PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

Development of Index Buildings

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 2020/13

Pacific Earthquake Engineering Research Center

Headquarters, University of California at Berkeley

November 2020

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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 2: *Development of Index Buildings* and focuses on the identification of common variations and combinations of materials and construction characteristics of California single-family dwellings. These were used to develop "Index Buildings" that formed the basis of the PEER–CEA Project testing and analytical modeling programs (Working Groups 4 and 5). The loss modeling component of the Project (Working Group 6) quantified the damage-seismic hazard relationships for each of the Index Buildings.

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EXECUTIVE SUMMARY

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Based on discussions among the PEER–CEA Project Team Working Group (WG) 2, a review of available documentation and research, and discussions with representatives from ATC-110, the CEA, and PEER Project Leadership and Review Panels, the Project Team identified the building variants to be considered in the development of the Index Buildings. The inclusion of a variant was based on three criteria:

- A significant representation among California homes (in excess of approximately 10% of housing stock, based on census or research data, or expert opinion);
- The potential to have a significant impact on building earthquake damage (assume approximately +/-5% of replacement cost, based on expert opinion to be verified through testing and analysis); and
- The amount of damage *reduction* resulting from the seismic retrofit of the cripple wall is dependent upon the presence of the variant.

Variants were divided into five categories.

- Primary, observable characteristics that broadly define the building (*date of construction and number of stories*);
- Secondary, observable characteristics (*siding, building weight including light and heavy roofs, bolting, and cripple wall dimensions*);
- Secondary characteristics that the typical underwriter or home inspector cannot generally observe, but which may vary by age (*siding/sheathing combination, building shear capacity, and condition*);
- Unobservable characteristics that are likely to have a single value regardless of age (*building size and configuration, sheathing nailing, sill bolt diameter, and hole size)*; and
- Variants that were initially considered but determined to not meet the three qualifying criteria (*plan irregularities, split levels, slabs on grade, chimneys, rotated foundations, soft stories, and roof sheathing*).

Based on the selected variants identified, the Project Team developed an initial list of Index Buildings, which was later refined following the work of the testing and analytical modeling project teams (WGs 4 and 5). Variants shown to have relatively minor impact on overall building performance, or for which property ranges could not be developed with confidence, were eliminated or the variant ranges reduced. The list of refined Index Buildings is shown on the next page.

List of building variants considered in Project Study.

Primary variants	
Observable	
Date of construction ranges	pre-1945, 1945–1955, 1956–1970
Number of stories	one or two
Secondary variants	
Observable	
Building weight	Interior finish materials: lath and plaster (pre-1945), gypsum wallboard (post-1955), average of results for 1945–1955 era. Exterior siding: stucco or wood siding
Sill bolting	Unbolted wet-set sill (pre-1945), bolted (post-1945)
Cripple wall height	Stem wall (zero-height), 2- and 6-ft raised cripple walls
Cripple wall slope differential	None considered
Siding	Stucco, horizontal wood, T1-11 (1956–1970 only)
Secondary variants	
Unobservable characteristics dependent on age	
Sheathing combinations	None, horizontal sheathing
Superstructure shear capacity	Per ATC-110 recommendations as function of age
Condition	A single best estimate of condition was assumed
Secondary variants	
Unobservable and single characteristic assumed for each independent of age	
Size and configuration	1200 sq ft footprint rectangular with 4:3 aspect ratio
Nail spacing in siding/sheathing	Two nails per board
Foundation bolt diameter	1/2 in. if present
Bolt hole diameter	1/4 in. oversize if present
Retrofit	Both unretrofitted and retrofitted conditions using ATC-110 plan set
Roofing	Only light (shake or composite shingle) roofing was considered

GLOSSARY

ATC-110:	A CEA-funded project that has the objective of developing details for the seismic retrofit of unbraced cripple walls. ATC-110 was published by FEMA as P-1100 in October 2019.
Damage Function	A curve that approximates building damage as a percentage of replacement cost as a function of a single ground-motion input parameter (e.g., spectral acceleration at 0.2 seconds).
Primary Variant:	A characteristic of the building that is expected to be identified and included as part of all underwriting documentation (location, age, number of stories).
Secondary Variant:	A characteristic of the building that may or may not be identified and included as part of underwriting documentation.
Observable Variant	Variants that are assumed to be observable and identifiable by an underwriter or homeowner without performing exploratory demolition.
Unobservable Variant:	Variants that are not assumed to be observable and identifiable by an underwriter or homeowner without performing exploratory demolition.
Index Building:	Combinations of primary and secondary variants that represent the majority of typical buildings. A unique damage function will be generated for each Index Building.
Soft Story:	A typical condition in a single-family home where living space is situated above either a garage, a porch or a wall line that is primarily glazing.
Sheathing:	The unobservable exterior material (horizontal or diagonal wood) that provides shear capacity for the building. Sheathing is not present in all homes.
Siding / Cladding:	The observable, exterior material (stucco or horizontal wood siding), that provides weatherproofing for the building and helps resist lateral forces.
Light / Heavy:	General designation for an Index Building that represents the type of siding, interior partitions, and roofing used. Examples of heavy materials include stucco, lath and plaster, and tile roofs. Examples of light materials include wood siding, gypsum wallboard, and composite or wood roofing. Concrete and clay tile roofs were not considered in

the study because they represent a small percentage of California homes and because the distinction is not consistently included in insurance loss models.

Raised Cripple Wall: A framing condition where the first-floor joists are raised above the foundation sill plate with a short, wood-framed, stud wall, which is sheathed similarly to the exterior superstructure walls.

Slope Differential: The difference in height between the front and back, or between the sides of a house that is built on a slope.

Stem Wall or Zero-Height Cripple Wall: A foundation condition where the first-floor joists sit directly on the foundation sill plate.

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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."

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.

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 the Working Group (WG) 2 denoted in bolded text above.

A number of studies have been conducted on the seismic performance of housing stock in the United States [Yancey et al. 1998; HUD 2001; and ATC 2009]. This report focusses on the identification of common variations and combinations of materials and construction characteristics of California single-family dwellings. Working Group 2 was responsible for developing "Index Buildings," which formed the basis of the PEER–CEA Project testing and analytical modeling programs. The loss-modeling program of the PEER–CEA Project quantified the damage-seismic hazard relationships for a subset of the Index Buildings.

The essential scope of work for this working group was to develop a list of "Index Buildings" representative of the single-family housing stock in California within the CEA's insurance portfolio and compatible with the damage functions used by the insurance loss modelers. Index Buildings contain a combination of "variants" that define the characteristics and seismic performance of the buildings. The selection of a variant was based on three criteria:

- A significant representation among California homes (in excess of approximately 10% of housing stock, based on census or research data, or expert opinion);
- The potential to have a significant damage on building in the event of an earthquake (assumed to be approximately +/-5% of replacement cost, based on expert opinion to be verified through testing and analysis); and
- The amount of damage *reduction* resulting from the seismic retrofit of the cripple wall is dependent upon the presence of the variant.

Three subtasks within the Project Team scope included:

Task 2.1: Develop Initial List of Building Variants. The Project Team was tasked with developing a database of building information that influenced the selection of primary and secondary parameters, and quantification of damage (repair cost). This database would be augmented with photos and information from the testing team (WG4), and used to solicit contractors, construction estimators, and insurance estimators for repair costs during a workshop conducted as part of the WG6 project scope. The deliverables for this task include a broad list of initially considered variants (included in this report) and a digital archive to enable both the CEA and the Project Team to collect, manage, and access information on typical index houses, damage, retrofit construction details, and testing images (developed separately).

Task 2.2: Refine Variant List. Through a series of engineering workshops including the Project Team, its practitioners, and invited engineers, together with evaluation of information developed in the Task 1 literature review, the Project Team refined the initial list of variants to meet the conditions above. Coordination with ATC-110 was an important component of this task. The Project Team met with ATC-110 researchers [Welch and Filiatrault 2017] to better understand the efforts and analytical research performed as part of the ATC-110 project, and to improve the selection of variants. The deliverable from this task is this report, which contains a list of variants to be used by the PEER–CEA Project WGs 4 and 5 for the testing program and modeling efforts.

Task 2.3: Develop Index Buildings to be Tested and Modeled. The Index Buildings formed the basis of the analysis performed by the PEER–CEA Project WG5 and interactions with catastrophe modeling companies performed by WG6. The design details required for each index configuration included: (a) building geometry and material/construction characteristics; (b) retrofit options consistent with plans and performance-targets recommended by the ATC 110 project; (c) drawings and details of the structural system in sufficient detail to develop analytical models; and (d) description of the interior and exterior wall finishes and other components necessary to develop building replacement value and loss estimates. The deliverables from this task included the initial list of Index Buildings (included in this report), and drawings described in sufficient detail to develop structural analysis and loss models. The Project Team determined that drawings similar to the ATC-110 simplified buildings were sufficient.

Section 2 of this report is the list of building variants chosen as meeting the three criteria above and which could either be observed by an insurance underwriter or home inspector, or could be inferred based on the age of the home from existing research.

Section 3 contains a priority list of initial testing based on discussions with WGs 4 and 5 and the Project Leadership Team.

Section 4 contains the list of Index Buildings that represent combinations of the ranges of variant values. In some cases, variant combinations are excluded (e.g., T1-11 siding in pre-1955 buildings, or horizontal wood siding over horizontal wood sheathing).

Section 5 and 6 includes documentation for the inclusion or exclusion of each variant and the range of values for each variant that were chosen for consideration.

A **Glossary** of the terms used in this report can be found on Page xi.

2 Building Variants To Be Considered

Variants were divided into five categories.

1. Primary, observable characteristics that broadly define the building (age and number of stories);
2. Secondary, observable characteristics (building weight, bolting, and cripple wall dimensions, and exterior siding);
3. Secondary characteristics that the typical underwriter or home inspector cannot generally observe, but which may vary as a function of age (sheathing under siding, building shear capacity, and condition);
4. Unobservable characteristics that are likely to have a single value regardless of age (building size and configuration, sheathing nailing, sill bolt diameter, and hole size); and
5. Variants that were initially considered but determined to not meet the three qualifying criteria described in the Introduction of this report. These include plan irregularities, soft stories, split levels, slabs on grade, chimneys, rotated foundations, heavy roofing (clay or concrete tile), and roof sheathing.

A raised foundation refers to the condition where the first floor is built on a wood-stud cripple wall that sits on the concrete footing. Cripple wall heights of 2, 4, and 6 ft were initially considered. A stem wall foundation refers to the condition where the first-floor joists rest directly on the sill plate, which sets on the footing. This can also be referred to as a zero-height cripple wall.

Table 2.1 Initial list of building variants considered in Project Study and range of values.

Primary variants	
Date of construction	<1945, 1945–1955, 1956–1970
Stories	one or two
Secondary variants	
Siding	stucco, horizontal wood, T1-11 plywood
Anchor bolt spacing	6 ft on center or better, unbolted
Cripple wall height	stem wall or raised: 2, 4, or 6 ft
Cripple wall slope differential	2, 4, or 6 ft
Soft story	yes or no
Building weight	light or heavy, based on siding and interior wall finish materials
Unobservable variants that will be considered as a function of building age (will be embedded in loss models and are not things that the underwriters will check)	
Sheathing type	none, straight sheathing, diagonal sheathing
Building shear capacity (V/W)	ranges to be determined based on ATC-110
General condition	variability around chosen values of other variables
Unobservable variants that will be considered as a function of building age (single value will be assumed)	
Nailing of sheathing/siding	
Foundation bolt diameter (1/2 in.)	
Holes in mudsill oversized for bolts (1/4 in.)	
Building variants that will not be considered	
Plan irregularities – primarily re-entrant corners, performance not dependent on cripple wall bracing	
Split levels – not common in California relative to true one and two story homes	
Slab on grade homes – exclude because not part of the retrofit program	
Roof sheathing – typically skip sheathing, much lower stiffness than ceiling	
Roofing – Only light roofing materials (shakes and shingles) were considered. Tile roofs were not considered.	
Chimneys – not a major percentage of damage resulting from unbraced cripple wall	
Nuts and washers placed on foundation bolts – minimal impact on performance	
Soft-story conditions consisting of living space over garages – in consultation with the CEA it was determined that this is such an independently significant issue not particularly related to cripple walls, that it should be considered in a separate study.	
Shape and size of homes	
From the ATC-110 study, the majority of one-story homes that project considered seem to be between 1100 and 1200 sq ft on average with 4:3 to 2:1 aspect ratios. Realistically, nearly all houses have a “double-loaded corridor,” and if rooms are on the average of 10 ft minimum width, this would necessitate a 25 ft to 30 ft width in one direction. Therefore, this sizing and shape makes sense from an efficiency perspective.	

3 List of Testing Priorities

Based on a discussion with the leaders of the PEER–CEA Project, WG4 (testing) and WG5 (analytical modeling), the Project Leadership Panel and review by the Project Team, the following is a list of initial high-priority testing cases implemented by WG4. The setup and form of the testing, including whether the individual components might be combined into system tests determined by WG4 and coordinated with WG5, provide the type of information that can best be incorporated into the analytical modeling.

3.1 Unretrofitted Cripple Wall

Initially, 2-ft- and 6-ft-tall cripple walls were considered, and results were interpolated to 4-ft-tall cripple walls if possible; non-yielding anchorage of the sill was assumed:

Test A: Stiffness of siding material

- A-1: Stucco nailed to studs – based on review of code and industry literature to identify stucco materials and fastening differences based on date of construction
  - A-1a: pre 1945s era stucco
  - A-1b: 1945–1955 era stucco
  - A-1c: 1956–1970 era stucco
- A-2: Horizontal wood siding nailed to studs
  - A-2a: Assume all siding eras are similar
- A-3 T1-11 only sheathing/siding nailed to studs
  - A-3a: Assume only in the 1956–1970 age group

Test B: Stiffness of combined siding and sheathing material

- B-1: Test cripple wall with stucco and wood sheathing
  - B-1a: Horizontal wood sheathing
  - B-1b: Diagonal wood sheathing

3.2 Retrofitted Cripple Wall

Tests A and B were combined with ATC-110 retrofit solution and acknowledging the possibility of multiple ATC-110 retrofit solutions.

Test C

C-1a: A-1a+retrofit
C-1b: A-1b+retrofit
C-1c: A-1c+retrofit
C-2a: A-2a+retrofit
C-3a: A-3a+retrofit

Test D

D-1a: B-1a+retrofit
D-1b: B-1b+retrofit

3.3 Zero Height Cripple Wall (Stem Wall)

1/4 in.-oversized bolt holes were assumed for the sill plate to footing connection.

Test E: Test different styles of zero height cripple walls

E-1a: Floor joist parallel to wall condition
E-1b: Floor joist perpendicular to wall condition

3.4 Anchor Bolt Spacing

Testing data was sufficient for information on anchor bolt capacity.

Test F: Capacity of bolted and unbolted wet set sill condition (mudsill with spikes pressed into wet foundation)

F-1a: Unbolteld, wet-set sill
F-1b: 1/2 in. anchor bolts @ 32 in. spacing
F-1c 1/4 in. anchors bolts @ 64 in. spacing

Table 3.1 Testing matrix developed and implement by PEER–CEA Project Working Group 4.

Phase	Specimen	Test no.	Existing or retrofit	Era	CW height (ft)	Anchorage (WS = wet set, S = spacing)	Exterior finish†	BC***
1	A-1	4	E	pre-1945	2	S(64 in.)	S+HSh	A, a
1	A-2	3	E	pre-1945	2	S(64 in.)	S+HSh	B, a
1	A-3	6	E	pre-1945	2	S(64 in.)	S+HSh	C, a
1	A-4	1	E	pre-1945	2	S(64 in.)	S+HSh	B, b
1	A-5	5	R	pre-1945	2	S(64 in.)	S+HSh	B, a
1	A-6	2	E	pre-1945	2	WS	S+HSh	B, b
2	A-7	7	E	1945–1955	2	S(64 in.)	HS	B, c
2	A-8	8	R	1945–1955	2	S(32 in.)	HS	B, c
2	A-9	11	E	1945–1955	2	S(64 in.)	HS+DSh	B, c
2	A-10	12	R	1945–1955	2	S(32 in.)	HS+DSh	B, c
2	A-11	9	E	1956–1970	2	S(64 in.)	T	B, c
2	A-12	10	R	1956–1970	2	S(32 in.)	T	B, c
2	A-13	13	E	1956–1970	6	S(64 in.)	HS	B, c
2	A-14	14	R	1956–1970	6	S(32 in.)	HS	B, c
3	A-15	20	E	pre-1945	2	S(64 in.)	S+DSh	B, c
3	A-16	21	R	pre-1945	2	S(32 in.)	S+DSh	B, c
3	A-17	18	E	Pre-1945	2	S(32 in.)	S	B, d
3	A-18	22	R	Pre-1945	2	S(32 in.)	S	B, d
3	A-19	19	R	Pre-1945	2	S(32 in.)	S+HSh	B, c
3	A-20	15	E	Pre-1945	2	S(64 in.)	S+HSh	B, d
3	A-21	17	E	Pre-1945	2	WS	S+HSh	B, c
3	A-22	16	E	Pre-1945	2	S(64 in.)	S	B, c
4	A-23	23	E	1956-1970	6	S(64 in.)	T	B, c
4	A-24	24	R	1956-1970	6	S(32 in.)	T	B, c
4	A-25	27	E	Pre-1945	6	S(64 in.)	S	B, c
4	A-26	28	R	Pre-1945	6	S(32 in.)	S	B, c
4	A-27*	26	E	Pre-1945	2	S(64 in.)	S+HSh	B, c
4	A-28**	25	E	1945-1955	2	S(64 in.)	HS+DSh	B, c

* All tests except A-27 used a cyclic loading pattern. Test A-27 employed a monotonic loading pattern.
** All tests except A-28 used an axial load of 450 plf. Test A-28 used an axial load of 150 plf.
*** BC = Boundary Conditions; see WG4 report for details.
†S = stucco only, HS = horizontal siding, HS+Dsh = horiz. siding over diag. sheathing, S+HSh = stucco over hor. sheathing, S+DSh = stucco over diag. sheathing, T = T1-11 siding.

4 Index Buildings

Based on the variants identified in the previous section, the Project Team developed the initial list of Index Building combinations shown in Table 4.1 and 4.2. The PEER–CEA Project WGs 4 and 5 coordinated the incorporation of the testing results into the analytical modeling.

Following the completion of the testing program conducted by WG4 and analytical modeling conducted by WG5, the initial list of building variants and Index Buildings were refined. Table 4.3 contains the final list of Index Buildings for which damage functions were developed. Chapter 6 of this report explains the justification for including or excluding particular variants.

Table 4.1 Initial list of Index Buildings to be considered in Project Study with parameters common to all combinations.

All cases	
Size and configuration	Generally 1200 sq ft rectangular footprint with 4:3 aspect ratios
Nail spacing in siding/sheathing	Two nails per board
Foundation bolt diameter	1/2 in. if present
Bolt-hole diameter	1/4 in. oversize if present
Building shear capacity	As per ATC-110 recommendations as function of age
Condition	Apply upper and lower bounds to achieve an average value of each index building
Retrofit	Both unretrofitted and retrofitted conditions

Table 4.2 Initial list of index buildings considered in Project Study.

Combinations		
pre-1945	stories	one or two
	sill bolting	unbolted (wet-set sill)*
	building weight	heavy or light
	cripple wall height / slope differential	stem wall (zero-height), 2-, 4-, and 6-ft raised cripple walls, and differential heights being combinations of these
	siding / sheathing combinations	stucco/none,stucco/horizontal, stucco/diagonal, horizontal/none
1945–1955	stories	one or two
	sill bolting	unbolted (wet sill), bolted (6 ft or better)
	building weight	heavy or light
	cripple wall height / slope differential	stem wall (zero-height), 2-, 4-, and 6-ft raised cripple walls, and differential heights being combinations of these
	siding / sheathing combinations	stucco/none, stucco/horizontal, stucco/diagonal, horizontal/none
1956–1970	stories	one or two
	sill bolting	bolted (6 ft or better)
	building weight:	heavy or light
	cripple wall height / slope differential	stem wall (zero-height), two, four and six foot raised cripple walls, and differential heights being combinations of these
	siding / sheathing combinations	stucco/none, stucco/horizontal, stucco/diagonal, horizontal/none, T1-11/none

* Unbolted (wet-set sill) condition occurs typically when contractor installs mudsill into the concrete footing when it is cast, using spikes or heavy nails in the sill to provide nominal anchorage to the footing.

Table 4.3 Final list of index buildings considered in Project Study.

All cases	
Size and configuration	Generally, 1200 sq ft rectangular footprint with 4:3 aspect ratios
Nail spacing in siding/sheathing	Two nails per board
Foundation bolt diameter	1/2 in. if present
Bolt-hole diameter	1/4 in. oversize if present
Building shear capacity	As per ATC-110 recommendations as function of age
Condition	A single best-estimate assumption of condition factors
Retrofit	Both unretrofitted and retrofitted conditions

Combinations		
pre 1945	stories	one or two
	sill bolting	unbolted (wet-set sill)
	building weight	lath and plaster interior finish exterior wood siding or stucco siding
	cripple wall height / slope differential	stem wall (zero-height), 2- and 6-ft raised cripple walls with no slope differential
	siding / sheathing combinations	stucco with no sheathing, Horizontal siding boards with diagonal cut in stud wall bracing
1945–1955	stories	one or two
	sill bolting	bolted (6 ft or better) – no differentiation in strength with wet-set sill condition
	building weight	average of lath and plaster and gypsum interior finish exterior wood siding or stucco siding
	cripple wall height / slope differential	stem wall (zero-height), 2- and 6-ft raised raised cripple walls, with no slope differential
	siding / sheathing combinations	stucco with no sheathing, horizontal siding boards with diagonal stud wall bracing
1956–1970	stories	one or two
	sill bolting	bolted (6 ft or better) with no differentiation in strength with wet-set sill condition
	building weight:	average of gypsum wallboard interior finish exterior wood siding or stucco siding
	cripple wall height / slope differential	stem wall (zero-height), 2- and 6-ft raised raised cripple walls with no slope differential
	siding / sheathing combinations	stucco with no sheathing, horizontal siding boards with diagonal stud wall bracing, T1-11 with diagonal stud wall bracing

5 Documentation for Selection of Building Variants

5.1 Variant: Date of Construction Ranges

Selected Range or Values: Pre 1945, 1945–1955, 1956–1970

Justification for Selection

Justification for these ranges is based on research from data provided by the CEA, the U.S. Department of Housing and Urban Development, queries to members of the American Society of Home Inspectors, and knowledge accumulated from various sources; see Tables 5.1, 5.2, and 5.3 for representative data. Homes built after 1970 were assumed to primarily use plywood sheathing that extended to the foundation, resulting in a condition that would not undergo retrofit consistent with the CEA's Earthquake Brace and Bolt (EBB) program. According to data provided by the CEA, the vast majority of these newer homes were constructed on slabs and do not contain cripple walls; therefore, they were also excluded from the EBB program.

> ***Pre-1945 construction*****:** Construction during this era was typically done by professional trade workers with many years of experience. In general, high-quality lumber was used although left in rough-sawn condition. Of specific importance for seismic resistance is the rare use of mudsill anchor bolts; instead, pairs of 30-penny spikes spaced at 24 in. were partially driven into mudsill stock and embedded into freshly poured foundation concrete. Concrete quality varied significantly before 1940, as it was mostly mixed on site by hand. Raw materials occasionally included aggregates from nearby beaches, sand dunes, or streams. Foundations rarely included steel reinforcement during this period. The foundation style also changed during this time period from "trapezoidal" (sometimes called "mass foundations") to the "inverted tee" foundations still designed today. Trapezoidal foundations are often very shallow, and because their center-of-bearing is offset from the gravity loads they support, they sometimes rotate gradually about their longitudinal axes. Pre-1940 construction used primarily plaster on wood lath for interior wall finishes.
>
> ***1945–1955***: This time period represents the transition from pre-WWII to modern construction methods. During this time, building departments and contractors adopted mudsill anchor bolts on a mostly universal basis. This was also a transitional time from rough-sawn lumber to surfaced lumber, site-mixed to transit-mixed concrete, and typically included a training period when apprentice carpenters who entered the trade

in the post-war building boom became skilled journeymen carpenters. For interior wall finishes, this period also saw the transition from the use of plaster on wood lath to plaster on gypsum lath (aka "button-board") to gypsum wallboard, which became the predominant choice in the late 1950s.

1956–1970: By 1956, the code requirement for 1/2-in.-diameter mudsill anchor bolts was fairly universally accepted. Alternative connections (such as those using light-gauge steel straps embedded into the footings and wrapped over mudsills to be secured with nails) made up a very small fraction of construction. The quality of the concrete was more uniform, and the use of steel reinforcement became more common; note, foundation reinforcement was not required by code until the end of the 1990s. The quality of the lumber used was excellent as the old-growth forests had not all been cut down by 1970. The workforce was experienced and produced high-quality construction.

Comments on other age breakdowns: The CEA uses breakdowns of pre-1940, 1940–1959, 1960–1979, 1980–89, and 1990 until present, as shown in Table 5.1 These ranges match the ones proposed by the Project Team fairly well. Note: one of the catastrophe modeling firms uses age-breaks of pre-1937, 1937–1973, 1974–1988, and 1989-to-present. Given that a great deal of progress was made in code development, building materials, construction methods, and so forth between 1937 and 1974, lumping all construction spanning that time into a single category did not seem appropriate. Table 5.2 shows data from the U.S. Census on the approximate breakdown of housing ages in California.

The Project Team was able to identify a single report from the Department of Housing and Urban Development [HUD 1994] that attempted to quantify damage to single-family houses in the 1994 Northridge, California, earthquake. Samples of 341 structures were surveyed and are summarized in Table 5.3.

Table 5.1 Approximate age breakdown of houses insured by the CEA.

	Slab (sf living area)				Raised (sf living area)			
	<1200	1200–1500	1501–2000	>2000	<1200	1200–1500	1501–2000	>2000
pre-1945	0.9%	0.6%	0.7%	0.9%	2.4%	1.8%	1.8%	1.7%
1945–1955	1.6%	1.4%	1.3%	1.0%	2.4%	2.3%	2.2%	1.4%
1956–1970	1.6%	3.2%	4.3%	3.9%	1.0%	1.8%	2.2%	1.7%
post-1970	2.4%	5.5%	11.2%	22.2%	0.7%	1.0%	1.8%	3.1%

Table 5.2 U.S. Census: California housing construction data [HUD 2001].

	Characteristic	2011–2015 estimates
Year structure built	**Total housing units**	**13,845,790**
	Built 2014 or later	0.1%
	Built 2010 to 2013	0.9%
	Built 2000 to 2009	11.9%
	Built 1990 to 1999	10.8%
	Built 1980 to 1989	15.3%
	Built 1970 to 1979	18.1%
	Built 1960 to 1969	13.5%
	Built 1950 to 1959	13.8%
	Built 1940 to 1949	6.3%
	Built 1939 or earlier	9.4%

Table 5.3 Building characteristics for HUD study of 1994 Northridge, California, earthquake damage [1994]; a sample of 341 homes at 75 sites.

Characteristic	Value	% of sample	Characteristic	Value	% of sample
Year built	1970 or before	88%	exterior framing	wood	99%
	1971 or later	12%		other	1%
Stories	one	79%	wall sheathing	none	80%
	two	18%		plywood	7%
	one-and-a-half	1%		unknown	13%
	three or more	2%	roof framing	wood rafter	87%
Shape	rectangular	41%		wood truss	5%
	irregular	59%		other	5%
Attachments	garage	64%		unknown	3%
	porch	20%	roof sheathing	board	69%
	addition	11%		panel / ply or OSB	16%
	other	3%		other	3%
Exterior finish	stucco mix	50%		unknown	12%
	stucco only	45%	foundation	crawl space—stem wall	68%
	wood siding	5%			
Interior finish	plaster	60%			
	gypsum wallboard	26%			
	other	1%			
	unknown	13%			

5.2 Variant: Number of Stories

Selected Range or Values: one or two

Justification for Selection

The number of stories in a building has a significant impact on its seismic performance because of the structure's weight and the applied height of the resulting inertial force. Weight is directly related to the overall seismic demand on the superstructure and the cripple wall space, and the height of the applied force affects the relationship between shear and overturning forces at the base. The performance of the cripple wall and the effectiveness of cripple wall and sill anchorage retrofit are directly related to the height and weight of the superstructure. The performance of the building's first story will also be affected by the presence of a second story.

Several references were used to determine the number of stories in homes prevalent in California. Data and database include those developed by:

- U.S. Department of Housing and Urban Development [1994] following the 1994 Northridge, California, earthquake; and
- CoreLogic® [2017], a national tax and deed property database.

These databases indicate that, typically, one-story or two-story construction comprises 95% of single-family homes in California, with about 70–80% of the total being single-story construction. Less than 5% of homes are one-and-a-half stories tall or more than two stories. Given this data, significant differences in expected performance of homes based on the number of stories, and the considerable analysis effort involved in modeling each configuration of house considered, the Project Team concluded that only one and two-story buildings would be considered in satisfying the first of the three Index Building criteria.

5.3 Variant: Sheathing Type

Selected Range or Values: None, horizontal sheathing

Justification for Selection

This section examines structural lumber sheathing (i.e., lumber sheathing that is covered with a final exterior finish layer such as stucco, shingles, milled siding, brick veneer, etc.).

Materials: Structural sheathing is predominantly nominally 1-in.-thick Douglas fir of (typically 3/4 in. to 7/8 in. thick). Typical width of boards ranges from 6 in. to 12 in.

Installation: 8-in. boards and narrower are attached with two 8-penny (0.131 in. × 2-1/2 in.) nails at each stud. Boards wider than 8 in. are attached with three 8-penny nails at each stud. These fastening requirements apply to both horizontal and diagonally installed sheathing. [Anderson and Heyer 1989].

Connection to mudsill: The Uniform Building Code did not specifically require connection of sheathing boards to the mudsill. The minimum connection would therefore be 8-penny nails in line with the studs (typically 16 in. on center). In Form 3 of the APA, a construction method is shown where the wall sheathing stops at the floor sheathing (the wall framing is inset from the perimeter of the floor diaphragm by the thickness of the wall sheathing so that the exterior face of the sheathing is flush with the exterior face of the rim joist).

Horizontal siding only (no structural sheathing): Most houses in San Francisco built before 1950 have horizontal redwood siding installed directly to the studs. The fastening schedule is the same as noted above for structural sheathing. Other cities in the San Francisco Bay Area used this material less often, perhaps because more variety was desired outside of San Francisco's "row-house" construction style.

When structural sheathing is provided, it may be under stucco, wood, or asbestos-cement shingles, wood siding, brick veneer, etc.

In the San Francisco Bay Area, sheathing is predominantly installed horizontally (approximately 80% of houses with structural lumber sheathing). Diagonal sheathing was typically limited to higher-end construction. Diagonal sheathing was not considered in the study because of its relatively low usage.

Diagonal bracing in the cripple wall space was considered to exist based on expert opinion and observations. Constructing a 2-ft or taller cripple wall without construction bracing would have made for an unstable condition once the first floor was placed, as sheathing was not typically added until the framing was complete.

5.4 Variant: Cripple wall Height

Selected Range or Values: Stem wall (zero height), 2-ft or 6-ft

Justification for Selection

In California, it is common for houses to contain a cripple wall connecting the first floor to the foundation. According to the *CEA South Napa Home Impact Study* [Rabinovici and Ofodire 2017] conducted in the aftermath of the August 24, 2014, M6.0 South Napa earthquake, it was found that 85% of all houses surveyed (for a 633 total of surveyed) contained a cripple wall with anchorage to the foundation. Of these dwellings, 35% contained cripple walls greater than 2 ft, and 8.8% contained cripple walls greater than 4 ft. More importantly, however, was the increased presence of taller cripple walls for older construction. Of the pre-1950 constructed houses considered in the survey (24.8% of the surveys), 92.9% contained a cripple wall, 61.3% contained a cripple wall of at least 2 ft, and 21.3% contained a cripple wall greater than 4 ft.

It is possible that the taller cripple walls in Napa were employed to combat flooding and may not be as common in non-flood prone areas. Note: only 11% of these homes were located on a slope [Rabinovici and Ofodire 2017]. Finally, of the houses surveyed, only 13.4% had undergone retrofit of the existing cripple wall. Although this survey's sample size is only 633, it raises alarms about the presence of tall cripple walls within the California housing stock, especially in older-era homes. According to the 2000 U.S. Census, 32.6% of the housing stock in California was constructed pre-1960 [U.S. Census Bureau 2000], thus, a significant amount of California houses (especially older homes) contains cripple walls with large range of heights.

During earthquakes, the intense shaking can cause houses to slide off their foundations and can cause racking of the cripple walls. From the 1989 Loma Prieta, 1994 Northridge, and many other California earthquakes, it has been observed that older wood-frame houses are extremely vulnerable to earthquakes because of the presence of cripple walls. Commonly found in older styles of construction, cripple walls do not contain sufficient lateral bracing to transfer horizontal seismic loads to the foundation, resulting in large lateral displacements of the dwelling or partial to complete collapse of the cripple wall.

Previously, studies have been done on the performance of retrofitted and unretrofitted cripple walls, namely the CUREE studies [Chai et al. 2002; Reitherman and Cobeen 2003] These studies did not consider the performance of cripple walls over 4 ft. Unlike shorter cripple walls, which are often controlled by a shear failure mechanism, taller cripple walls are more likely to have a combination of shear and flexure characteristics. It is important to understand how these taller walls perform to assess which retrofitting strategy(s) will provide a sufficient and efficient increase in lateral capacity to resist the horizontal seismic forces.

Four-foot cripple walls were considered in the initial variant list, but because of the early analyses performed by the WG5 team, it was determined that a linear interpolation between 2 ft and 6 ft tall would be sufficient to approximate the performance of cripple walls of intermediate heights.

Cripple wall heights can exceed 6 ft, especially for dwellings lying on slopes, but they are not common enough in the California housing stock for them to be considered in an experimental testing program.

5.5 Variant: Siding

Selected range or values: Stucco, horizontal wood siding, and T1-11 siding

Justification for Selection

Given that there are many different construction styles and materials used in California; it is not feasible to evaluate all of them, but there are trends in construction, and the most common siding finishes are worthy of study. According to the *CEA South Napa Home Impact Study* [2017], conducted in the aftermath of the August 24, 2014, M6.0 South Napa earthquake, of the 633 houses surveyed, 55.6% of the houses contained stucco siding finishes and 24.9% contained horizontal wood-siding finishes [Rabinovici and Ofodire 2017]. Reconnaissance reports from PEER [Stewart et al. 1994; Kang and Mahin 2014], EERI [Hall 1994], and GEER [Storesund et al. 2010] for various earthquakes in California have also pointed to an abundance of these two styles of finishes being the most common within the California housing stock. Within the CEA's ATC-110 project, the exterior finishes considered for analytical modeling were stucco, horizontal siding, gypsum, stucco plus gypsum, and lath and plaster [FEMA 2019]. The material selection is in agreement with field observations and ATC-110's work but limited to the most common materials used. Note: stucco and horizontal siding are the most common finishes seen in older homes, which are generally at the highest risk of damage due to an earthquake.

Plywood siding came into common use in the 1960s and remained popular through the 1980s, seeing use on perhaps 50% of new homes built in that era. The most common style of siding is "T1-11." Most styles incorporate grooves in the exterior surface to mimic individual wood boards. Plywood siding panels are made with half-lap ("shiplap") edges.

T1-11 siding suffers from three common problems:

- The first problem is the grooves themselves. Plywood relies on the several veneers that make up the panel thickness to bridge defects in adjacent veneer layers. When grooves are cut into a five-ply panel and leave only three plies intact, defects at the grooves have fewer redundant layers to bridge across them. After the 1994 Northridge, California, earthquake, observers reported tearing of grooved siding panels along the grooves.
- The second concern is that panel nailing must occur in the grooves. The shear capacity depends on plywood thickness through which the panel edge nails are driven. The panel at the grooves is typically 5/16 in thick. This limitation in available strength is usually offset by the entire house being sheathed with plywood siding.
- The third concern is improper nailing of the panel edges. Often, the first panel is installed with nails along only three edges; the fourth edge will be overlapped by the subsequent panel's shiplap edge. This process is repeated across the wall, resulting in each vertical panel joint having no nails installed along one side of the joint. This installation error occurs in a significant majority of the installations observed (approximately 80%). Prominent failures shown in EERI report following the 2003 San Simeon, California, earthquake [EERI 2004] and others show 4-ft-wide plywood panels that disconnected from the wall framing because of this installation defect.

In experimental modeling, it is important to limit the amount of consideration within the testing matrix so that a feasible number of tests can be conducted and compared with one another. By considering too many variables, the testing program becomes too large to account for all the variables; if kept small, multiple variables must be changed in each test making results less reliably compared. For this reason, the experimental modeling should focus on the three most prevalent siding finishes: stucco, horizontal wood siding, and T1-11 plywood siding.

5.6 Variant: Construction Material Weight

Selected Range or Values: four combinations: gypsum wallboard + wood siding, gypsum wallboard + stucco, lath and plaster + wood siding, lath and plaster + stucco

Justification for Selection

The weight of a single-family residential building will influence the seismic demands on the cripple walls, which are the primary components of interest to the PEER–CEA Project. Several factors determine the seismic weight of a single-family residence, the most significant of which include the mass of the materials used to construct the roof, floor diaphragm, and exterior and interior walls. As described in the subsequent paragraphs, these factors were used to establish four building weight categories.

In addition to the weight of the wood-framing, insulation, mechanical, electrical and plumbing, and other miscellaneous items were assumed to be the same across all Index Buildings. Four combinations of interior and exterior wall materials were considered. Construction materials considered for the interior panels include gypsum wallboard or wood lath and plaster on both sides, the latter being the heavier material (e.g., approximately 15 psf for wood lath and plaster versus 5 psf for gypsum wallboard). The variations in the weight of exterior walls were determined based on a combination of one layer of stucco or 1-in.-thick lumber siding (with paper) on the exterior facing side, and one layer of wood lath and plaster or gypsum wallboard on the interior facing side.

Based on research and expert opinion, the Project Team determined that prior to 1945, interior finishes were typically lath and plaster; after 1956, gypsum wallboard was used. Stucco and wood siding were widely used in both eras. For homes built between 1945 and 1955, the results of the modeling study averaged the earlier and later eras, assuming a transition occurred between the use of the two interior finish materials. The Project Team did not consider conditions where older homes were renovated, and the lath and plaster was replaced with gypsum wallboard.

The seismic weight of the roof in a single-family residential building is generally determined based on the mass of the structural wood framing (e.g., joists and blocking), sheathing (e.g., OSB), insulation, and the roofing material (e.g., shingles). The Project Team assumed a single weight for the wood framing, insulation, and sheathing. One type of roofing material was considered, composite or asphalt shingle (3.5 psf or 7 psf if re-roofing is considered). Heavier tile roofs were not considered because:

- tile roofs are not considered to be prevalent in California homes;
- only one of the insurance loss models contains roof weight as a building modifier, so a comparison with the Project Team models could not be based on this parameter; and
- for ATC-110 retrofits, there is consideration for concrete tile roofs and asphalt shingle roofs. Retrofitting of homes with classic clay tile is limited to one-story homes and must use the equivalent two-story retrofit details if clay tiles exist. Two-story homes with classic clay tile are not covered by the plan sets.

The Project Team assumed the floor diaphragm consisted of a single construction type (wood joists with diagonal sheathing); therefore, mass variations were not considered.

5.7 Variant: Mudsill Anchors, Oversized Holes, Presence of Nuts

Selected Range or Values: Unbolted (wet-set sill), bolted (1/2 in.), and 1/4-in. oversized holes are typical.

Justification for Selection

Pre-1945 construction: Construction during this era was typically done by professional trade workers with many years of experience. Lumber was generally of high quality, although left in rough-sawn condition. Of specific importance for seismic resistance is the rare use of mudsill anchor bolts. Pairs of 30-penny spikes spaced at 24 in. were partially driven into mudsill stock and embedded into freshly poured foundation concrete. This is commonly called a “wet-set sill” condition.

1945-1955: This time period represents the transition from pre-WWII to modern construction methods. During this time, building departments and contractors adopted mudsill anchor bolts on a mostly universal basis.

1956-1970: By 1956, the code requirement for 1/2 in.-diameter mudsill anchor rods was fairly universally accepted. Alternative connections (such as those using light-gauge steel straps embedded into the footings and wrapped over mudsills to be secured with nails) made up a very small fraction of construction.

Oversized holes at mudsill anchor bolts: Meeting the National Design Specification for Wood Construction [AWC 2018] requires that bolt holes be oversized no more than 1/16 in. This stipulation requires more skill or attention than almost any builder is willing to invest. Holes for anchor bolts in mudsills are routinely drilled to be oversized as much as 3/8 in. and have been since the building code began requiring anchor bolts for mudsill attachment. In our estimation, 10% of anchors have properly sized holes, 40% are 1/16 in. to 1/4 in. oversized, and 50% are more than 1/4 in. oversized. Of course, there is no consistency of where the anchor bolts fall within the oversized holes. As the mudsill tends to slide, some anchors will bear immediately against the wood, whereas other anchors may not engage until the mudsill has overcome the friction between the rough concrete and the sill and has slid the full "extra" hole width.

Wet set sill**:** Testing performed by WG4 determined that unbolted, wet-set sills exhibited considerable strength, such that failure at the sill plate to concrete interface did not occur (a similar response to a condition where the sill is bolted). Therefore, the analytical modeling performed by WG5 did not differentiate between an unbolted, wet-set sill condition and a bolted condition.

Floor joist to sill attachment: Although not initially considered within the Index Building variants, WG5 ultimately determined that the weak link for zero-height cripple walls (stem-wall condition) was the connection of the joists to the mudsill, which was typically effectuated by toenails. Once the seismic demand on the first floor exceeded the capacity of the connection, the first floor would effectively tear loose from the mudsill and become somewhat isolated from the foundation; therefore, the capacity of the floor to sill attachment in the zero-height stem-wall condition was explicitly modeled. The retrofit condition of this attachment was modeled as complying with the ATC-110 plan sets, which require the addition of clips between the joists and mudsill to improve the connection capacity.

5.8 Variant: Building Shear Capacity

Selected Range or Values: Based on ATC-110 research and categorized by the home's base shear capacity (V) divided by its area (A), and the weight of building.

Justification for Selection

Cripple walls are generally only constructed on the perimeter of single-family dwellings. As such, the ratio of the length of exterior wall ($L_{W,EXT}$) to the total floor area (A_T) of a residence is expected to be correlated with the seismic demand per unit length of cripple wall and the potential for damage during an earthquake.

It is assumed that the presence of interior lath and plaster or gypsum wallboard walls will contribute to the overall superstructure capacity of the building because the relative stiffness of the floor diaphragm—in particular at the first floor that often contains subfloor sheathing as well as finished wood flooring—allows forces to be transferred to the perimeter cripple walls. The Project Team determined that calculating the net length of exterior and interior walls, and the determination as to whether the walls were lath and plaster, button board and plaster or gypsum wallboard, was beyond the ability of most underwriters, particularly given the available resources.

A simpler approach would be to categorize the variant as shear capacity as a function of building weight, *V/W*. Weight would be a direct proxy for seismic demand when coupled with the seismicity. Because weight in kips cannot be directly calculated by the underwriter, the Project Team determined that the variant of construction material weight (interior finish and exterior siding combinations) could be used to determine the building weight.

V/W will be considered a secondary variant and will be determined based on the building age, number of stories, and construction materials. In the ATC 110 project, the average superstructure strength was found to be correlated with the era of construction. This correlation will be used to determine the range of *V/W* for this variant.

5.9 Variant: Condition

Selected Range or Values: A single, best-estimate of material conditions

Justification for Selection

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, labor quality, and other factors. The base shear capacity and damage states of buildings will be dependent on these factors. Furthermore, the benefit of seismic retrofit will vary depending on the condition of the existing structures. Therefore, the condition of the building does meet the criteria that the project scope of work lays out for consideration.

Unfortunately, little data is available to quantify the difference in performance characteristics of materials with these condition variations. Furthermore, in the testing program developed by WG4, it found that it was unrealistic to construct tests with “built-in” poor or superior condition levels. For example, the contractors building the test mock-ups could not use rusted nails or introduce cracks in the stucco or dry rot in the stud walls.

The PEER–CEA Project Review Panel also considered this issue and determined that based on the paucity of research data on the subject, the only possible option to consider a range of condition factors would be to place confidence bounds around the strength and stiffness, or hysteretic properties of the various materials that would be modeled within the WG5 program. The Panel concluded that any such confidence bounds would be arbitrary, based primarily on expert opinion and not established research, thus introducing an unwanted variable into the overall modeling results. The Project Team, therefore, determined to use the best estimates of material properties derived through the WG4 testing program and available research. The PEER–CEA

Project reports will note that the properties may exhibit better or worse behavior dependent on *in situ* conditions, and that insurance pricing should reflect this uncertainty in an actuarially appropriate manner.

6 Excluded Variants

6.1 Variant: Plan Irregularities, Split Levels, Slab-on-Grade Homes, Chimneys, Rotated Foundations, and Roof Sheathing

Selected Range or Values: N/A

Justification for Selection

***Plan irregularities*:** Identification of plan irregularities would be difficult for underwriters. Furthermore, a plan irregularity on a wood-frame structure would generally occur only when a substantial portion of the exterior wall length in one area of the building is not sheathed (i.e., at a large window or garage door) or at re-entrant corners. Soft-story conditions will not be considered based on the reasoning above. Plan irregularities caused by L- or T-shaped homes resulting in a re-entrant corner are not likely to see a *delta* in loss whether the cripple wall is braced. In other words, damage at the corner is not lessened because the cripple wall under the corner is braced. Damage would generally occur at the second story or roof regardless of the bracing condition. Plan irregularities caused by cripple wall height differentials at sloped sites are already captured in the cripple wall differential variant.

***Split levels*:** Split-level homes came into popularity in the 1950s and 1960s. Prior to 1950, the percentage of true split-level homes in California—where the first-floor diaphragm is discontinuous on the interior of the building—is relatively small. Given the wide variety of split-level designs, the Project Team concluded that it would be difficult for an underwriter to determine whether the condition contained a true discontinuity in the first-floor diaphragm or if a footing was present at the split (as in the case with a partially above-grade basement). For future study, WG5 should consider how to capture a range of split-level conditions to create damage functions that are averages of the performance of existing and retrofitted buildings with and without split levels.

***Slab on grade homes*:** Shawna Ackerman at the CEA suggested that these homes be excluded because identifying the presence of anchor bolts in a slab home cannot be made without exploratory demolition, thus the retrofit is outside the scope of the CEA's EBB program.

***Roof sheathing*:** In pre-1970 homes, most roof sheathing consisted of skip sheathing that supported wood shingles or tile. The stiffness of the roof sheathing is likely to be significantly lower than the stiffness of the gypsum wallboard or a lath and plaster ceiling (which functions as the primary diaphragm element). Therefore, the stiffness of the roof sheathing can likely be ignored in the modeling.

***Chimneys*:** Chimneys can be a major component of damage in a home. In moderate earthquakes, a masonry chimney is often the main element affected. Damage to chimneys is primarily dependent on their construction and bracing to the superstructure (second floor and roof). The performance of chimneys is not significantly affected by the performance of the cripple wall, nor is a chimney likely to provide a substantial alternative load path to the foundation in lieu of the cripple wall. Therefore, the *delta* in loss due to chimney damage between an unretrofitted and a retrofitted house in accordance with ATC-110 is likely to be minimal.

***Lack of nuts on mudsill anchor bolts*:** Further consideration of this defect indicates that it likely occurs on no more than 10% of houses constructed between 1940 and 1955 and possibly under 5%. Overall, this may not be statistically significant. Unfortunately, these cases may be concentrated in areas developed by particularly stubborn builders who took an early stand against "government over-reach."

***Soft-story conditions*:** Soft-story conditions consist generally of living space over either a garage, a porch, or a very large window/door opening. Soft-story conditions have been documented repeatedly in past earthquakes as having a substantial, negative impact on the performance of structures in earthquakes because of the vertical discontinuity in the lateral system. Soft-story conditions in single-family homes do not usually include the entire first story, as might be the case with a large multi-family apartment or a traditional commercial building. Thus, the damage resulting from a soft story is generally somewhat localized.

In two-story homes the prevalence of attached garages, porches, or particularly large window openings that create a soft story are high. That said, the configurations of the specific condition can vary widely given the overall shape of the house; therefore, the amount of damage that may result specifically from a soft story can vary substantially.

In the case of a garage under a living space, the garage foundation itself will be a slab on grade, not a cripple wall. In the case of porches, it can be either, regardless of the rest of the house, and in the case of a large window opening, the foundation condition is likely to match the rest of the house.

While the condition of a soft story satisfies the first two variant criteria—being prevalent in California construction and having an overall significant impact on building performance (even in a potentially localized area)—it is unclear how well it satisfies the third criteria, i.e., the amount of damage will be significantly mitigated by retrofitting the cripple wall space in the house; for a garage in a home with unretrofitted cripple walls, the relative stiffness between the garage and the rest of the house might be similar. If the cripple wall is retrofitted and becomes stiff and strong, the garage may receive less load as the cripple wall portion attracts more force. This may be the case with a porch as well, with less damage occurring at the garage or porch. The converse of this is that the retrofitted cripple walls and the superstructure walls above them may suffer greater damage than if the garage or porch were stiff enough to attract their share of the force. Say, if there is a large window atop a cripple wall; it is possible that bracing the cripple wall below will make the window a weaker link and drive damage to that area.

The conclusion reached by the Project Team committee is that it would be difficult within the context of this study—focused primarily on the benefits of cripple wall bracing and sill anchorage—to determine how to model the effects of soft stories, given their wide variety, and to quantify the *difference in the reduction* in damage that is likely to occur with retrofit *depending on the presence of a soft story* would be appropriate for a subsequent study.

Cripple wall Slope Differential: Since cripple wall heights of 0 ft, 2 ft, and 6 ft were used, the potential exists for slope differentials to be the same values. The ATC-110 Project indicated that the presence of sloped sites—to be differentiated from hillside homes where the slopes are more than one story—is prevalent in California, and that a slope differential can have a significant impact on the stiffness of the foundation and the potential for torsional response. However, the vast range of potential slope differentials would have been difficult to model within the allocated time of the Project. Therefore, the Project Team determined to consider cripple wall slope differential appropriate for a subsequent study.

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