Examining the accuracy and validity of loss estimations using the PBEE methodology for wood residential buildings through integrated experimental findings and expert panel solicitation

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The validity and accuracy of loss estimations using the Performance Based Earthquake Engineering (PBEE) approach compared to the real-world loss estimations is studied through integrated experimental findings (full-scale shake table experiment on a three-story wood residential building) and expert panel solicitation. The panel comprised of experts from academia and industry with a deep knowledge and experience in using the PBEE approach to conduct seismic risk analysis. The expert panel study had two parts focusing on component- and building-level studies. In the component-level study, the experts estimated damage to the components of the building and provided repair specifications and their associated costs and times for the components of the building incurred specific damage states. In the building-level study, the experts assessed damage to the building in details using the damage dataset collected during the shake table experiments, including damage photographs and measurements. Using the assessed damage, the experts prepared a detailed repair procedure to restore the building back to its undamaged condition. The resulting repair cost and time for the building were used as the reference loss to evaluate the accuracy of loss estimations using the PBEE analysis. Loss estimation using the PBEE was conducted using various combinations of damage fragility and loss models from different resources. It was shown that accurate damage and loss models result in loss estimates close to the real-world obtained from the expert panel, while inaccurate fragility or loss models even for one component type of the building can cause significant discrepancies with the reference losses.

Keywords: Performance Based Earthquake Engineering; seismic risk; damage fragility; expert panel; loss assessment.

Introduction

Natural hazards and their effects on communities have been the subject of various studies in the disaster literature. A large number of studies focused on the direct impacts of the disaster loads on the infrastructures (Aghababaei & Mahsuli, 2018; Koliou, Masoomi, & van de Lindt, 2017; Li & Ellingwood, 2006; Bashir & Basu, 2018), while a wide range of others studied resilience of the communities subject to their threatening hazards accounting for both direct impacts and restoration of the community in the aftermath (Aghababaei et al., 2020; Aghababaei, Koliou, Watson, & Xiao, 2019; Dehghani, Fereshtehnejad, & Shafieezadeh, 2020; Dong, Esmalian, Farahmand, & Mostafavi, 2020; Loggins, Little, Mitchell, Sharkey, & Wallace, 2019; Lounis & McAllister, 2016; Moradi & Nejat, 2020; Roohi, van de Lindt, Rosenheim, Hu, & Cutler, 2020). To study direct impacts of seismic hazard, two prominent risk analysis methods are commonly used in the literature, namely, the structural reliability methods and the Performance-Based Earthquake Engineering (PBEE) method (Aghababaei & Mahsuli, 2018; Mahsuli & Haukaas, 2013b; Moehle & Deierlein, 2004; Yang, Moehle, Stojadinovic, & Der Kiureghian, 2009). Structural reliability methods comprise the first- and second-order reliability methods (FORM and SORM, respectively) (Der Kiureghian, 2005), and sampling methods (Ditlevsen & Madsen, 1996). Haukaas (2008) initiated the application of structural reliability methods in risk analysis by proposing a limit-state function based on the resulting seismic loss rather than traditional representations, such as demand and capacity. Mahsuli & Haukaas (2013a) proposed three levels of refinement in conducting risk analysis using structural reliability methods, namely, component, building and region levels. Mahsuli & Haukaas (2013a,b) also presented region and building levels with an application to the Vancouver Metropolitan area, Canada, while Aghababaei & Mahsuli (2019, 2018) introduced models required for the component level analysis along with an application to a building located in a high seismic region in Tehran, Iran. Additionally, the application of structural reliability methods to conduct risk analysis was extended to other types of infrastructures, including transportation networks, levees, and gravity dams (Ganji, Alembagheri, & Khaneghahi, 2019; Rahimi, Dehghani, & Shafieezadeh, 2019; Yazdi-Samadi & Mahsuli, 2018). Risk analysis using the PBEE approach was proposed by the Pacific Earthquake Engineering Research (PEER) Center (Cornell & Krawinkler, 2000; Moehle & Deierlein, 2004), and has been the most prominent method for seismic risk analysis within the literature. This method, which is based on the theorem of total probability and conditional probability models, can be expressed and computed based on a triple integral as follows (Moehle & Deierlein, 2004):

$$v(DV) = \iiint G(DV|DM)\,|dG(DM|EDP)||dG(EDP|IM)|d\lambda(IM) \quad (1)$$

where $v(DV)$ is the annual probability of a decision variable of interest (e.g., monetary loss) exceeding threshold DV, DM is the damage measure, EDP is the engineering demand parameter (e.g., inter-story drift ratio), IM is the intensity measure, $G(.)$ is the complementary cumulative distribution function (CCDF), and $d\lambda(IM)$ is the differential of the mean annual frequency of exceeding the intensity measure. The triple integral of Equation (1) is formed as a product of a number of conditional distributions. Given the earthquake intensity, one distribution expresses the uncertainty of the structural response, another expresses the uncertainty of the damage given the structural response, and finally another models the uncertainty of the decision variable given the damage measure. A large number of studies have employed the PBEE approach to conduct loss assessment and life-cycle cost analysis on various types of building structures, including reinforced concrete (Baradaran Shoraka, Yang, & Elwood, 2013; Liel & Deierlein, 2008; Ramirez et al., 2012), wood (Pei & Van De Lindt, 2009; Porter, Scawthorn, & Beck, 2006; Black, Davidson, Pei, & Lindt, 2010; Muto, Krishnan, Beck, & Mitrani-Reiser, 2008), and steel frame (Cha, Agrawal, Phillips, & Spencer Jr, 2014; Hwang, Elkady, & Lignos, 2015). In addition, numerous studies developed damage fragilities and cost estimation models for a wide range of building components which are key components in conducting the PBEE analysis (Khakurel et al., 2019; Pagni & Lowes, 2006; Petrone, Magliulo, Lopez, &

Manfredi, 2015; Soroushian et al., 2015).

The accuracy level of the PBEE analysis becomes more critical when considering the widespread use of this approach to conduct seismic risk analysis in order to identify mitigation actions for enhancing the resistance and resilience of communities against seismic hazards. Towards that direction, the current study aims to evaluate the accuracy and validity of loss estimation predictions using the PBEE method compared to the real-world estimates through an expert panel study focusing on the response of a shake table test on a full-scale three-story wood residential building. The expert panel consisted of a combination of researchers from academia and industry who have been actively involved in the performance-based design, as well as the response of wood residential structures throughout their career. The shake table test, considered in the expert panel study, was conducted on a full-scale three-story wood residential building subject to strong ground motions, Japan Meteorological Agency (JMA) 100% and Japan Railway (JR) 100% (two ground motions recorded from two stations during the catastrophic 1995 Kobe earthquake) at the E-Defense facility in Miki, Japan (Aghababaei et al., 2021).

In the remainder of this paper, first a review of the PBEE approach is presented followed by the details of the building in the experimental program and the shaking details. Thereafter, the expert panel study and the results solicited from the experts are discussed, and the losses estimated for the damaged building were adopted as the reference real-world loss estimates. In the last section, a set of PBEE analyses using various combinations of damage fragility and loss models from different resources was conducted and the results were compared with the real-world losses estimated by the experts.

Performance Based Earthquake Engineering Approach

In this section, a brief description of the PBEE approach and its implementation to perform seismic risk analysis of buildings is provided. This method is based on the theorem of total probability and conditional probability and presented mathematically in Equation (1). Yang et al. (2009) proposed a framework to implement PBEE practically based on Equation (1) using sampling methods. Although this method can be generalized to various decision variables of interest (e.g., casualties, fatalities, downtime, etc.), Yang et al. (2009) illustrated its application for cost estimation. Based on this study and FEMA P-58 (2012b), five main steps comprise the PBEE approach:

(i) *Define structural and non-structural components of the building and its performance groups*. A performance group (PG) is defined as one or more components of a building with similar performance subject to an engineering demand parameter (EDP).

(ii) *Perform seismic hazard analysis*. In most of the studies, a set of ground motions are selected for this purpose based on the site characteristics. It should be noted that in the current study since results of an experimental study are utilized, seismic hazard analysis is not conducted, and the applied seismic ground motion is known (JMA 100% and JR 100%).

(iii) *Evaluate response of the building and engineering demand parameter (EDP) of each PG*. Studies in the literature used different methods to evaluate EDP of each PG, such as nonlinear time-history analysis and simple linear models. In the current study, EDPs are calculated based on the time-history results obtained from the tested structure using measurement instruments.

(iv) *Estimate the decision variable (losses in most cases) to each PG*. Typically, this is performed by randomly generating a damage state (DS) for each PG based on its EDP using damage fragility functions. In each sample, the realization of damage using fragilities is determined using a uniform random number generated between 0 and 1.

(v) *Accumulate loss to all PGs to calculate the total loss*. After DS for each PG is determined, the repair quantities are summed over all PGs. Considering the bulk repair discount (if applicable), repair cost of the building is calculated by summing cost of different repair types. For example, damage states defined by FEMA P-58 are repair-based damage states, and hence, components damaged to a certain level of damage (e.g., DS1, DS2, etc.) need a specific set of repair activities to return back to their undamaged condition.

This framework is utilized in the current study to estimate loss of the considered building damaged in the shake table experiment. Steps (ii) and (iii) of this framework were not performed in this paper because the applied motion and EDPs of all components are known. Other steps are discussed in details in the following sections. Studies available in the literature (Han, Li, & Van De Lindt, 2017; Haukaas & Javaherian Yazdi, 2013; Yang et al., 2009) adopted sampling-based methods for PBEE analysis to quantify the uncertainties, which is also adopted in the current study, where Monte Carlo sampling is used to include the uncertainties in the resulting economic losses. According to this review of the PBEE approach, the outcomes of this analysis depend on:

(i) How PGs are defined; in the PBEE analysis, components are grouped in some PGs to simplify the analysis, while components in a PG may experience different demands (e.g., inter-story drift ratio (IDR)) during actual earthquakes, and hence, experience different damage levels. In the PBEE analysis, a single damage state is assigned to all components in a PG.

(ii) Damage and loss models used; the descriptions of a damage (or loss) model should exactly fit the characteristics of a component in order for it to be a good representative for the component. Using damage or loss models which are not good representatives for the component in the PBEE analysis can be a source of inaccuracy in the results.

(iii) Method used to aggregate the repair of different component types into the building level considering the real-world assumptions, such as bulk discount on the repair of a large amount of a component type.

In the current study, the effect of these three items on the accuracy of the results of the PBEE analysis were investigates and discussed.

Building and Shaking Details

The building considered in this study was one of the two three-story wood residential buildings tested during a set of shake table experiments conducted on the largest shake table in the world in the E-Defense facility in Miki, Japan (Aghababaei et al., 2021). This experimental program was a part of a five-year project called "Tokyo Metropolitan Resilience Project" to assess resilience of Tokyo urban area (Nagae et al., 2020). These two buildings represent the current trend of construction in densely populated areas in Tokyo, Japan.

The building selected for the purpose of the current study was a full-scale wood residential 161.5 m^2 (1738 ft^2) building constructed using the post-and-beam method. In this structural system, wood let-in X-braces were installed in both horizontal directions to withstand the lateral seismic loads. Elevation views of all four sides of this building are presented in Figure 1, while its plan views of all floors are illustrated in Figure 2. As Figure 2 shows, a garage, kitchen, dining room, along with a bathroom and laundry room were located on the first floor, three bedrooms were located in the second floor, while a master bedroom and a large living room were located on the third floor.

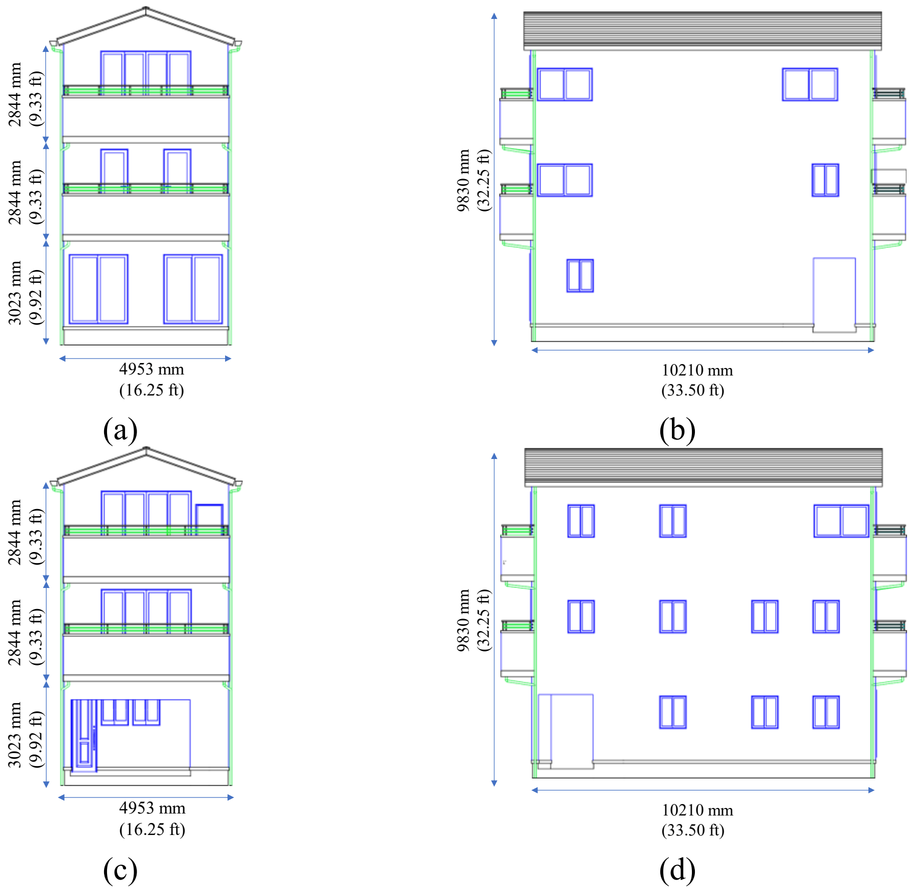

Figure 1: Elevation view of the building: (a) North side, (b) West side, (c) South side, and (d) East side (Aghababaei et al., 2021).

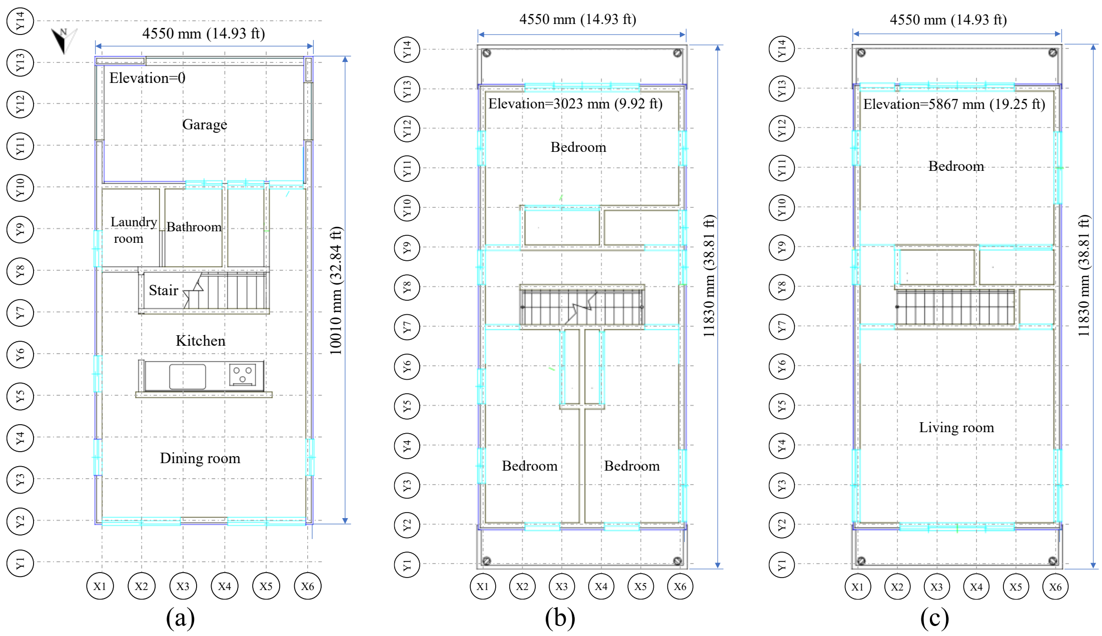

Figure 2: Architectural layout floor plan of the building for: (a) Story 1, (b) Story 2, and (c) Story 3 (Aghababaei et al., 2021).

Three types of component were identified as the main components of the building to be considered in the loss assessment in the current study, namely, wood bracings, partition walls, and façade. These components were divided into different PGs based on their story level (i.e., Story 1, 2, and 3) and their orientations with the North-South direction being direction 1 and the East-West direction being direction 2. This division was adopted based on the definition of PG as components having similar performance subject to the same EDP. In this building, since components of the same type (e.g., partition walls) located in different locations within the building were homogeneous (i.e., had the same characteristics), it was expected that they have similar performance when they are located in the same direction and on the same floor because they were affected by approximately the same EDP. Based on this rule, PGs along with their quantity/amount are summarized in Table 1.

Table 1: Performance groups (PGs) and their quantity/amount throughout the building.

Component type	Story	Direction	
		1 (North-South)	2 (East-West)
Partition walls, m^2 (ft^2)	1	11.0 (118.4)	30.2 (325.5)
	2	18.1 (194.9)	31.0 (334.2)
	3	5.2 (55.7)	23.3 (250.5)
Façade, m^2 (ft^2)	1	60.5 (651.4)	27.5 (296.1)
	2	67.3 (724.3)	25.9 (278.6)
	3	67.3 (724.3)	25.9 (278.6)
Bracing, m^2 (ft^2)	1	46.8 (503.4)	24.8 (266.5)
	2	33.6 (362.2)	38.8 (417.9)
	3	22.0 (236.8)	22.0 (236.8)

The experimental program included four days of shaking, and the building in this study was mounted on a base-isolation system, and hence, experienced very minor damage in the first two test days. In the third day of experiments, this building was fixed on the base to avoid the effect of the base-isolation system on the building movement, while the damages incurred by the building during the third day of experiments along with its structural responses are the focus of the current study. In this (third) test day, the shaking intensities applied were JR 25%, JR 50%, JR 100%, and JMA 100%. Damage observations at the end of this test day were used in this paper as well as the time-history response of instruments installed in the building, measuring maximum inter-story drift ratio of each story in Directions 1 and 2, as presented in Figure 3. These values are the EDPs assigned to each PG of Table 1 and will be used later to predict damage of each PG using damage fragilities (PBEE analysis in Loss Estimation Analysis section of this paper).

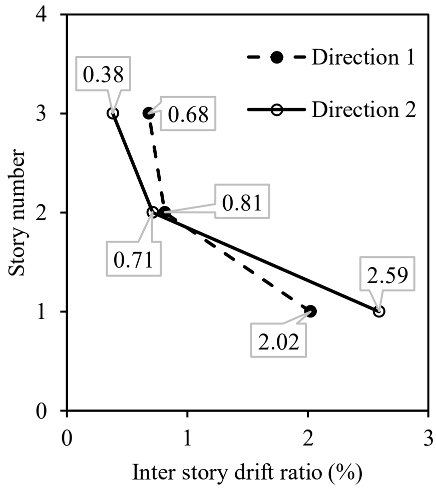

Figure 3: Maximum inter-story drift ratio (%) in all directions at each story in Test Day 3 subject to JMA 100% and JR 100%.

Expert Panel Study Design

The panel comprised of 13 experts from academia and industry with a deep knowledge and experience in using the PBEE approach and FEMA P-58 to conduct seismic risk analysis. This study was conducted in two phases, first, through a set of online questionnaires, and second, through an in-person panel. The response rate in the first phase was 100%, meaning that all experts provided their responses to the online questionnaires prior to the in-person meeting. The expert panel study included tasks on evaluating the damage to the building at the component level as well as developing a restoration procedure/sequence for the considered damaged building and its associated cost and time. More specifically, loss assessment was conducted in two levels of refinement, namely, *component* and *building* levels. In the *component level*, the repair cost of the damaged building was calculated by aggregating repair costs of damaged components using the PBEE approach. For this level of assessment, in Phase I, the experts were asked through online questionnaires to provide repair actions and their associated cost and time to repair/restore a damaged component to its undamaged state. In addition, they assigned appropriate damage states to the components of the damaged building using photographs taken during the shake table experiments. This information was later used in this study to calculate the cost of repair of the building using the PBEE method. For the *building level assessment*, the experts in Phase II, which was held in person, provided repair activities to repair the damaged building along with the cost and time for each repair activity. For this purpose, the experts were provided with sufficient information about damage the building incurred using photographs depicting damage to all parts of the building and tools to conduct damage measurements. The loss estimation in this level of assessment was based on the real-world repair practices, and hence, was employed as a reference to compare the validity and accuracy of estimations resulted from PBEE analyses with various combinations of fragility and loss models. In the following sections, more information about Phases I and II of expert panel solicitation are provided.

Component-level Study

This phase of the expert panel study was conducted through a set of online questionnaires where experts were asked to: (i) estimate the damage to the components of the building through photographs provided, and (ii) propose detailed repair activities to repair each identified component (i.e., partition walls, façade, and bracing) conditioned on a certain level of damage (e.g., DS_i, i=1,…,n, where n is the number of defined damage states) as well as associated cost and time.

Through the online questionnaire (performed ahead of the in-person meeting), the experts were provided with photographs of the damaged components, and based on their observations they could choose one DS among a list of predefined DSs. Figure 4 presents an example of the photographs provided in the online questionnaire for a façade component. The experts assigned a DS to each component from a list of DS definitions provided to them based on the observations from the photographs and their engineering judgment. These DS definitions were adopted from the literature with the majority from FEMA P-58 (2012a), as tabulated in Table 2. Since FEMA P-58 has not provided individual fragility functions for partition walls with *wood* studs, this study employed damage state descriptions from the damage fragility models proposed by FEMA P-58 for gypsum wallboards on the interior side of perimeter walls with Oriented Strand Board (OSB) and stucco on the exterior face for the first two damage states (DS1 and DS2). For damage state three (DS3), no fragility function is provided and hence, the description of the damage is captured from fragility models of gypsum wallboard partition walls with *steel* studs. In addition, three damage states are proposed for plasterboard façade in the current study as described in Table 2. For diagonal bracing, only one damage state is defined as the failure of the bracing elements. According to the responses by the experts, a DS was assigned to each PG as presented in Table 3. These results were used later in this study as prescribed/deterministic DSs in the PBEE analysis for estimating the time and cost of repair of the building.

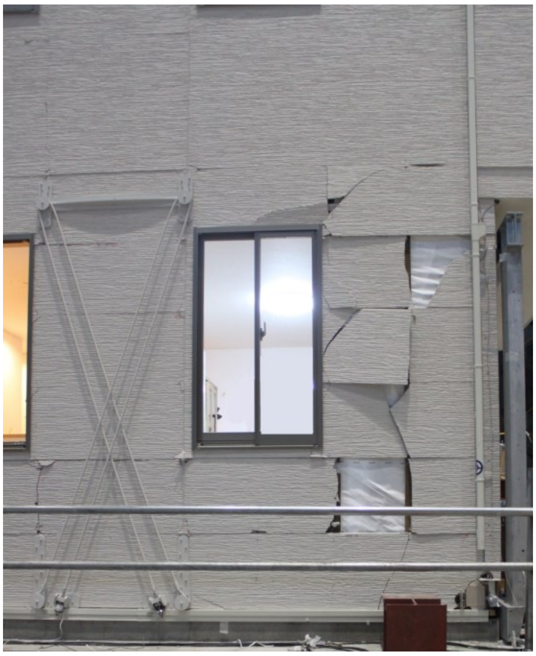

Figure 4: A sample photograph provided to the experts in the online questionnaire to estimate the damage to façade components.

Table 2: Damage states and their brief description.

Component	**Damage States**	**Description**	**EDP**
Gypsum wallboard partition walls	DS1	Minor damage on gypsum wallboards that can be repaired without need to replace them.	ISD(%)
	DS2	Severe cracks, spalling, or out-of-place buckling of wallboards that needs replacement of boards.	ISD(%)
	DS3	Damage to studs, so needs replacement of the wall.	ISD(%)
Diagonal bracing	DS1	Failure of diagonal bracing members.	ISD(%)
Plasterboard façade	DS1	Minor cracks on the tapes connecting sidings or minor cracks on the boards.	ISD(%)
	DS2	Large and extensive cracks on the tapes and considerable cracks on the sidings.	ISD(%)
	DS3	Buckling and spalling of sidings.	ISD(%)

Table 3: Summary of damage state estimations for each PG based on expert panel results.

Component type	Story	Direction	
		1 (North-South)	2 (East-West)
Partition walls	1	DS2	DS2
	2	DS1	DS1
	3	DS0	DS1
Façade	1	DS0	DS2
	2	DS0	DS1
	3	DS0	DS0
Bracing	1	DS0	DS0
	2	DS0	DS0
	3	DS0	DS0

In the second step of the component-level assessment, another set of online questionnaires were designed to acquire the experts' estimations related to the unit repair cost and repair time of the components of the building. These estimates were later used to aggregate the repair costs and times of the damaged components to calculate the cost and time needed to repair the damaged building in the PBEE analysis. To do so, repair activities for each component to return back to its undamaged state were collected from FEMA P-58 involving a series of repair activity categories including: (i) *Demolition*: it refers to the demolition of all parts that are damaged and not reusable or impossible not to be demolished in the repair process (such as wall finishes when repairing a bracing element inside the wall), (ii) *Remove, store, and reinstall*: it comprises all parts which are reusable, and hence, they are removed, stored, and reinstalled again once the repair process is finalized (like furniture and mechanical and electrical components), (iii) *Temporary actions*: it encompasses the temporary actions during the repairs needed for the execution of the repair activities and/or to protect other parts of the building during the repair process (for example, shoring and scaffolding, floor protections, and dust curtains), (iv) *Necessary repairs*: it entails repairing the damaged component of interest to its pre-event state, and (v) *Replacements*: it focuses on replacing the parts demolished during the repair (like demolished wall finishes). It should be noted that some repair items involve demolition and then replacement of the component which is conventionally evaluated as a single repair activity for cost estimation purposes. As a result, categories (i) and (v) mentioned above may be combined for cost estimations in some cases.

As an illustration of repair activities, per the FEMA P-58 consequence estimator tool (FEMA P-58, 2012a), a sample repair activity is presented in Table 4 for a metal stud gypsum wall partition experiencing damage state 3 (DS3 in Table 2) to return back to its pre-damage state. The estimated amount of repair per item, unit costs, and total costs according to the approximations provided by the consequence estimator tool of FEMA P-58 are included in Table 4. It should be noted that the estimates refer to a wall of 30.48 meters (100 ft) length and 3.96 meters (13 ft) height damaged at DS3. For each individual component, the repair activities, their associated costs, and times were studied and quantified based on expert opinions similar to what presented in Table 4. Similar templates related to the repair activities based on the consequence estimator tool of FEMA P-58 were provided to the experts in order to revise the activities based on their judgement and experience as well as provide estimates for the associated repair costs and times.

Table 4: Sample repair activities for a metal stud gypsum wall partition experienced DS3.

Repair activities	**Quantity**	**Unit**	**Cost/Unit ($)**	**Total Cost ($)**
Remove, store and reinstall				
Office furniture and equipment	1	—	500.00	500
Mechanical and electrical components	1	—	3000.00	3,000
Temporary actions				
Floor protection	55.74	m^2	43.06	2,400
Demolition and Replacements				
Remove and replace wood studs	120.77	m^2	12.42	6,500
Remove and replace gypsum wallboards	241.54	m^2	64.59	15,600

According to the results of the questionnaires, lognormal distributions were fitted to the experts' responses for repair costs and times, as presented in Table 5. To develop each distribution, 13 datapoints resulted from the online questionnaires were used and Kolmogorov-Smirnov (K-S) test at 5% significance level was used to check for goodness of fit. These values were then used in the PBEE analysis to estimate the repair time and cost to restore the damaged building to its undamaged condition.

Table 5: Lognormal distributions for repair cost and time fitted to responses of experts.

Damage State	Cost ($)		Time (Days)	
	Mean (μ)	Standard deviation (σ)	Mean (μ)	Standard deviation (σ)
Partition wall (100 ft L × 13 ft W)				
DS1	6.689	0.912	0.446	0.931
DS2	8.504	1.120	1.441	0.919
DS3	8.942	1.373	2.192	0.924
Façade (100 ft L × 13 ft W)				
DS1	8.320	1.214	1.547	0.971
DS2	8.357	1.028	1.519	0.846
DS3	9.362	1.066	2.600	0.714
Bracing (100 ft L × 13 ft W)				
DS1	9.913	1.118	2.939	0.810

Building-level Study

This part of the study was conducted through an in-person meeting with the 13 experts that previously responded to the online questionnaires. In contrast to the previous part where the experts were asked to fill out the online questionnaires individually, it was necessary for the second part to have a panel discussion in order to: (i) discuss the summary of the results of the first part (e.g., component-level study) and any necessary modifications/adjustments, and (ii) develop restoration steps to repair the damaged building.

First, a summary of the results of the online questionnaires, such as their damage assignments to each PG (shown in Table 3) as well as cost and time estimates for each DS (shown in Table 5) were presented to the experts. After a thorough discussion related to their criteria in responding to the questions (online questionnaire), a number of experts requested to re-respond to one or more of the questionnaires after the meeting to modify some of their responses. This step was required to ensure experts had enough understanding of the objective of the questionnaires and responded to them to the best of their knowledge and expertise. The results provided in the previous section represent outcomes after the modifications were applied.

Second, in order to develop a restoration procedure, two tasks were performed during the in-person meeting: (i) Task 1 related to detecting and quantifying the damage, and (ii) Task 2 focused on developing a repair procedure and the consequent costs and times. These two tasks are discussed in detail in the following sections.

Task 1: Damage inspection and quantification

In this task, the amount of damage to the building components was estimated. Experts were divided into five groups of two and one group of three such that preferably one expert from academia and one from industry were assigned to each group. Prior to the meeting, the building was divided into sections so each group estimated the amount of damaged components and their extent (e.g., DS_i, i=1,…,n, n=number of defined DSs) in their assigned sections. For this purpose, as demonstrated by an example in Figure 5a, the architectural layout floor plan of the building was provided to the groups with their section marked in red so they were directed to their assignment. As shown in Figure 5a, dimensions were also added to the plan to allow them making calculations when estimating the amount of damage. To estimate damage, simple and panoramic photographs of the assigned sections were provided to each group so they could also conduct visual damage inspection. An example panoramic photograph used by one of the groups to estimate damage in a section of the building is presented in Figure 5b, and the experts were able to zoom into these high-quality photographs to inspect damage from a closer view and they could utilize other simple photographs to further inspect the damage. Using these photographs and dimensions on the floor plans, experts quantified the extent of damage, and a summary of this task's results is provided in Table 6 as the amount of damage in m^2 (and ft^2 in the parenthesis). This table does not show any results for bracings because per the experts' opinion no bracing had experienced failure in this test. According to the results of Table 6, damage to partition walls was detected in all stories of the building with the most extent in the first story, while no component was classified as DS3 per the experts' opinion. Furthermore, damage to the building's façade was detected only in the first two stories with the most extent in the first story, while no component was classified as DS3. The total amount of components in each DS are presented in bold in Table 6, which will be later used in Task 2 to estimate cost and time of repair.

Figure 5: A section assigned to a group for detailed damage assessment: (a) architectural layout floor plan of the building with the assigned section highlighted in red, and (b) a panoramic photograph of the section used for damage assessment.

Table 6: Amount of damage estimated by experts for each component type in m^2 (ft^2).

	DS1	DS2	DS3
	Partition wall		
Story 1	20.8 (223.4)	51.3 (552.4)	0
Story 2	29.0 (311.7)	0	0
Story 3	15.5 (166.8)	0	0
Total	**65.2 (701.9)**	**51.4 (553.5)**	**0**
	Façade		
Story 1	5.1 (55.4)	14.1 (151.9)	0
Story 2	0.9 (10)	0	0
Story 3	0	0	0
Total	**6.1 (65.4)**	(151.9)	**0**

Task 2: Restoration procedure and cost/time estimates

In the second task, a summary of the teamwork by experts to estimate the extent of damage (as shown in Table 6) was presented to them followed by a panel discussion to develop a repair sequence based on real-world repair practices. After a comprehensive discussion, experts proposed repair activities to restore the building back to its undamaged condition as presented in Table 7. For each repair activity in this table, experts provided an estimated unit cost based on the San Francisco Bay area as the assumed location of the building. In addition, values from Table 6 were captured and used in Table 7 as the amount of each repair activity. According to Table 7, the average total repair costs of the damaged partition walls and plasterboard facade are estimated to be \$5,702 and \$3,421, respectively, which leads to a average total building repair cost of \$9,123. In addition, the experts provided the upper and lower bounds for the 90% confidence interval for their total cost estimations, as are presented in Table 7, similar to the method used by FEMA P-58 consequence estimator tool. The experts did not propose repair times for each repair activity since these activities may have overlaps. Rather, they estimated the required time to repair all damaged partition walls and all plaster board façade, to be approximately two days with two workers, and one day with two workers, respectively. Based on these estimates, repair time of the building was computed to be two days if repair of interiors and exteriors are performed simultaneously, and otherwise, three days would be needed. It should be noted that the experts emphasized the importance of considering impeding factors which delay the construction, similar to the observations from previous major disasters (Aghababaei et al., 2020; Almufti & Willford, 2013). Repair activities in Table 7 represent actions from the initiation of repair after funds are secured, contractors are hired, and repair materials are acquired. The experts also mentioned the impeding factors tabulated in Table 8 as significant delay contributors after major earthquakes and for some of these factors, they provided estimated delays. Impeding factors of Table 8 represent delays in the initiation of construction starting from tagging the building after earthquake based on its safety and ranging to pre-mobilizations to start the repair. As mentioned, based on the expert panel study's outcomes, the repair time was estimated approximately 2-3 days after the initiation of the repairs, which is a negligible timeframe when comparing to the long delays due to impeding factors identified in Table 8, which could take weeks or months to overcome.

Table 7: Repair procedure proposed by the expert panel to repair the building back to its undamaged condition.

Repair activity	Unit cost ($)	Amount	Average total cost (upper bound-lower bound) ($)
Partition wall			
Storing the appliance and furniture	0	1	0
Floor protection, dust screens	0.75	1,500 ft^2	1,125
Remove damaged materials (DS2)	2	553.5 ft^2	1,107
Survey and discovery	600	1	600
Gypsum wallboard (DS2) including taping, drywall mud, sanding	3	553.5 ft^2	1,661
Taping, drywall mud, sanding (DS1)	0.6	701.9 ft^2	421
Trim around all opening and all walls and caulking around	0.15	1,255.4 ft^2	188
Replacing the damaged door	500	1	500
Put the railing back	100	1	100
Partition walls total repair cost			**5,702 (2,280-8,000)**
Façade			
Detach boards and remove any damaged caulking (DS2)	2	151.9 ft^2	304
Survey and discovery after the facades are removed - water damage?	1500	1	600
Replace insulation if needed	0.9	151.9 ft^2	137
Air infiltration & Moisture barriers to be installed on top of insulation	0.5	151.9 ft^2	76
Replace panels	15	151.9 ft^2	2278
Caulking around the panels	0.4	65.4 ft^2	26
Façade total repair cost			**3,421 (1,200-5,642)**
Building total repair cost (partition walls + façade)			**9,123 (3,648-12,790)**

Table 8: Impeding factors delaying the repair.

Impeding factor	Estimated delay
Tag the building (e.g., red, yellow, or green)	3-7 days
Insurance payout, FEMA assistance (especially for non-significant damage), and securing funds	4-12 weeks
Scoping and getting quote from contractors	3 weeks to 6 months
Acquiring engineer's inspection	—
Construction permit approval	—
Preparation for repair actions, getting supplies, cleaning, etc.	—
Pre-mobilization	—

Loss Estimation Analysis

Loss Estimation using the PBEE approach

In this study, three initial cases with different combination of tools to estimate the building damage and associated losses were considered. These cases were further modified afterwards to yield estimates closer to the results of the building-level expert panel study, which hereafter are referred to as reference losses. Figure 6 presents these three initial cases, the applied modifications, and their outcomes, where the mean repair cost of each component type along with the mean total repair cost of the building resulted from Monte Carlo sampling are presented for each case in the initial condition and after applying the modifications. The costs are highlighted with three colors of red, green, and black, where *red* means that the calculated cost is larger than the upper bound of 90% confidence interval provided by the experts (see Table 7), *green* means that the calculated results are within the 90% confidence intervals provided by the experts in Table 7 and also the description of fragilities used are compatible with the details of the components in the full-scale shake table test considered in this study, and *black* means that the calculated cost is within the confidence interval but the fragility model used was not a proper representative. *Blue* color was also used to illustrate any applied modifications at each step indicating the updated fragility and/or loss model in Figure 6. Since the results of Case 2 were satisfactory from the initial analyses (i.e., all costs are highlighted in green), no further modifications were applied on it.

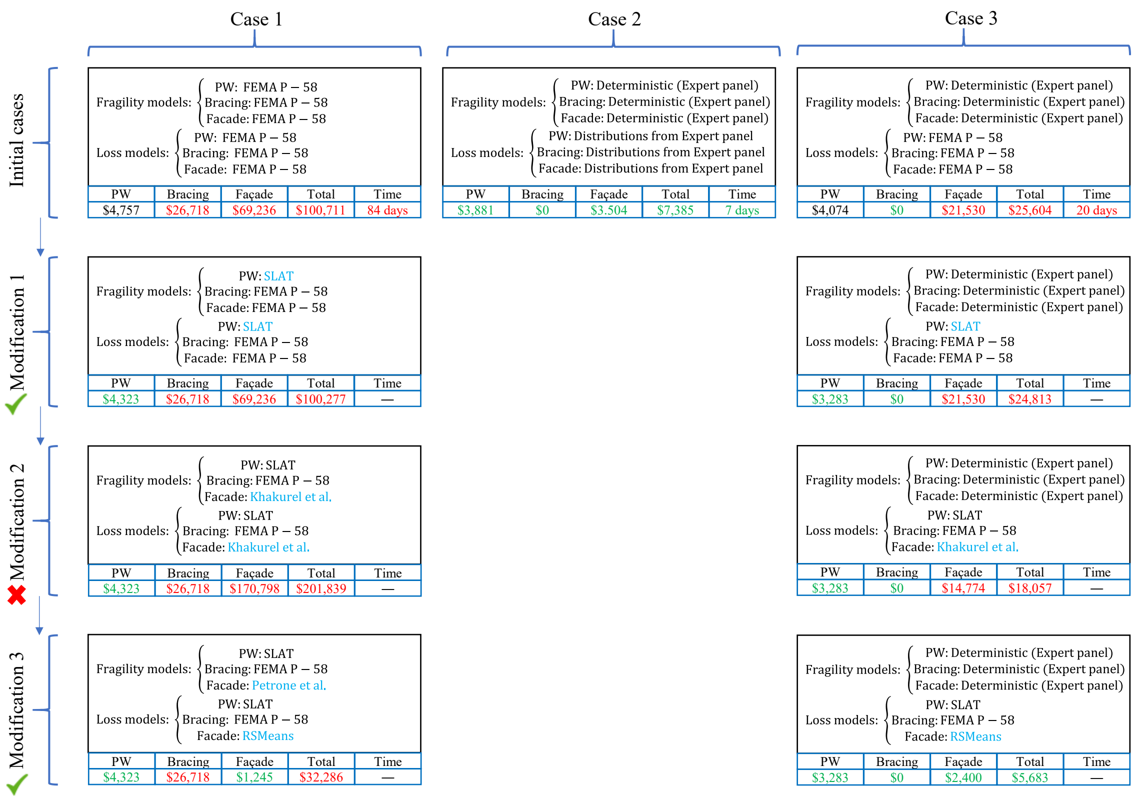

Figure 6: Three initial cases in this study, the adopted modifications, and their effects.

As Figure 6 presents, in Case 1, the PBEE analysis was initially conducted using fragility and loss models all adopted from FEMA P-58 resources. Although it was attempted to adopt the most representative fragility and loss models for the three main components of the building in this study (i.e., partition wall, façade, and wood bracing), the selected models did not match the exact details of the components in this study. The selected components from FEMA P-58 and their differences with the components in the current study are described below:

(i) Partition walls (item C1011.001a in PACT): gypsum wallboard with steel studs, full height, fixed below, and fixed above. The main difference is that partition walls in the current study had wood studs, but the selected component from FEMA P-58 has steel studs. Although there is one wood stud partition wall representative (item C1011.011a in PACT) in FEMA P-58, the description of damage states had major discrepancies, and hence, it was decided to use the one with steel stud as a starting point.

(ii) Bracing (B1071.031): wood walls with diagonal let-in bracing. The descriptions of this component in FEMA P-58 was similar to the wood bracing in this study.

(iii) Façade (B2011.001b): exterior wall with cold formed steel walls with wood structural panel sheathing and exterior-stucco on one side. There was no component in FEMA P-58 matching the details of the plasterboard façade used in the building in this paper. The selected candidate had the closest construction details and damage state definitions to the one used in the experimental study.

In Case 2, no damage fragility was utilized, and rather, deterministic damage states resulted from the component-level study of this paper, as presented in Table 3, were adopted. In addition, loss distributions from Table 5 resulted from the component-level study were employed in the PBEE approach to estimate the unit repair costs.

In Case 3, deterministic damage states for the PGs similar to Case 2 were used, while loss distributions from FEMA P-58 were employed to calculate the repair cost and time per unit of repairs. Results of this case compared to Case 2 indicated the effect of loss models on the calculated building loss.

Results of all three aforementioned initial cases are presented in Figure 6, including the average repair cost of the building and its disaggregation into its component types (i.e., partition wall (PW), bracing, and façade). By comparing the results of Figure 6 with the reference losses (i.e., loss estimates obtained from the experts) in Table 7, it can be observed that Case 1 has largely overestimated the repair cost of the building. The disaggregated repair costs show that large repair cost estimates for bracings and façade are driving this large number calculation. In contrast to Case 1, the repair cost estimate in Case 2 ($7,385) is within the 90% confidence intervals estimated by the experts and is

20% lower than the average reference loss implying that by using accurate damage and loss models, the PBEE approach is able to give estimates close to what expected by the experts (i.e., close to the real-world estimates). The reason for the 20% difference between these estimates ($7,385 compared to $9,123) can be attributed to the damage and cost estimation conducted in the expert panel and the PBEE approach. In the PBEE approach, a single DS is assumed for all components in a PG (e.g., all partition walls in a story in direction 1), while the experts in this study conducted a detailed damage assessment for all components separately without grouping them. In addition, the PBEE approach aggregates repair cost of all components considering a bulk discount, while the experts in this study proposed a repair procedure based on the detailed damage assessment and calculated cost and time accordingly. In spite of these differences, results of the PBEE analysis in Case 2 was within the 90% confidence interval provided by the expert panel study. Similarly to Case 1, results of Case 3 indicate a considerable overestimation of repair cost and time compared with the expert panel results. The only difference between Case 2 and 3 was loss distributions used in these cases, and hence, this large difference can be attributed to the fact that the cost and time distributions adopted from FEMA P-58 were not good representatives for the building under study. Furthermore, the only difference between Cases 1 and 3 is that damage fragilities from FEMA P-58 are utilized in Case 1, while deterministic DSs resulted from the expert panel were used in Case 3. Since results of Case 1 are significantly larger than Case 3, it was concluded that inappropriate damage fragilities are exacerbating the discrepancies between the loss estimates through the PBEE analysis and the reference losses.

To further modify the results of Cases 1 and 3, a detailed literature review was conducted to identify more representative damage fragility models and loss distributions from resources other than FEMA P-58. Journal papers and technical reports (Black, Davidson, Pei, & Lindt, 2010; Bradley, 2009; Filiatrault et al., 2010; Fiorino, Bucciero, & Landolfo, 2019; Khakurel, Yeow, Chen, Wang, Saha, & Dhakal, 2019; Muto, Krishnan, Beck, & Mitrani-Reiser, 2008; Petrone, Magliulo, Lopez, & Manfredi, 2015; Porter et al., 2002; Porter, Beck, & Shaikhutdinov, 2002) were considered for possible fragility and loss models, however, no possible fragilities matching the details of the diagonal let-in wood bracings were found in any resource. As a consequence, the same bracing used in Case 1 was used in the next steps as well, and this indicates a shortcoming of the literature on damage fragilities for wood bracings. From the set of models extracted initially, the selection was later narrowed down to those more appropriately matching the descriptions of the building components in this study, their damage states, and repair measures (as identified in blue in Figure 6).

As Figure 6 shows, in Modification 1, a better representative of partition walls was employed from Seismic Loss Assessment Tool (SLAT) (Bradley, 2009), which is a computer program (similar to PACT in FEMA P-58) to perform seismic loss assessment of structures subject to earthquakes. The adopted partition wall had gypsum wallboards and wood studs compared with the initially selected model from PACT that had steel studs, while the damage state definitions also exactly matched the definitions provided in Table 2. By substituting this component into Cases 1 and 3, the resulting repair costs of partition walls decreased by 9% and 19% for Cases 1 and 3, respectively, as summarized in Figure 6. Although this reduction was not considerable, it was concluded that the new partition wall employed from SLAT represents better the partition walls used in the tested building as it better matches their characteristics. After this point, fragility and loss models from this type of partition wall were utilized in the PBEE analyses.

As the second modification effort, this study looked for more accurate representatives for the façade components since the details of the façade adopted from PACT had significant differences with the used façade in the test. As Figure 6 illustrates, damage fragility and loss distributions of a monolithic cladding from a study by Khakurel et al. (2019) on different types of cladding were employed in Modification 2. According to Figure 6, the computed repair cost in Case 1 significantly increased by this modification from around $100k to $200k. It was found out that this significant increase stems from the sensitivity of this type of cladding to small inter-story drift ratios which in turn significantly increased the predicted DSs (i.e., most façade were classified as DS3). On the other hand, average repair cost of the façade and consequently the building's were reduced in Case 3, which is attributed to the fact that only the loss model from monolithic cladding was utilized in Case 3 and deterministic DSs from expert panel were adopted. These two cases imply that damage fragility of this monolithic cladding is not a good candidate for the current study, and hence, Modification 2 was rejected and not adopted in the remaining of the study.

The second candidate selected to represent the plasterboard façade was plasterboard partitions tested by Petrone et al. (2015). Although they were partition walls, their construction and material details as well as fragility specifications were similar to the plasterboard façade in the current study, and hence, they were among the closest available candidates in the literature. Since the study by Petrone et al. (2015) only contained damage fragilities and not loss model, repair cost estimates were adopted from the RSMeans catalog (Mewis, 2018). To calculate the unit replacement cost of plasterboard façade, both construction and demolition costs were accumulated from the RSMeans, which represents unit repair cost of DS3. The calculated repair cost and time prescribed as DS3 were then proportioned into DS1 and DS2 using the costs for PACT item B2011.001b, which was initially used as the façade in the Case 1. Ultimately, fragilities from Petrone et al. (2015) and loss distributions resulted from RSMeans were used together as Modification 3 and results are provided in Figure 6, where the calculated repair costs in Cases 1 and 3 reduced significantly and reached closer to the reference losses in Table 7. This means that the last modifications better represent the damage mechanism of the components of the building in this study, and loss distributions utilized are closer to the real-world estimates computed by the expert panel. Case 1 still has a large total repair cost which is due to large repair cost value of bracings. No appropriate candidate for wood bracings was found in the literature, and as a consequence, the same model initially captured from FEMA P-58 was used in Case 1 when applying all modifications.

Comparison and Discussion of Results

To better compare the results of the applied modifications on the results of each case, repair costs for partition walls and plasterboard façade are presented separately in Figure 7a and b, respectively. Additionally, Figure 7c presents the calculated total repair cost in each case once the described modifications were applied. As Figure 7a shows, although not significantly, repair cost of partition walls in all cases was underestimated compared to the reference estimates provided by the experts. On the contrary, Figure 7b shows significant overestimation of repair costs for the plasterboard façade in Cases 1 and 3 compared to the reference estimates by the experts prior to adopting Modification 3, indicating that after this modification repair cost estimates of plasterboard façade in Case 3 got close to the reference estimates. Finally, Figure 7c presents the significant difference between the total cost estimates compared to the reference estimates in all cases prior to Modification 3. Overall, Figure 7 indicates that the results of Case 2 were very close to the reference losses (within the 90% confidence interval and 20% above the average reference total loss) indicating the importance of damage and loss models in the accuracy of the resulting losses in the PBEE methodology. In Case 2, damage states of all performance groups were assigned deterministically by the experts after careful damage assessment of the building, while loss models from the expert panel solicitation were utilized. These loss distributions were developed based on the repair cost estimates of each performance group considering their details and material characteristics, and hence, were an accurate representative of their unit repair cost.

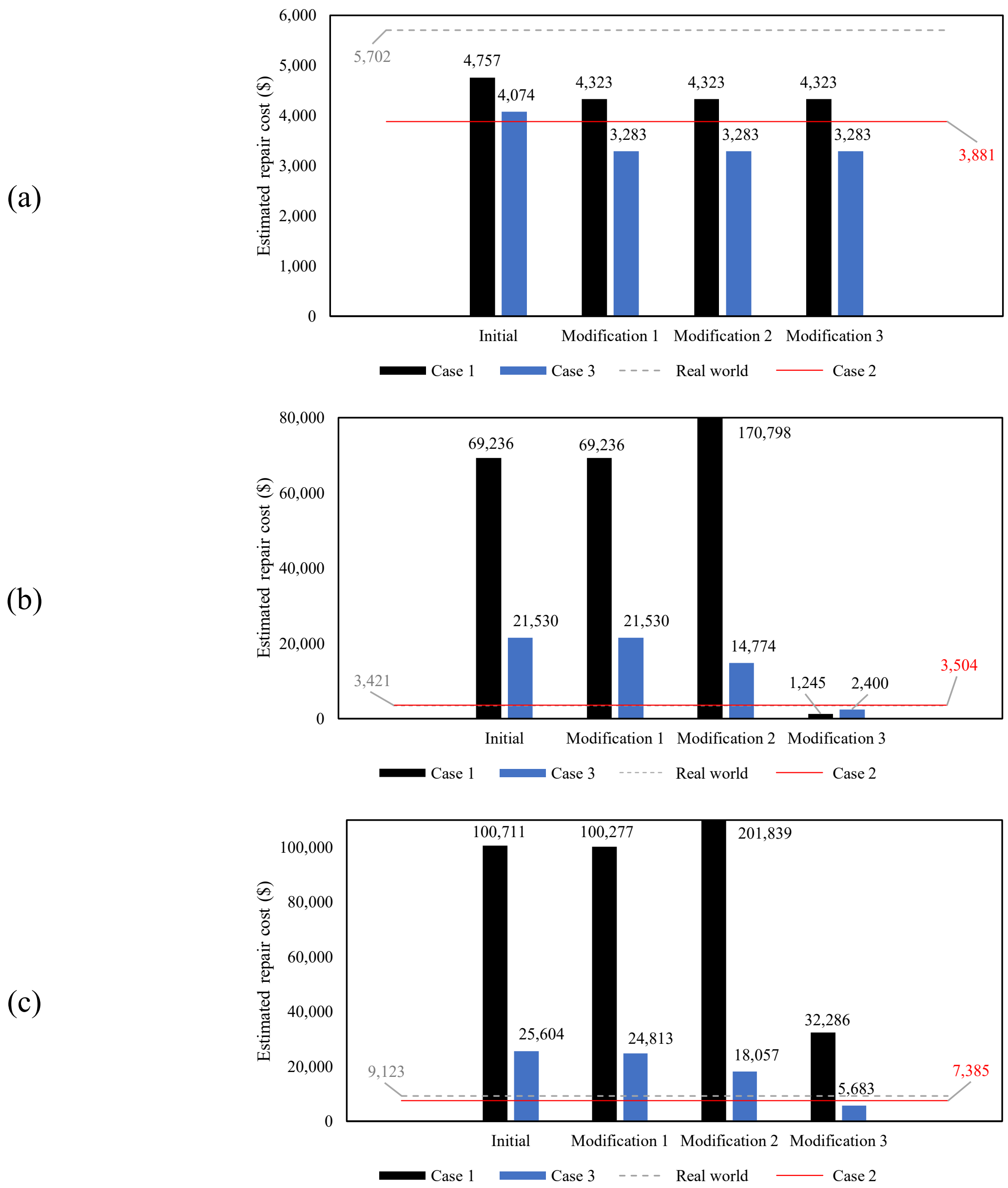

Figure 7: Comparison of the estimates of (a) partition wall repair cost, (b) façade repair cost, and (c) building toral repair cost with the real-world estimates (i.e., reference losses).

Based on the sensitivity study conducted and presented herein the findings are as summarized below:

(i) With accurate damage fragility and loss models (e.g., cost distributions), the PBEE analysis yields results close to the real-world loss estimates provided by a group of experts. The calculated losses in Case 2 of this study as well as Case 3 after applying Modification 3 were close to those estimates because accurate damage estimates and appropriate loss models were utilized. Although loss in these cases was underestimated compared to the real-world reference losses, the accuracy of the results was acceptable (within the 90% confidence interval) considering the simplicity (e.g., all components in a PG are assigned the same DS) and efficiency of the PBEE approach compared to the detailed loss assessment conducted in the expert panel.

(ii) Inaccurate damage and loss models even for one building component can cause significant inaccurate repair cost estimates, which indicates the significance of adopting appropriate models in risk analysis using the PBEE methodology. This is of great importance considering the aim of the PBEE to be utilized in studying the performance of a building or a portfolio of buildings subject to seismic loads. Typically, the results of such analysis are utilized to make decisions for mitigating the seismic risk.

(iii) Although FEMA P-58 encompasses a large number of building components, it lacks many other commonly used building components, such as partition walls with wood studs, wood bracings, and different types of façade. As a consequence, users may not be able to conduct the PBEE analysis using only the fragility and loss models provided in this resource. In the current study, since proper representatives for the components of the building under study were not identified in the FEMA P-58, further explorations were conducted in the literature. It was indicated that adopting fragility and loss models only from FEMA P-58 (Case 1 before modifications) resulted in inaccurate building loss estimation for the tested building in this paper.

(iv) There are no appropriate representatives for damage fragility and loss distribution of wood bracings in the literature. Although this component is not very common in the US, it is widely used in other countries (e.g. Japan). Hence, more research is required to develop fragility and loss models for this component. One method to overcome the lack of appropriate damage fragilities is developing analytical damage fragilities using methods such as finite element modelling, as was discussed and addressed in the literature for pipelines (Iannacone & Gardoni, 2018; Jahangiri & Shakib, 2018; Makhoul, Navarro, Lee, & Gueguen, 2020; Tsinidis, Di Sarno, Sextos, & Furtner, 2019b, 2019a, 2020) and other infrastructure (Kakareko, Jung, & Vanli, 2020; Karim & Yamazaki, 2001; Li & Ellingwood, 2006; Mishra, Vanli, Kakareko, & Jung, 2019; Pinelli et al., 2011).

Summary and Conclusions

This paper targeted the area of seismic risk analysis using the Performance Based Earthquake Engineering (PBEE) approach which is a commonly used method to conduct risk analysis for physical systems. This study utilized the structural response and damage observations from a full-scale three-story wood residential building tested on the largest shake table in the world in the E-Defense facility in Miki, Japan, to study the validity and accuracy of the loss estimations using the PBEE analysis. For this purpose, a panel comprised of experts from academia and industry with extensive experience in utilizing PBEE method was conducted. This expert panel study had two focuses of component- and building-level studies. In the component-level study, the experts performed damage assessments on the components of the damaged building. In addition, they provided repair activities and their associated costs and times for the building component types (partition walls, façade, and bracing) incurred certain damage states to repair them back to their undamaged state. The results of the component-level study were then used in the PBEE analyses. In the building-level study, the experts first inspected the damaged building through photographs and measurements provided to them from a damage dataset collected during the shake table experiments. After a thorough discussion, the experts proposed a detailed restoration plan for the damaged building to repair it back to the undamaged state. The estimated costs and times provided in this step by the experts were adopted as the real-world loss estimates to be used as a reference to investigate validity and accuracy of the PBEE analysis results.

Loss estimation using the PBEE methodology started with three initial cases. **Case 1** included damage fragility and loss distributions for all components employed from FEMA P-58, which is a commonly used resource for this purpose; **Case 2** included deterministic damage states and cost and time distributions adopted from the component-level study of the expert panel, while **Case 3** included deterministic damage states similar to Case 2, but with cost and time distributions from FEMA P-58. After conducting the PBEE analysis on these three initial cases, major discrepancies were identified between loss estimates of Case 1 and 3 compared to the real-world estimates provided by the expert panel during the building-level study (i.e., reference losses). In contrast, results of Case 2 were close to the reference losses which indicates the validity of the PBEE methodology when appropriate damage and cost models and estimates are employed (i.e., when damage and loss are estimated accurately). A sensitivity analysis was then conducted to identify the main sources of these discrepancies identified in Cases 1 and 3, based on which some modifications were further adopted and examined to enhance the results. These modifications included employing more representative damage fragilities and loss models for partition walls and façade of the building from resources other than FEMA P-58. By adopting these modifications, the results of Case 3 got close to the reference losses. Based on the literature review in this study, there were no alternative damage fragility and loss model for wood bracing elements other than the ones employed from FEMA P-58. This caused a large bracing repair cost resulting in also large building total repair cost in Case 1, even after modifications for partition walls and façade were adopted. By comparing results of Case 1 and Case 3, it was indicated that how inaccurate damage and loss estimates only for one component type can end up in a very large and inaccurate building total loss results indicating that researchers should choose models for estimating damage and loss accurately. The results of the PBEE analyses typically are used to make decisions to enhance the resilience of a community or a building portfolio, which indicates the significance of accuracy of the resulting losses.

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