due mostly to difference in weight of the structures, with the exterior stucco case weighing approximately 30% more than the wood siding case. Despite the different trend in retrofit performance, the expected benefits provided in Table 1 clearly demonstrate the importance of the existing cripple wall material, with the wood siding case showing two to three times the loss reduction due to retrofit compared to stucco for the metrics presented.

Similar trends are observed for the two-story cases in Fig. 12, yet with a few other observations to highlight. When comparing one- versus two-story, absolute values of loss increase for both existing and retrofit cases. For the existing case, this occurs because the cripple wall for the two-story house must resist approximately 60% more lateral mass than for one-story cases. The increase in the two-story retrofit losses (poorer performance) is due to two factors. The first is that the two-story retrofit has a much stronger design (33% more cripple wall bracing than one-story). This increase in cripple wall strength is coupled with the first occupied story now having an additional story above when compared to one-story cases. The result is that the cripple wall is no longer the weakest story, where the largest displacements move up to the occupied first story of the two-story house. This incurs significant repair costs at higher intensities since the occupied stories are much more expensive to repair than the cripple wall level. This observation suggests that cripple wall retrofit can drive damage into the occupied stories, which is a concern associated with this remedial action. However, this increase in story damage is commonly reported following earthquakes when comparing observations between one- and two-story dwellings without cripple walls. Despite an increase in losses expected for the two-story retrofit cases, the relative benefits compared to the existing cases are shown to be larger for the two-story than one-story cases, as summarized in Table 1.

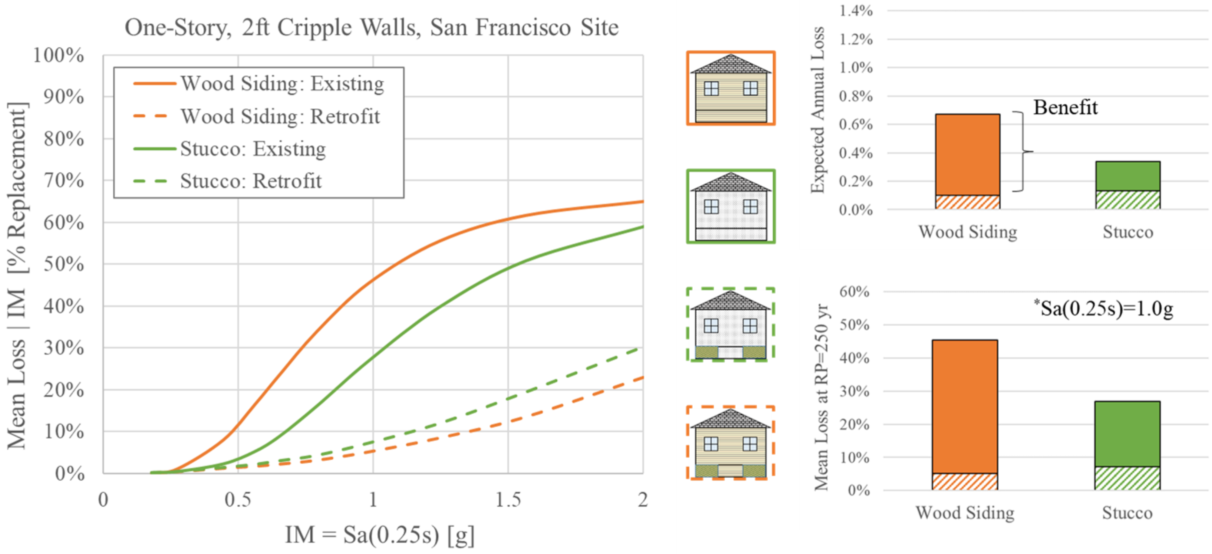

Fig. 11 – Performance estimated for post-1955 era cripple wall dwellings with 2-foot level cripple walls located in San Francisco: One-story dwellings with horizontal wood siding (orange) and stucco (green).

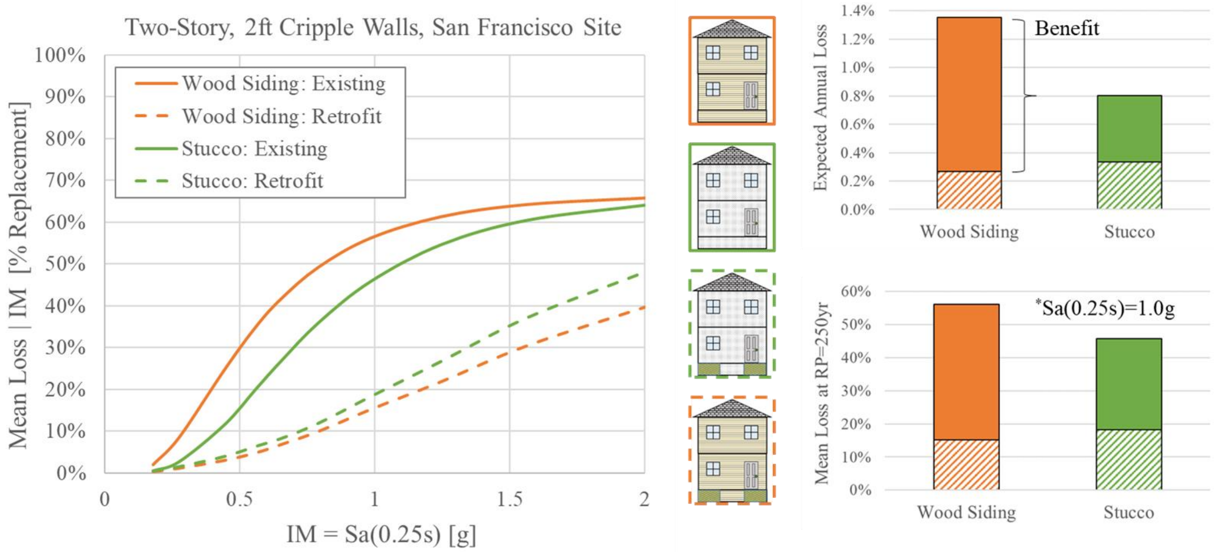

Fig. 12 – Performance estimated for post-1955 era cripple wall dwellings with 2-foot level cripple walls located in San Francisco: Two-story dwellings with horizontal wood siding (orange) and stucco (green)

Table 1 – Performance summary for selected building variants (all values in % replacement cost)

Variant	$\mathbf{EAL}_{\mathbf{Existing}}$	$\mathbf{EAL}_{\mathbf{Retrofit}}$	Benefit		$\mathbf{RC250}_{\mathbf{Existing}}$	$\mathbf{RC250}_{\mathbf{Retrofit}}$	Benefit
1-Story Wood Siding	0.67%	0.10%	-0.57%		45.4%	5.1%	-40.3%
1-Story Stucco	0.34%	0.13%	-0.21%		26.9%	7.2%	-19.7%
2-Story Wood Siding	1.35%	0.27%	-1.08%		56.1%	15.2%	-40.9%
2-Story Stucco	0.80%	0.33%	-0.47%		45.8%	18.2%	-27.6%

*EAL = expected annual loss, RC250 = mean loss at the 250 year return period intensity with Sa(0.25s) = 1.0g for SF site

5. Concluding Remarks

An overview of the PEER-CEA Wood-frame project was presented. With the aim of quantifying the benefits due to retrofit of unbraced cripple wall dwellings, a large team effort was required in order to achieve project goals. Using the FEMA P-58 framework as a basis, the study required the efforts of the many sub-disciplines involved with performance-based earthquake engineering in order to best extend the applicability of building-specific loss assessment to older wood-frame homes. This included extensive review of existing literature and discussion among experts in many fields, in addition to an experimental testing campaign that extended the current knowledge and numerical modelling capabilities of older wood-frame materials.

A select sub-set of archetypes was illustrated to highlight key findings and trends. The analysis results demonstrate a significant range in the reduction in damage and repair costs from retrofit of cripple walls, depending on the house configurations and construction materials. The study finds that older houses with wood siding are considerably more vulnerable to cripple wall failure than houses with stucco exteriors, and two-story configurations are more vulnerable than single-story houses. The benefits of cripple wall retrofit follow accordingly, ranging from substantial reductions in expected annual loss ratios for the most vulnerable two-story wood siding cases to a more modest reduction for the one-story stucco cases.

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