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Updated Fragility Functions for Cold-Formed Steel Light-Frame Structural Systems

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ABSTRACT

Today, performance-based earthquake engineering (PBEE) provides a robust alternative to traditional earthquake design. PBEE can estimate expected damage, repair costs, and economic losses due to downtime for a candidate design, potentially leading to novel new designs or retrofit solutions. With the increasing application of light-frame structural systems, such as cold-formed steel (CFS) panels, in residential and commercial construction, it is necessary to develop and employ fragility functions for these systems to enable PBEE. In this regard, a set of fragility curves was previously developed by researchers based on a series of monotonic and cyclic tests for CFS-framed shear walls with wood structural panel sheathing, flat strap X-bracing, and steel sheet sheathing. These fragility curves were developed in accordance with the reporting requirements for the U.S. FEMA P-58 project using story drift ratio as the engineering demand parameter and two or three pre-defined damage states. Recently, the senior author has led in the development of a large database of CFS-framed shear wall tests, now including 617 monotonic and cyclic tests conducted in the last 20 years from 25 primary sources. These tests support the CFS-framed shear wall provisions provided in the North American Standard for Cold-Formed Steel Structural Framing (AISI S240-15), the North American Standard for Seismic Design of Cold-Formed Steel Structural Systems (AISI S400-15), and the U.S. Seismic Evaluation and Retrofit of Existing Buildings standard (ASCE41-17). Using this database, the fragility functions for shear walls with wood structural panel sheathing, flat strap X-bracing, and steel sheet sheathing are re-evaluated based on the wider data. The developed fragility functions provide updated data for application of PBEE in the FEMA P-58 method and are recommended for future use. Examination of the impact of these proposed changes, and consideration of the formal Bayesian updating procedure recommended in P-58 constitute ongoing efforts.

Keywords: fragility, cold-formed steel, wood sheathing, flat strap X-bracing, steel sheet sheathing

INTRODUCTION

In conventional seismic design, design criteria are based on strength and serviceability limits of structural components and systems. In this process, the uncertainties and variabilities in seismic demand and capacity of structural components are aggregated into probabilistic load and resistance factors. However, these design criteria do not specify the expected level of damage, and recent natural disasters have shown that even structures compliant with building codes can undergo significant damage including human and financial losses [1]. Traditional seismic design codes attempt to ensure life safety, but in many buildings, it is desired that less damage occurs under a given earthquake hazard; e.g. critical infrastructures such as hospitals should be kept operable post-event, and some school buildings or other public buildings may need to operate as shelters to provide post-event occupancy. In this regard, the U.S. Federal Emergency Management Agency (FEMA) has focused efforts on developing and promoting performance-based seismic design in the past two decades. A key result of these efforts is the FEMA P-58, Seismic Performance Assessment of Buildings, Methodology and Implementation, which provides the necessary information and recommended procedures for developing basic building information, response quantities, fragilities, consequence data used as inputs to the methodology, and guidelines on how to implement the methodology.

As the application of light-frame structural systems such as cold-formed steel (CFS) panels is increasing in the construction industry, it is essential to study the fragility of different types of CFS systems. CFS-framed shear walls (panels) provide the primary lateral resistance and are thus the first target for study. The fragility functions of CFS panels are used in performance-based earthquake engineering (PBEE) approaches. CFS structures show significant nonlinearity at connections, in the framing, and in the behavior of sheathing materials, specifically under lateral loads. As a result, understanding and estimation of fundamental behaviors such as lateral capacity is acquired using experimental testing [2]. In this regard, a series of monotonic and cyclic tests were conducted on CFS-framed shear walls with different sheathing materials and structural characteristics [3]–[23]. Based on a portion of these tests, a set of fragility functions was previously developed for CFS-framed shear walls with wood structural panel sheathing, flat strap X-bracing, and steel sheet sheathing using story drift ratio as the engineering demand parameter and two or three pre-defined damage states [24] in accordance with the reporting requirements for the U.S. FEMA P-58 project [25].

Recently, the senior author has led in the development of a large database of CFS-framed shear wall tests, including 617 monotonic and cyclic tests conducted in the last 20 years from 25 primary sources [2]. These tests support the CFS-framed shear wall provisions provided in the North American Standard for Cold-Formed Steel Structural Framing (AISI S240-15), the North American Standard for Seismic Design of Cold-Formed Steel Structural Systems (AISI S400-15), and the U.S. Seismic Evaluation and Retrofit of Existing Buildings standard (ASCE41-17). Using the database, a set of fragility functions for CFS shear walls with wood structural panel (WSP) sheathing, flat strap X-bracing, and steel sheet sheathing is developed based on the wider data. The fragility functions for walls with WSP sheathing are developed in four groups based on the type of wood used for sheathing: Oriented Strand Board (OSB), Douglas Fir Plywood (DFP), Canadian Softwood Plywood (CSP) or other Plywood, and all types inclusive. The functions for walls with flat strap X-bracing are developed in three groups based on the steel grade of straps (230 (33), 345 (50) MPa (ksi), and all inclusive). In the process of developing these fragility functions, walls with gypsum wallboard and walls with aspect ratios of 4:1 or larger were excluded.

FRAGILITY FUNCTIONS OF CFS WALLS WITH WSP SHEATHING

Background

The fragility functions for CFS walls with WSP sheathing are developed regardless of the spacing of the sheathing fasteners and in four groups based on the type of the wood used for the sheathing: OSB, DFP, CSP or Plywood, and all types together. These functions are useful for damage assessment when the fastener spacing is unknown and for different types of wood sheathing (known or unknown). To develop these fragility functions, monotonic and cyclic tests from the following sources are used: [3], [4], [10]–[12], [15]–[19]. Wall specifications in these tests are as follows:

- 2440 (8) or 2743 (9) mm (ft) in height and 610 (2), 1220 (4), or 2440 (8) mm (ft) in length
- Top and bottom tracks: 230 (33) or 345 (50) MPa (ksi) steel with 0.84 (33) to 1.73 (68) mm(mil) thickness
- Studs: 230 (33) or 345 (50) MPa (ksi) steel, 0.84 (33) or 1.73 (68) mm (mil) thickness, spaced at 610 mm (24 in.) o.c.
- 9.5 (3/8), 11.1 (7/16), or 11.9 (15/32) mm (in.) wood structural panel sheathing attached with long dimension parallel to studs on one side only with screw spacing of 50, 75, 100, or 150 mm (2, 3, 4, or 6 in.)
- Capacity designed seismic hold-downs at wall ends

Definition of damage states

The engineering demand parameter (EDP) used to define damage states is the story drift ratio (SDR) in percentage (%). SDR is defined as the ratio of the amount of horizontal drift of the wall specimen to the height of the wall. Damage State 1 (DS1) is defined as the SDR corresponding to the end of the elastic behavior of the wall specimen. Damage State 2 (DS2) is defined as the SDR corresponding to the peak load in the wall specimen. Damage State 3 (DS3) is defined as the SDR corresponding to the 80% of post-peak load in the wall specimen. For cyclic tests, the average values from both negative and positive cycles are taken. Figure 1 depicts an example of how damage states are obtained from data of a wall specimen. Description of damage states for walls with WSP sheathing and their corresponding SDR are listed in Table 1.

Table 1. Description of damage states and corresponding story drift ratios for walls with WSP sheathing

Damage State	Description	Drift Ratio
DS1	End of elastic behavior; minor bearing damage at fasteners; minor fastener tilting; cosmetic damage at wall face or screw heads.	@ 40% peak load
DS2	Maximum capacity of wall; significant amount of permanent damage; noticeable bearing/tilting damage at fasteners; multiple fastener locations pulled through; significant degradation in initial stiffness if unloaded.	@ Peak load
DS3	Numerous failures at fastener locations including pull through and potentially edge tear out; detachment of sheathing from studs and track for significant portion of sheathing perimeter; significant unrecoverable damage.	@ 80% of post peak load

CFS walls with WSP sheathing may undergo different failure modes. The preferred failure mode per design by AISI S400 [26] is tilting and bearing damage at the sheathing to stud/track fastener locations. If edge distances are insufficient, fastener tear out at the panel edges will occur, resulting in more dramatic losses in load carrying capacity as shown in Figure 2a. With proper edge distance tilting, bearing of the fasteners evolves to fastener pull-through as shown in Figure 2b. Properly designed other failure modes (screw shear, screw withdrawal, stud buckling, track bending, hold-down failure etc.) will not occur, either due to prescriptive limits established from testing or capacity protection principles (over-strength design) detailed in AISI S400.

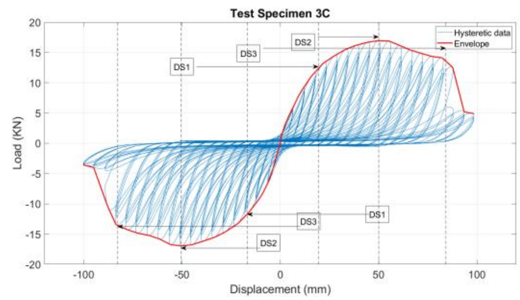

Figure 1. Example of damage states for a test specimen; test data from Boudreault (2005).

Figure 2. Examples for failure of walls with WSP sheathing (corresponding to DS3):
(a) Sheathing tear-out at corners; (b) Wood Bearing Failure (image source: [3]*)*

Fragility functions

The procedure to develop fragility functions is in accordance with the fragility reporting requirements of P-58 [25]. To obtain the mean and dispersion parameters of the fragility function, P-58 Method A has been used where all the specimens failed at observed values of EDP. In this paper, the fragility functions are idealized using the lognormal distribution. Before analyzing the data, outliers were excluded using Peirce's Criterion according to Section 3.2 of [25]. The developed functions were then tested for goodness-of-fit at 5% significance level using the Lilliefors test according to Section 3.3 of [25]. Figure 3 illustrates the development of the fragility function for DS3 of walls with WSP sheathing.

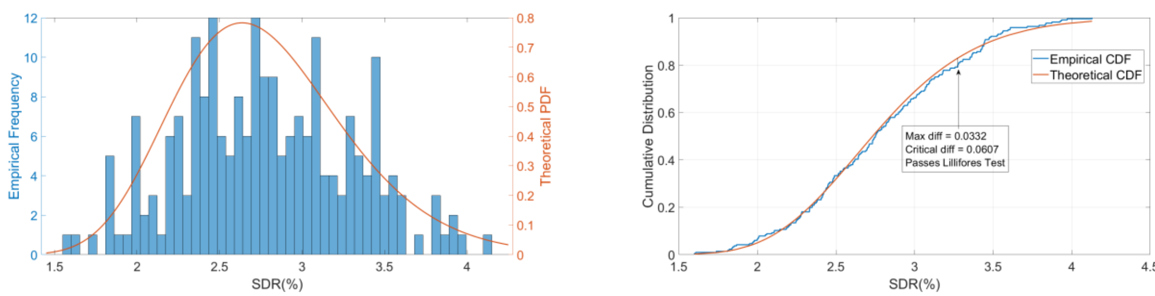

Figure 3. Distribution (left) and cumulative distribution (right) corresponding to DS3 for all walls WSP sheathed walls.

The fragility functions for walls with WSP sheathing are shown in Figure 4 including separate curves for each type of wood sheathing and curves for all types of WSP considered together. The values for median and dispersion are listed in Table 2. In each case, the fragility functions developed in [24] are compared to the results developed here from the wider database of tests. In general, the fragilities developed here provide slightly larger or similar story drift ratios at a given probability of exceedance as those from [24] with the exception of OSB sheathed shear walls at DS2 and DS3.

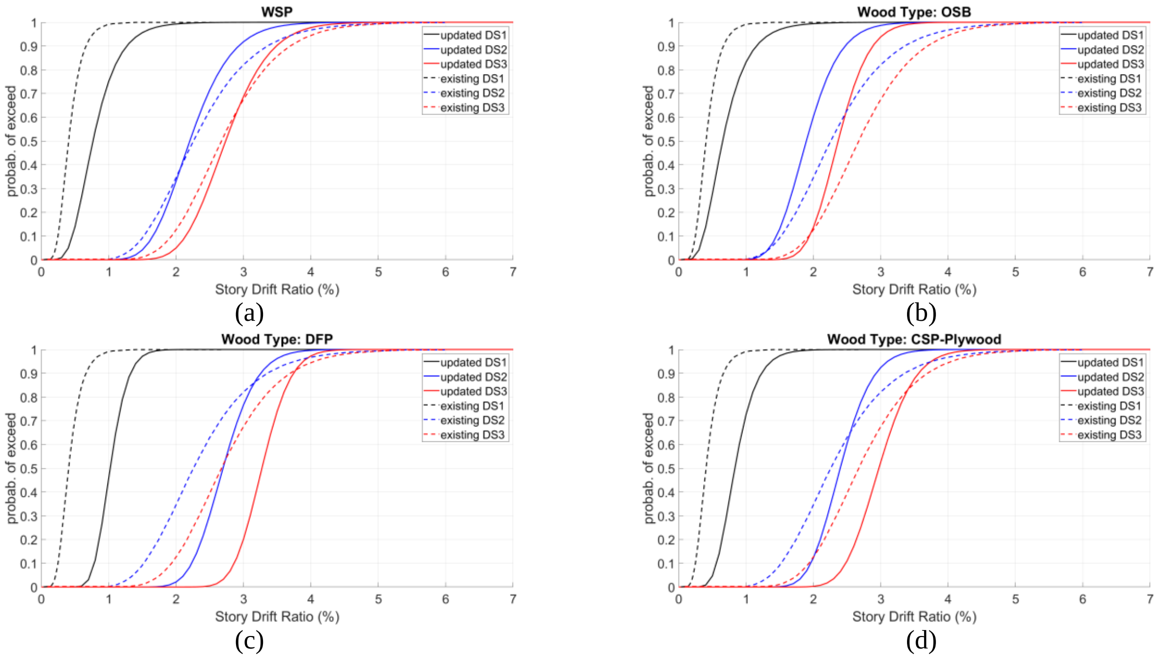

Figure 4. Fragility curves for CFS walls with WSP sheathing: (a) all; (b) OSB; (c) DFP; (d) CSP or Plywood.

Table 2. Parameters of fragility curves for CFS walls with WSP sheathing. Demand parameter: Story Drift Ratio (%)

Wood Type	Damage State	Median	Dispersion	# Samples	Lilliefors Test
All	DS1	0.77	0.39	224	Fails
	DS2	2.20	0.22	224	Fails
	DS3	2.73	0.19	219	Passes
OSB	DS1	0.65	0.45	95	Passes
	DS2	1.89	0.21	95	Passes
	DS3	2.37	0.15	93	Passes
DFP	DS1	1.02	0.20	26	Passes
	DS2	2.69	0.15	26	Passes
	DS3	3.27	0.10	26	Passes
CSP/Plywood	DS1	0.83	0.30	103	Passes
	DS2	2.40	0.16	103	Passes
	DS3	2.97	0.14	101	Passes

FRAGILITY FUNCTIONS OF CFS WALLS WITH STEEL SHEET SHEATHING

Background

The fragility functions for CFS walls with steel sheet sheathing are developed independent of the spacing of the sheathing fasteners. To develop these fragility functions, monotonic and cyclic tests from the following sources are used: [6]–[8], [10], [11], [13], [14]. Wall specifications in these tests are as follows:

- 2440 mm (8 ft) in height and 610 (2), 1220 (4), 1830 (6), or 2440 (8) mm (ft) in length
- Top and bottom tracks: 230 (33) or 345 (50) MPa (ksi) steel, 0.84 (33), 1.09 (43), or 1.37(54) mm (mil) thickness
- Studs: 230 (33) or 345 (50) MPa (ksi), 0.84 (33), 1.09 (43), 1.37 (54) mm (mil) thick, spaced @ 610 mm (24 in.) o.c.
- Steel sheet sheathing: 230 MPa (33 ksi) steel, 0.5 (18) to 0.84 (33) mm (mil) thick, attached with long dimension parallel to studs on one side of wall only
- Fastener spacing ranging from 15 mm (perimeter) / 30mm (field) to 5 mm / 30mm (6 in. / 12in. to 2 in. / 12in.)
- Capacity designed seismic hold-downs at wall ends

Definition of damage states

DS1 is defined as the SDR corresponding to the end of the elastic behavior of the wall specimen. DS2 is defined as the SDR corresponding to the peak load in the wall specimen. DS3 is defined as the SDR corresponding to 80% of post-peak load in the wall specimen. For cyclic tests, the average values from both negative and positive cycles are taken. Description of damage states for walls with steel sheet sheathing and their corresponding SDR are listed in Table 3.

Table 3. Description of damage states and corresponding story drift ratios for walls with steel sheet sheathing

Damage State	Description	Drift Ratio
DS1	End of elastic behavior; visual buckling of steel sheet; minor bearing damage at perimeter fasteners and small wavelength buckling along perimeter.	@ 40% peak load
DS2	Maximum capacity of wall; significant buckling of steel sheet; bearing damage at multiple fasteners; some fastener locations pulled through; significant degradation in initial stiffness if unloaded.	@ Peak load
DS3	Numerous failures at fastener locations including pull through and bearing/edge tear out failure; detachment of sheathing from studs and track for significant portion of sheathing perimeter; potentially bending of stud and track flanges; significant unrecoverable damage.	@ 80% of post peak load

CFS walls with steel sheet sheathing may undergo different failure modes. The preferred failure mode per design by AISI S400 [26] is yielding in the steel sheet followed by bearing damage at the sheathing to stud/track fastener locations. Buckling in the thin steel sheets is a prominent feature of the response even at low deformation (Figure 5a). Although ideally the stud and track are not appreciably deformed by the steel sheet, many of the tests included in the AISI S400 standard (and the database used here) include some bending deformation in the attached stud flange and track – post-peak this deformation can be appreciable as shown in 5b. As the bearing damage progresses at the fasteners, eventually edge tear out at the panel edges will occur, resulting in more dramatic losses in load carrying capacity and redistribution of load within the wall. Properly designed other failure modes (screw shear, screw withdrawal, chord stud buckling, hold-down failure etc.) will not occur, either due to prescriptive limits established from testing or capacity protection principles (over-strength design) as detailed in AISI S400.

Figure 5. DS3 example for walls with steel sheet sheathing (a) buckling of steel sheet; (b) Twisting of stud (image: [6]*)*

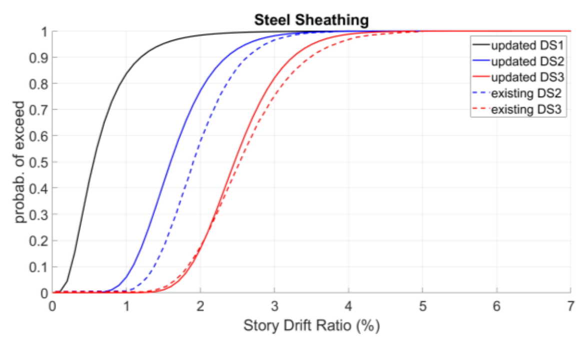

Figure 6. Fragility curves for all CFS walls with steel sheet sheathing.

Fragility functions

The fragility functions for walls with steel sheet sheathing are shown in Figure 6. The values for median and dispersion are listed in Table 4. The updated fragilities are slightly more conservative than those developed in [24] and are recommended for use in PBEE with this wall type.

Table 4. Parameters of fragility curves for CFS walls with steel sheet sheathing. Demand parameter: Story Drift Ratio (%)

Damage State	Median	Dispersion	# Samples	Lilliefors Test
DS1	0.56	0.60	101	Passes
DS2	1.60	0.30	101	Passes
DS3	2.46	0.22	84	Passes

FRAGILITY FUNCTIONS OF CFS WALLS WITH FLAT STRAP X-BRACING

Background

The fragility functions for CFS walls with flat strap X-bracing are developed in three groups based on the grade of steel used for the straps: 230 MPa (33 ksi), 345 MPa (50 ksi), or all data together. The developed fragility functions are useful for damage assessment when the strap material grade is specifically known, or when it is unknown (all data together). To develop these fragility functions, monotonic and cyclic tests from the following sources are used: [9], [10], [20]–[23]. Wall specifications in these tests are as follows:

- 2440 mm (8 ft) in height and 610 (2), 1220 (4), or 2440 (8) mm (ft) in length
- Top and bottom tracks: 230 (33) or 345 (50) MPa (ksi) steel with 0.84 (33) to 2.46 (97) mm (mil) thickness
- Studs: 230 MPa (33 ksi) steel, 0.84 (33), 1.09 (43), or 1.22 (48) mm (mil) thickness, spaced @ 610 mm (24 in) o.c.
- Flat strap X-bracing: 230 (33) or 345 (50) MPa (ksi) steel, 0.84 (33) to 1.91 (75) mm (mil) thick, attached to one or both sides of the walls
- Capacity designed seismic hold-downs at wall ends

Definition of damage states

DS1 is defined as the SDR corresponding to the end of the elastic behavior of the wall specimen. DS2 is defined as the SDR corresponding to the peak load in the wall specimen. DS3 is defined as the SDR corresponding to the 80% of post peak load in the wall specimen. For cyclic tests, the average values from both negative and positive cycles are taken. Description of damage states for walls with flat strap X-bracing and their corresponding SDR are listed in Table 5.

Table 5. Description of damage states and corresponding story drift ratios for walls with steel sheet sheathing

Damage State	Description	Drift Ratio
DS1	End of elastic behavior; visual buckling of flat strap in compression; minor elongation of tension strap; minor bearing damage at strap to stud fasteners if screwed (note, welds also typical).	@ 40% peak load
DS2	Maximum capacity of wall; buckling of flat strap in compression; noticeable elongation of tension strap; bearing damage at strap to stud fasteners if screwed (note, welds also typical); significant degradation in initial stiffness if unloaded.	@ Peak load
DS3	Necking and yielding in tension strap accompanied with large elongation; if older wall without proper capacity protection: strap net section failure at connection, anchorage failure, bending of stud and track flanges all possible and observed in testing; significant unrecoverable damage.	@ 80% of post peak load

The desired limit state for CFS walls with flat strap X-bracing is yielding of the strap. AISI S400 [26] has developed provisions that ensure this failure mode (primarily though capacity-based design of the wall and connections) due to observations in testing regarding a number of undesirable limit states including: fracture of the flat strap in the net section at the stud to strap connection (Figure 7a), anchorage failures (Figure 7b), and local bending of the chord stud and/or track at the strap to stud connection. The most noticeable feature of tested specimens with flat strap X-bracing is the unloading and buckling of the compression strap; however, this has little influence on the behavior. Yielding of the flat strap is visually difficult to observe when the wall is deformed, but a plumb wall which has yielded will have slack straps due to elongation – only upon drifting the wall back out to previous deformations does the strap again become taught.

Figure 7. Potential undesirable failure modes in flat strap shear walls (corresponding to DS3): (a) Improperly detailed connection leading to net section failure; (b) Improperly sized rod leading to anchorage failure (image source: [20]*)*

Fragility functions

The fragility functions for walls with one-sided flat strap X-bracing are shown in Figure 8 including separate curves for each steel grade of straps and curves for all straps considered together. The values for median and dispersion are listed in Table 6. Initially, the developed fragility functions for DS2 and DS3 in all three cases were crossing. These functions were modified and corrected based on the procedures provided in Section 3.4 of [25]. Additional work with the data to further limit the selected specimens based on whether or not the details meet current AISI S400 requirements could be completed to further improve the results.

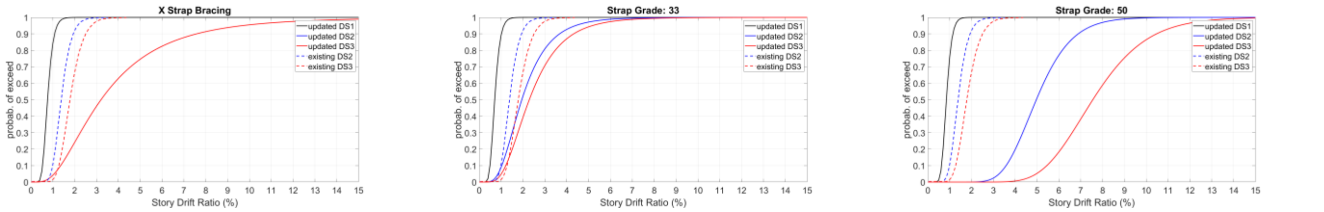

Figure 8. Fragility curves for CFS walls with X-bracing: (a) all; (b) 33 ksi straps; (c) 50 ksi straps.

Table 6. Parameters of fragility curves for CFS walls with X-bracing. Demand parameter: Story Drift Ratio (%)

Steel Grade	Damage State	Median	Dispersion	# Samples	Lilliefors Test
All	DS1	0.76	0.28	93	Passes
	DS2	3.21	0.67	93	Passes
	DS3	3.21	0.67	42	Passes
33 ksi	DS1	0.71	0.28	58	Passes
	DS2	1.95	0.50	58	Fails
	DS3	2.29	0.50	29	Passes
50 ksi	DS1	0.85	0.23	35	Passes
	DS2	4.97	0.25	35	Fails
	DS3	7.55	0.25	13	Fails

DISCUSSION

FEMA P-58 is the result of a decade of effort to promote PBEE. The final products of this effort provide the methodology as well as basic building information, response quantities, fragilities, and data to be used as input to the methodology. To encourage practical implementation, FEMA provides a set of fragility and consequence data for common structural systems and building occupancies, along with a set of spreadsheet tools and a Performance Assessment Calculation Tool (PACT) to assist engineers in performing probabilistic computations and accumulation of losses. Since its release in 2012, the P-58 methodology has been used in practice and implemented into other engineering tools, such as the Resilient Design Initiative (REDi), the U.S. Resiliency Council (USRC) rating system, and the Seismic Performance Prediction Program (SP3) software. The fragility functions provided in this paper are intended to replace current fragility functions for damage assessment of buildings with CFS shear walls. These updated functions give an improved estimate for the probability that a given CFS shear wall would observe the defined damage states under different story drift ratios. Further development of these fragility functions should address the impact of modern design specifications such as AISI S400 – providing different levels of predicted fragility based on whether or not the tested shear walls meet all current AISI S400 criteria. The fragility functions developed in this study included a limited number of wall specimens that did not meet all current AISI S400 criteria. Therefore, these functions provide a conservative estimate of new design and are believed to provide a reasonable estimate of past designs. Additional needed future work related to this study includes the expansion of fragility functions to other types of CFS walls, such as load-bearing CFS gravity walls and non-structural CFS walls.

CONCLUSIONS

Performance-based earthquake engineering (PBEE) aims to help societies better understand and manage earthquake risks through resilient design of new buildings and better quantification of seismic risks for existing buildings. In this process, it is essential to understand how damage is connected to seismic hazard. In this regard, a set of fragility functions is developed for Cold-Formed Steel (CFS) walls with wood structural panel sheathing, steel sheet sheathing, and flat strap X-bracing. These functions are developed based on a large database of CFS-framed shear wall tests and in accordance with the reporting requirements for the U.S. FEMA P-58 project. To further enable PBEE, more research needs to be conducted on the development of such fragility functions for other types of CFS walls, and more extensively, for other structural systems.

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