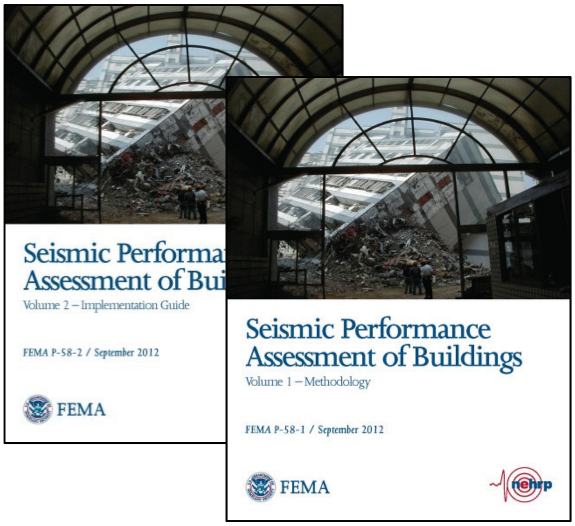

Background Document

FEMA P-58/BD-3.8.1

Fragility Curves for Wood Light-Frame Structural Systems

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Prepared for

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U.S. Department of Homeland Security
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Washington, D.C. 20472

February 20, 2008

FEMA

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Background Documentation

FEMA P-58 Background Documents are a series of reports documenting the technical background and source information for key aspects of the FEMA P-58 methodology and its implementation. These reports were developed over the course of the 10-year ATC-58/ATC-58-1 Projects funded under FEMA Contracts EMW-2001-RP-0056 and HSFEHQ-06-D-1105.

Background Documents were developed by consultants, serving at various levels within the project hierarchy, reporting the results of: (1) decisions on technical development protocols; (2) focused studies on the development of key aspects of the methodology; (3) documentation of recommended procedures; and (4) collection of available data for the development of structural and nonstructural fragilities. They were initially intended to serve as a record of the technical state-of-knowledge at the time they were produced, and as resources for the development of the eventual project reports. As such, they represent a snapshot in time, and may, or may not, match the technical content, recommended procedures, or data incorporated into the final methodology and its implementation.

This Background Document is intended for the purpose of providing supplemental knowledge to users of the FEMA P-58 methodology. Information contained herein has not been independently verified for accuracy as a stand-alone document, and may have been superseded in its final implementation within the methodology. Users of information in this document assume all liability arising from such use.

Notice

Cover illustration – Primary resource documents for the FEMA P-58 *Seismic Performance Assessment of Buildings, Methodology and Implementation* series of products: FEMA P-58-1, *Volume 1 – Methodology*, and FEMA P-58-2, *Volume 2 – Implementation Guide*.

Fragility Curves for Wood Light-Frame Structural Systems

Developed for the ATC-58 Project SPP Team

by

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Final Report
February 20, 2008

Table of Contents

1. Introduction and Scope

This document summarizes the development of fragility curves for wood light-frame structural systems, such as shear walls and sill plates. The fragility curves developed for typical wood studded shear walls include walls constructed from Orientated Strand Board (OSB), Plywood sheathing and Hem/Douglas fir framing. Only walls built within a platform construction are considered. Multi–stories balloon type walls are not considered in this document. The wood light-frame structural systems considered in this document are associated with systems #47 to #52 listed in Table D-1 of the ATC-58 35% Draft Guidelines (ATC 2007).

- System #47: *Structural panel sheathing (plywood or OSB) shear walls with interior gypsum Wallboard, basic strength design*.
- System #48: *Structural panel sheathing with stucco exterior and gypsum Wallboard interior, basic strength design*.
- System #49: *Stucco on gypsum wallboard*.
- System #50: *Structural panel sheathing (plywood or OSB) shear walls with interior gypsum Wallboard, strength design with seismic tie downs and nail/screw details*.
- System #51: *Structural panel sheathing (plywood or OSB) shear walls with stucco exterior and gypsum Wallboard interior, strength design with seismic tie downs and nail/screw details*.
- System #52: *Light Wood Frame, Diagonal Strut Bracing*

The fragility curves developed in this document are primarily for systems #50 (Section 3) and #51 (Section 4). No subassembly test data were conducted in the CUREE-Caltech Woodframe Project for systems #47 and #48, associated with conventional wood light-frame construction, and their fragility values needed to be established by judgment. A review of Section 10.3.9 of the shake table test report by Fischer et al. (2001) from the CUREE-Caltech Woodframe Project revealed that the relative displacements of a large-scale wood light frame structure using conventional construction increased by a factor of 1.5 compared to the same structure incorporating engineering construction. Considering that numerical models are currently unable to capture the effect of the omission of holdown in wood shear walls, the authors recommend reducing the median values for the fragility curves of systems #47 and #48 by a factor of 2/3 compared to the median values for systems #50 and #51. Also, considering the higher uncertainties associated with systems #47 and #48, the authors recommend increasing their dispersion value to 0.40.

System #49 is not a construction practice used in North America and is not considered in this document. The authors suggest that this system designation be removed from future ATC-58 Draft Guidelines.

System #52 is associated with wood stud framing braced by diagonal bracing. This system is seldom used in North America. The fragility values for system #52 were established by judgment based mainly on the results of a limited number sub-assembly testing conducted in Japan (Isoda 2007).

Shear walls framed by steel studs are not considered in this document. Also, hill-side construction or older wood buildings founded on cripple walls are not considered in this document.

Cyclic tests on wood studded wall assemblies (McMullin and Merrick 2001, Gatto and Uang 2002, Pardoen et al. 2002, Arnold et al. 2005) and shake table tests on complete wood light-frame structures (Fischer et al. 2001, Mosalam et al. 2002, Christovasilis et al. 2007) have shown that framing members (studs) distort into a parallelogram under lateral loading with the top plate and sill remaining essentially horizontal. Previous research has shown that the in-plane bending of framing members has only a second-order effect on wall response (Gupta and Kuo 1985). Therefore, the Inter-Story Drift (ISD) is assumed constant along the height of a floor and the fragility curves developed in this document for wood studded wall assemblies are independent of the floor-to-floor height. The special design provisions for wind and seismic of the 2005 National Design Specification for Wood Construction (ANSI/AFPA SDPSW 2005) limits the aspect ratio of vertical diaphragm in light-frame wood construction to 3.5:1. The assumption that the Inter-Story Drift (ISD) is assumed constant along the height of a floor is considered valid for wall piers with aspect ratio not exceeding 2:1. This is the limiting value defined in SDPSW (2005) for which the nominal full shear capacity of a wall panel is mobilized. For wall with aspect ratios between 2:1 and 3.5:1, SDPSW 2005 requires that the nominal shear capacity be multiplied by 2bs/h, where b_s and h are the width and the height of the wall pier, respectively. Therefore, to be conservative, it is recommended that the median values of the fragility curves developed for wall piers with aspect ratios between 2:1 and 3.5:1 be multiplied by the same reduction factor.

Fragility curves are also developed for partition walls with gypsum wallboard (Section 2) since it has been shown experimentally that they modify substantially the seismic response of wood light-frame buildings. Although partition walls are considered as nonstructural components in heavier construction types, it is recommended to consider them as part of the structural system in wood light-frame construction. Fragility curves for sill plates (with and without holdowns) are developed separately (Section 7). A recent shake table study on a full-scale wood light-frame building has shown that damage to sill plates could occur before failure of the other components of the shear walls and would be very expensive to repair. The authors recommend including sill plates as part of wood light-frame systems in Table D-1 of the ATC-58 Draft Guidelines (ATC 2007). Finally, test results on wood floor diaphragms from Dolan et al. (2002) were reviewed. The authors judged based on these experimental results and the results of shake table studies on complete wood light-frame buildings (Fischer et al. 2001, Mosalam et al. 2002, Christovasilis et al. 2007) that damage to wood diaphragms is unlikely in the event of a seismic event. Therefore fragility curves for wood diaphragms were not developed.

The fragility curves developed in this document are consistent with the fragility reporting requirements developed for the ATC-58 Project (Porter 2007) and were obtained from experimental test data where the actual damage states were observed (Method A) and from judgment by the authors (Method E). It was the decision of the authors to use laboratory tests conducted only with the CUREE-Caltech loading protocol. This protocol was developed during the recently completed CUREE-Caltech Woodframe Project and was shown to be more realistic then other loading protocols such as the Sequential Phased Displacement (SPD) or ISO loading protocols. The test data used to construct the various fragility curves came from experiments conducted by McMullin et al. (2001), Fischer et al. (2001), Gatto and Uang (2002), Pardoen et al. (2002), Mosalam et al. (2002), Mahaney et al. (2002), Arnold et al. (2005) and Christovasilis et al. (2007).

For each wood light-frame subsystem considered in this study, a demand parameter (DP) and a family of damage states (DS_i) were developed. Each family consisted of two or three damage states depending on the amount of available experimental data and how well the fragilities of the subsystem were documented. For example, some reports discussed or showed the damage only at the end of testing. The damage states were decided based on the different levels of repairs that would need to be made (e.g. repair or replace stucco).

The demand parameter (DP) was either Inter-Story Drift (ISD) expressed in % of story height for wall assemblies or shear force per anchor bolt (VB) expressed in pounds for sill plates. The experimental data used was checked for outliers using both the procedure of Appendix C of the ATC-58 35% Draft Guidelines and of the ASTM-E178 standard (ASTM 2002). The DP was graphed against the probability of exceedance as shown in Appendix A. The probability of exceeding each damage state was calculated using the Hazen plotting position, $P = (i-0.5)/n$, since it does not imply a zero probability of damage for any specified DP value. The fragility functions were then checked for goodness of fit using the Lilliefors Test (Lilliefors 1967).

Appendices B, C and D of this document presents the experimental data used to construct the fragility curves for gypsum wallboard partitions, OSB/Plywood shear walls with and without holdowns and sill plates, respectively. A summary of the fragility data in tabular formal used to construct these fragility curves is given in Appendix E of this document.

2. Fragilities of Partition Walls with Gypsum Wallboard

Fragility curves for gypsum wallboard partitions were considered in this study even though they are not considered part of the structural system for the seismic design of wood light-frame buildings. However, recent shake table studies of large and full-scale wood light frame buildings (Fischer et al. 2001, Mosalam et al. 2002, Christovasilis et al. 2007) have shown that gypsum wallboard partitions or gypsum wallboard installed on the interior surfaces of structural wood shear walls can influence significantly the seismic response of wood buildings. Furthermore, the fragilities of gypsum wallboard partitions will serve as a reference for wood structural walls with gypsum wallboard attached to them. For example, if a wall is constructed from Oriented Strand Board (OSB) and stucco finish on the exterior surface and gypsum wallboard on the interior surface and one needs to know when the gypsum wallboard would need to be repaired or replaced, these fragility curves could be used independently of the fragility curve for the OSB with stucco.

The gypsum wallboard partitions that were considered in the development of the fragility curves were based on cyclic tests on partition assemblies (Arnold et al. 2005, McMullin and Merrick 2001) as well as on shake tables tests on complete wood light-frame buildings including wallboard partitions (Fischer et al. 2001, Mosalam et al. 2002, Christovasilis et al. 2007). The gypsum wallboard partitions in these tests were constructed using:

- Walls 8’ tall by either 8’ or 16’ in length
- Grade No. 2 or better 2x4 Hem-Fir/Douglas-Fir studs spaced at 16”on center
- Horizontally attached ½” thick gypsum wallboard on both sides of the studs fastened either by 1.25” drywall screws placed 16” on center or 1-5/8” drywall nails spaced 8” on center along the vertical studs.
- Fixed or floating construction[1]
- Fully sheathed walls or walls incorporating window or pedestrian door openings

2.1 Definition of Damage States

For gypsum wallboard partitions, two damage states were defined based on the extent of the repairs required to return the wall to its pre-earthquake condition. The two types of repair considered are 1) DS_1, cosmetic repair, and 2) DS_2, replacement of gypsum wallboard. The cosmetic damage state DS_1 would be considered when the damage to the gypsum wallboard

[1] Floating construction is a common term in gypsum wallboard construction that refers to the lack of connector within the first 12 inches from the ceiling line in order to improve the flexibility of the wall-to-ceiling connection and reduce damage under lateral loading. Rigid construction, on the other hand, incorporates connectors on the top plate of the wall near the ceiling line.

could easily be repaired by replacing the tape along the seam of two adjacent panels, applying new joint compound, sanding and re-painting. For the complete replacement damage state DS_2, the entire panel would need to be replaced along with the application of new tape and joint compound, sanding and re-painting. Experimental results have shown that studs are typically not damaged by the failure of gypsum wallboard and, therefore, replacement of the studs is not considered in the damage states. These two damage states for gypsum wallboard partitions are listed in Table 1 and illustrated by photographs in Figs. 1 and 2.

Table 1 - Description of Damage States for Partition Walls with Gypsum Wallboard.

Damage States (DS_i)	Description of Damage State
DS_1	Cracking of paint over fasteners or joints (Fig. 1)
DS_2	Local and global buckling out-of-plane and crushing of gypsum wallboard (Fig. 2)

Figure 1 - Damage State 1 for Partition Walls with Gypsum Wallboard: Dimpling of Wallboard over Nail/Screws, Cracking at Vertical or Horizontal Seams (from Christovasilis et al. 2007).

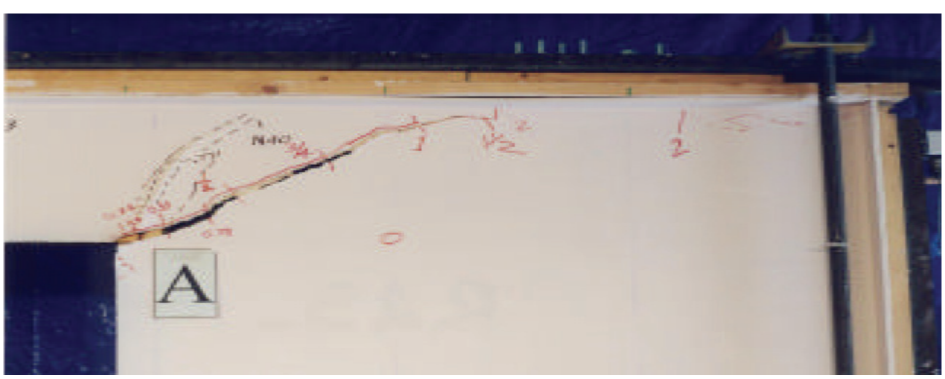

Figure 2 - Damage State 2 for Partition Walls with Gypsum Wallboard: Global/or Local Buckling and Crushing of Wallboard (from McMullin et al. 2001).

2.2 Development of Fragility Curves

The fragility curves for the two damage states of gypsum wallboard partitions are shown in Fig. 3. The median and dispersion for each fragility curves are listed in Table 2.

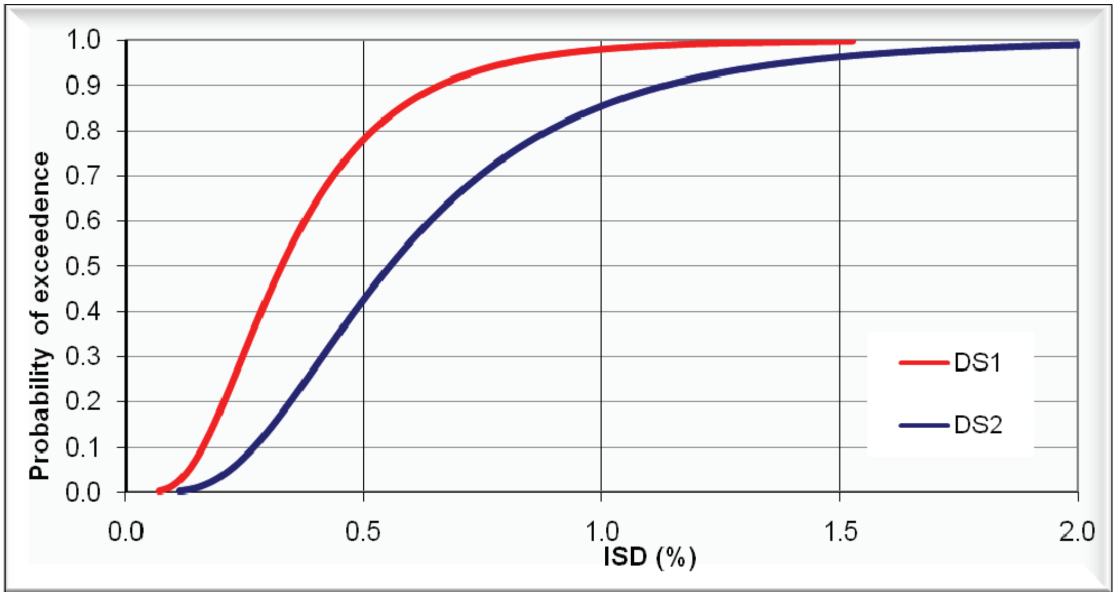

Figure 3 - Fragility Curves for Partition Walls with Gypsum Wallboard.

Table 2 - Medians and Dispersions for Partition Walls with Gypsum Wallboard.

Damage States	Demand Parameter (DP)	Median (θ)*	Dispersion (β)
DS_1	Inter-Story Drift	0.33	0.55
DS_2	ISD (%)	0.56	0.56

*For wall piers with aspect ratios between 2:1 and 3.5:1, median value should be multiplied by $2b_s/h$.

3. Fragilities of Shear Walls with OSB/Plywood Sheathing and Interior Gypsum Wallboard (System # 50)

The fragility curves in this section are for walls incorporating either Oriented Strand Board (OSB)/Plywood sheathing on the exterior surface with an exterior siding that does not affect substantially the lateral stiffness of the wall, such as vinyl siding, along with gypsum wallboard applied on the interior surface.

The shear walls that that were considered in the development of the fragility curves were based on cyclic tests on wall assemblies (Gatto and Uang 2002, Pardoen et al. 2002) as well as on shake tables tests of complete wood light-frame buildings incorporating walls sheathed with OSB/Plywood and gypsum wallboard (Fischer et al. 2001, Mosalam et al. 2002, Christovasilis et al. 2007). The shear walls in these tests were constructed using:

- Walls 8’ tall by either 8’ or 16’ in length
- Grade No. 2 or better 2x4 Hem-Fir/Douglas-Fir studs spaced at16” on center
- Double top plate and single bottom plate
- 3/8” OSB or 15/32” Plywood sheathing fastened vertically using 8d box nails spaced at12” in the field and 4” to 6” around the panel edges.
- Fully sheathed walls or walls incorporating window or pedestrian door openings
- Holdowns at the end of wall piers

3.1 Definition of Damage States

For walls incorporating OSB/Plywood sheathing, three damage states were defined based on the type of repairs that would need to be conducted besides that to the gypsum wallboard. For damage to gypsum wallboard, the fragility curves developed in Section 2 and shown in Fig. 3 should be used independently. The three types of repairs considered are 1) DS_1, re-nailing of wood sheathing, 2) DS_2, replacement of wood sheathing and 3) DS_3, replacement of the entire wall. For the re-nailing damage state DS_1, a contractor would need to remove the exterior siding, replace the nails that came loose in the wood sheathing and reapply the siding. The DS_2 repairs would consist of removing the siding and wood sheathing, then replace with new sheathing and reapply the siding. For the complete DS_3 replacement, the entire wall, including studs, top plate and sill, would need to be taken out and all new members installed. The damage states are listed in Table 3 and illustrated by photographs in Figs. 4 to 6.

Table 3 - Description of Damage States for Walls with OSB/Plywood Sheathing (System #50).

Damage States (DS_i)*	Description of Damage State
DS_1	Slight separation of sheathing or nails come loose (Fig. 4)
DS_2	Permanent rotation of sheathing, tear out of nails or sheathing tear out (Fig. 5)
DS_3	Fracture of studs, major sill plate cracking (Fig. 6)

*Gypsum wallboard damage states shown in Table 1 should be considered independently

Figure 4 - Damage State 1 for Walls with OSB/Plywood Sheathing (System #50): Slight Separation of OSB/Plywood from Framing (from Pardoen et al. 2002).

Figure 5 - Damage State 2 for Walls with OSB/Plywood Sheathing (System #50): Replacement of OSB/Plywood (from Gatto and Uang 2002).

Figure 6 - Damage State 3 for Walls with OSB/Plywood Sheathing (System #50): Replacement of Entire Wall (from Gatto and Uang 2002).

3.2 Development of Fragility Curves

The fragility curves shown in Fig. 7 were developed based on both the judgment of the authors (Method E) and laboratory test data (Method A). The fragility curves for damage states DS_2 and DS_3 are from test data, while the fragility curve for damage state one (DS_1) was determined using the judgment of the authors, because of the limited reported experimental data at which nails loosen. The dispersion parameter (β) is arbitrarily set to a higher value of 0.40 for damage state DS_1 to reflect the higher uncertainties with this damage state. The median and dispersion values for these fragility curves are listed in Table 4.

Table 4 - Median and Dispersion Values for Walls with OSB/Plywood Sheathing (System #50).

Damage States*	Demand Parameter (DP)	Median (θ)**	Dispersion (β)
DS_1	Inter-Story Drift ISD (%)	1.50	0.40
DS_2		2.62	0.16
DS_3		3.69	0.17

*Gypsum wallboard damage states shown in Table 1 should be considered independently

**For wall piers with aspect ratios between 2:1 and 3.5:1, median value should be multiplied by $2b_s/h$.

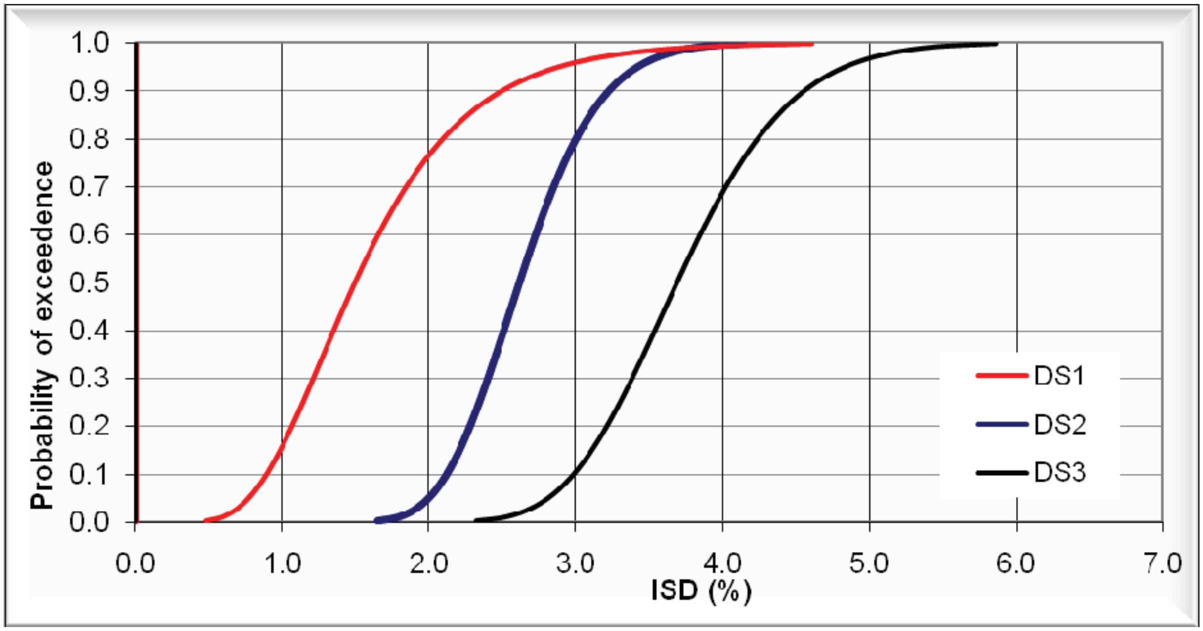

Figure 7 - Fragility Curves for Walls with OSB/Plywood Sheathing (System #50).

4. Fragilities of Shear Walls with OSB/Plywood Sheathing and Interior Gypsum Wallboard, Basic Strength Design (System # 47)

The fragility curves in this section are for walls incorporating both Oriented Strand Board/Plywood sheathing on the exterior surface with an exterior finish that does not affect substantially the lateral stiffness of the wall, such as vinyl siding, along with gypsum wallboard applied on the interior surface, but without holdown devices installed at the end of wall piers. As discussed in Section 1, the authors recommend basing the fragility curves for this system #47 on the same median values derived in Section 3 for system #50 multiplied by a factor of 2/3 and with an increased dispersion value of 0.4.

4.1 Definition of Damage States

The damage states are the same as described in Section 3.1. These damage states are listed again in Table 5.

Table 5 - Description of Damage States for Walls with OSB/Plywood Sheathing, Basic Strength Design (System #47).

Damage States (DS_i)*	Description of Damage State
DS_1	Slight separation of sheathing or nails which come loose (Fig. 4)
DS_2	Permanent rotation of sheathing, tear out of nails or sheathing (Fig. 5)
DS_3	Fracture of studs, major sill plate cracking (Fig. 6)

*Gypsum wallboard damage states shown in Table 1 should be considered independently

4.2 Development of Fragility Curves

The fragility curves based on the judgment of the authors are shown in Fig. 8. The median and dispersion values for these fragility curves are listed in Table 6.

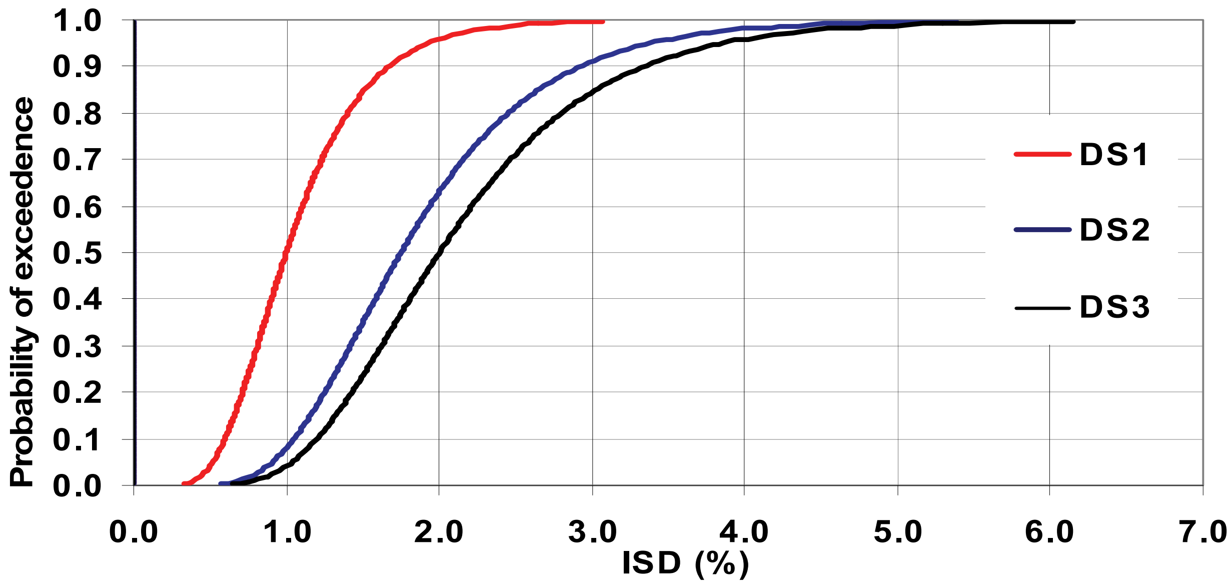

Figure 8 - Fragility Curves for Walls with OSB/Plywood Sheathing, Basic Strength Design (System #47).

Table 6 - Median and Dispersion Values for Walls with OSB/Plywood Sheathing Basic Strength Design (System #47).

Damage States*	Demand Parameter (DP)	Median (θ)**	Dispersion (β)
DS_1	Inter-Story Drift ISD (%)	1.00	0.40
DS_2		1.75	0.40
DS_3		2.50	0.40

*Gypsum wallboard damage states shown in Table 1 should be considered independently

**For wall piers with aspect ratios between 2:1 and 3.5:1, median value should be multiplied by $2b_s/h$.

5. Fragilities of Shear Walls with OSB/Plywood Sheathing, Interior Gypsum Wallboard and Exterior Stucco (System #51)

The fragility curves in this section are for shear walls with Oriented Strand Board/Plywood sheathing with interior gypsum wallboard and exterior stucco finish. Experimental results have shown that exterior stucco finish influence substantially the seismic response of wood light-frame buildings.

The shear walls that that were considered in the development of the fragility curves were based on cyclic tests on wall assemblies (Gatto and Uang 2002, Arnold and Uang 2005) as well as on shake tables tests of complete wood light-frame buildings incorporating walls sheathed with OSB/Plywood, gypsum wallboard and stucco (Fischer et al. 2001, Mosalam et al. 2002, Christovasilis et al. 2007). The shear walls in these tests were constructed using:

- Walls 8' tall by either 8' or 16' in length
- Grade No. 2 or 2x4 better Hem-Fir/Douglas-Fir spaced 16" on center
- Double top plate and single bottom plate
- 3/8" OSB or 15/32" Plywood sheathing fastened vertically using 8d box nails spaced at12" in the field and 4" to 6" along the panel edges.
- Fully sheathed walls or walls incorporating window or pedestrian door openings
- Holdowns installed at the end of wall piers
- Three-layer 7/8" thick stucco with ½" chop strand fibers applied over wire mesh fastened with 1.25" long staples

5.1 Definition of Damage States

For shear walls incorporating OSB/Plywood sheathing with exterior stucco finish, three damage states were chosen based on the type of repairs that would need to be conducted besides that to gypsum wallboard. For damage to gypsum wallboard, the fragility curves developed in Section 2 and shown in Fig. 3 should be used independently. The types of repairs considered are 1) DS_1, repair of stucco, 2) DS_2, replacement of stucco and wall sheathing that may have separated from the wood studs (in this damage state, it is assumed that the studs have not fractured) and 3) DS_3, replacement of the entire wall, including studs, top plate and sill. Experimental results have shown substantial damage to the wood studs due to higher stiffness provided by the stucco, which induces significant tension perpendicular to grain along the height of the studs (see Fig. 11). Therefore, a damage state involving only the replacement of the stucco and wood sheathing, without replacement of the studs, is not considered. For the repair of stucco, DS_1, a contractor would need to clean out the cracks and fill them with appropriate cement compound. The second type of repair, DS_2, would include removing pieces of spalled stucco, then replacing them with new stucco. For the complete replacement, DS_3, the entire wall would need to be taken out and all new members replaced. These damage states are listed in Table 7 and illustrated in Figs. 9 to 11.

Table 7 - Description of Damage States for Walls with OSB/Plywood Sheathing and Stucco Exterior Finish (System #51).

Damage States (DS_i)*	Description of Damage State
DS_1	Cracking of Stucco (Fig. 9)
DS_2	Spalling of stucco, separation of stucco and sheathing from studs (Fig. 10)
DS_3	Fracture of studs, major sill plate cracking (Fig. 11)

*Gypsum wallboard damage states shown in Table 1 should be considered independently

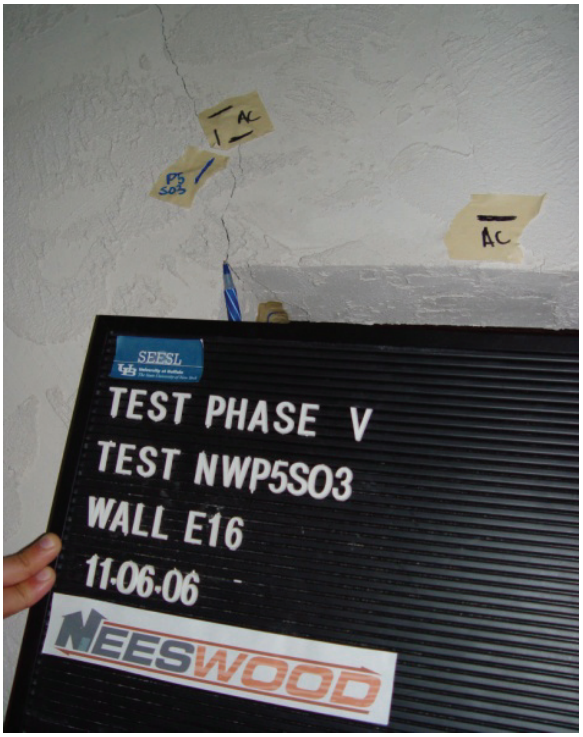

Figure 9 - Damage State 1 for Walls Incorporating Stucco as Exterior Finish: Small Cracking of Stucco (from Christovasilis et al. 2007).

Figure 10 - Damage State 2 for Walls Incorporating Stucco as Exterior Finish: Replacement of Spalled Stucco (from Christovasilis et al. 2007).

Figure 11 - Damage State 3 for Walls Incorporating Stucco as Exterior Finish: Replacement of Entire Wall (from Gatto and Uang 2002).

5.2 Development of Fragility Curves

The fragility curves for shear walls with Oriented Strand Board/Plywood sheathing with exterior stucco finish are shown in Fig. 12. The median and dispersion values for these fragility curves are listed in Table 8.

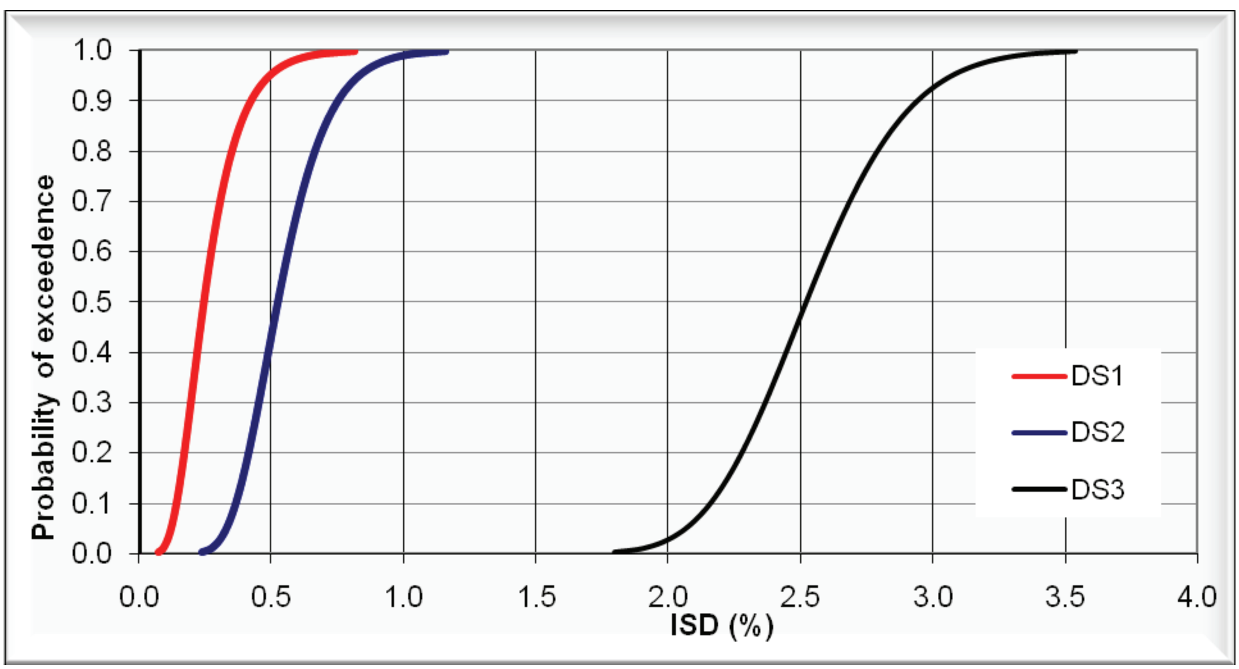

Figure 12 - Fragility Curves for Walls with OSB/Plywood Sheathing and Stucco Exterior Finish (System #51).

Table 8 - Median and Dispersion Values for Walls with OSB/Plywood Sheathing and Stucco Exterior Finish (System #51).

Damage States*	Demand Parameter (DP)	Median % (θ)**	Dispersion (β)
DS_1	Inter-Story Drift ISD (%)	0.25	0.43
DS_2		0.52	0.28
DS_3		2.52	0.12

*Gypsum wallboard damage states shown in Table 1 should be considered independently

**For wall piers with aspect ratios between 2:1 and 3.5:1, median value should be multiplied by $2b_s/h$.

6. Fragilities of Shear Walls with OSB/Plywood Sheathing, Interior Gypsum Wallboard and Exterior Stucco, Basic Strength Design (System #48)

The fragility curves in this section are for walls with Oriented Strand Board/Plywood sheathing with interior gypsum wallboard and exterior stucco finish but without holdowns installed at the end of wall piers. As discussed in Section 1, the authors recommend basing the fragility curves for this system #48 on the same median values derived in Section 5 for system #51 multiplied by a factor of 2/3 and with an increased dispersion value of 0.4 (or to a higher value than of System #51 if larger than 0.40).

6.1 Definition of Damage States

The damage states are the same as described in Section 5.1. These damage states are listed again in Table 9.

Table 9 - Description of Damage States for Walls with OSB/Plywood Sheathing and Stucco Exterior Finish Basic Strength Design (System #48).

Damage States (DS_i)	Description of Damage State
DS_1	Cracking of Stucco (Fig. 9)
DS_2	Spalling of stucco, separation of stucco and sheathing from studs (Fig. 10)
DS_3	Fracture of studs, major sill plate cracking (Fig. 11)

*Gypsum wallboard damage states shown in Table 1 should be considered independently

6.2 Development of Fragility Curves

The fragility curves based on the judgment of the authors are shown in Fig. 13. The median and dispersion values for these fragility curves are listed in Table 10.

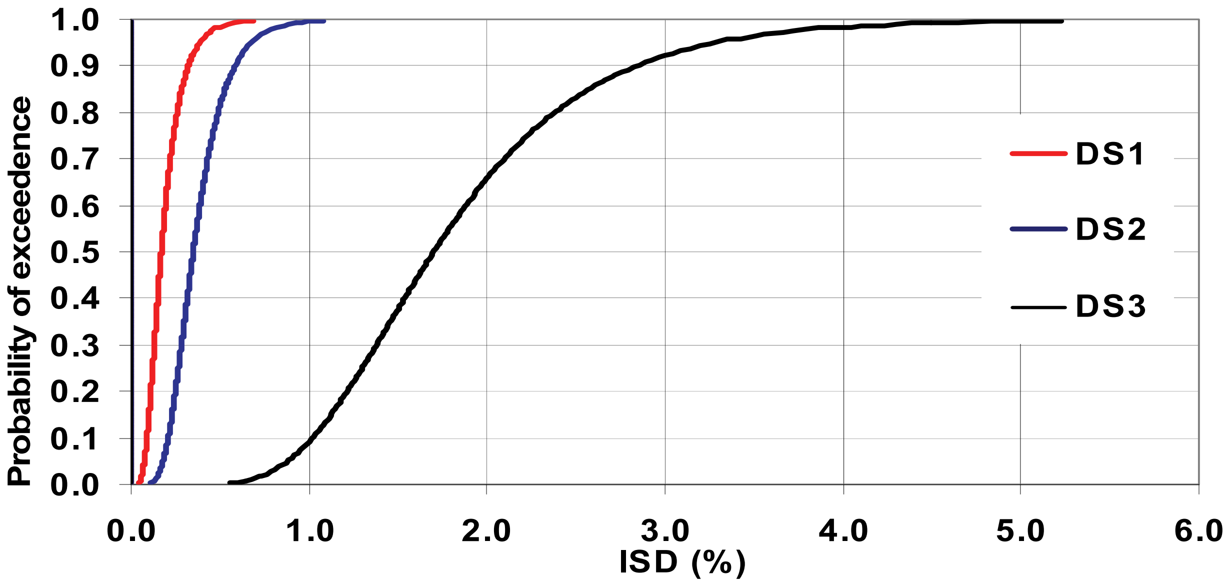

Figure 13 - Fragility Curves for Walls with OSB/Plywood Sheathing and Stucco Exterior Finish, Basic Strength Design (System #48).

Table 10 - Median and Dispersion Values for Walls with OSB/Plywood Sheathing and Stucco Exterior Finish Basic Strength Design (System #48).

Damage States	Demand Parameter (DP)	Median (θ)**	Dispersion (β)
DS_1	Inter-Story Drift ISD (%)	0.17	0.50
DS_2		0.35	0.40
DS_3		1.70	0.40

*Gypsum wallboard damage states shown in Table 1 should be considered independently

**For wall piers with aspect ratios between 2:1 and 3.5:1, median value should be multiplied by $2b_s/h$.

7. Fragilities of Light Wood Frame, Diagonal Strut Bracing (System #52)

The fragility curves in this section are for wood stud framing braced by wood diagonal bracing. This system is seldom used in North America and the fragility values were established by judgment based mainly on the results of a limited number sub-assembly testing conducted in Japan (Isoda 2007).

7.1 Definition of Damage States

For wood stud framing braced by wood diagonal bracing, a single damage state, DS_1, failure of the diagonal bracing member, is considered. After failure of the diagonal bracing, it is assumed that the strength and stiffness of the wall is reduced essentially to zero and the entire wall will need to be replaced. This damage state is listed in Table 11 and illustrated in Fig. 14.

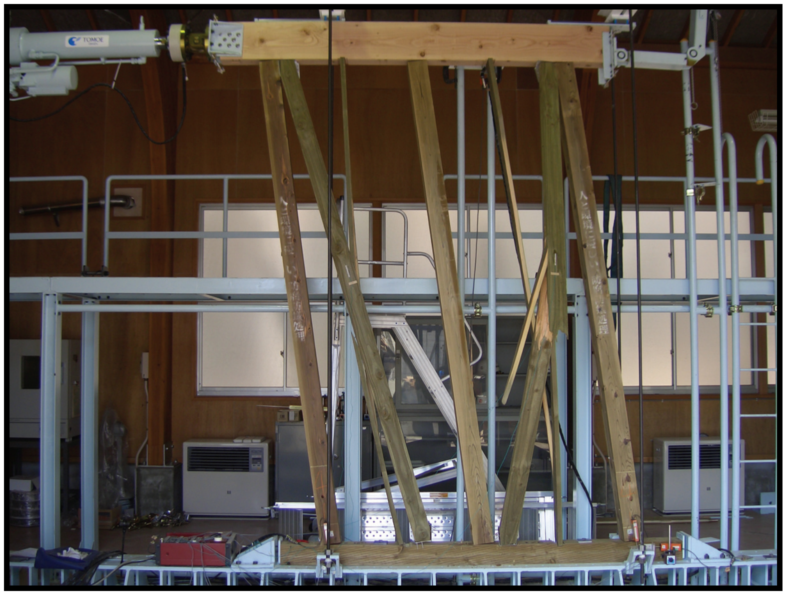

Figure 14 - Damage State 1 for Wood Stud Framing Braced by Diagonal Bracing: Failure of Diagonal Bracing (from Isoda 2007).

Table 11 - Description of Damage States for Light Wood Frame, Diagonal Strut Bracing (System #52).

Damage States (DS_i)*	Description of Damage State
DS_1	Failure of Diagonal Bracing (Fig. 14)

*Gypsum wallboard damage states shown in Table 1 should be considered independently

7.2 Development of Fragility Curves

The fragility for wood stud framing braced by diagonal bracing was established from the judgment of the authors based on a limited number of subassembly cyclic test data performed in Japan on 6 ft long by 10 ft high wall assemblies incorporating diagonal bracing. Figure 15 shows the experimental lateral load-displacement obtained from one of these wall assemblies. The peak lateral load in each loading direction is reached for an Inter-Story Drift, ISD, between 1% and 2%. After this peak load is reached, the stiffness and strength of the wall assembly degrades very quickly. Based on these experimental results, the authors recommend basing the fragility curve for this system #52 on a median ISD value of 1% with a moderate dispersion value of 0.3. This fragility curve is shown in Fig. 16. The median and dispersion values for this fragility curve are listed in Table 12.

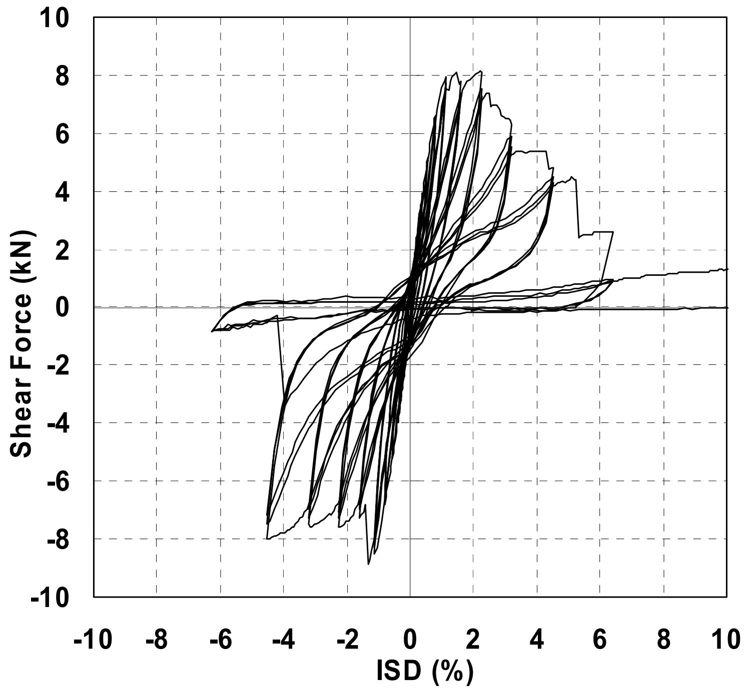

Figure 15 – Experimental Load-Displacement Curve for Wood Stud Framing Braced by Diagonal Bracing (from Isoda 2007).

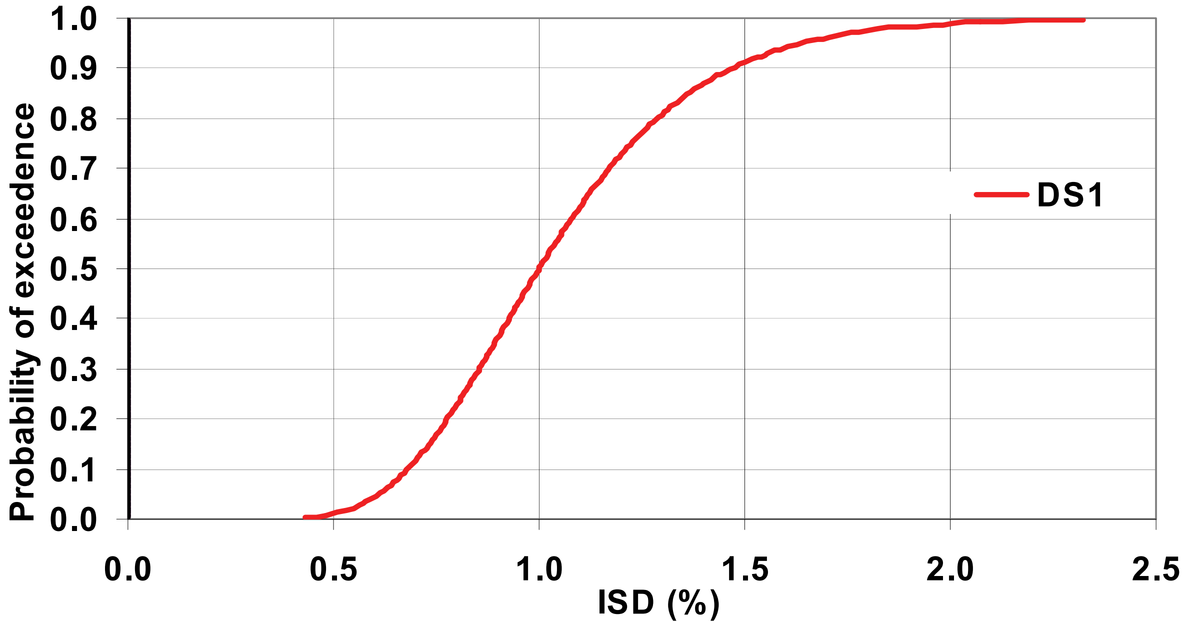

Figure 16 - Fragility Curve for Light Wood Frame, Diagonal Strut Bracing (System #52).

Table 12 - Median and Dispersion Values for Light Wood Frame, Diagonal Strut Bracing (System #52).

Damage States	Demand Parameter (DP)	Median (θ)**	Dispersion (β)
DS_1	Inter-Story Drift ISD (%)	1.00	0.30

*Gypsum wallboard damage states shown in Table 1 should be considered independently

8. Fragilities of Sill Plates

The fragility curves in this section are for sill plates connected by anchor bolts to a concrete foundation with (Section 7.1) and without (Section 7.2) holdowns installed at the end of wall piers. The demand parameter considered for sill plates is the base shear force carried by each anchor bolt, VB, in pounds (lbs). This demand parameter is equal to the total shear force carried by a wall pier divided by the number of anchor bolts and holdown devices installed on that wall pier.

The simplified assessment procedure being developed as part of the ATC-58 Project will generate maximum inter-story drifts and maximum absolute floor accelerations. Knowing the peak floor accelerations, the total shear force at the base of the building can be easily obtained by summing the floor inertia forces (mass x acceleration). The total shear force carried by a wall pier can then be obtained by distributing the total shear force at the base of the building through tributary areas or relative lateral stiffness of the wall pier.

The fragility curves for sill plates developed in this section were based on cyclic tests (Method A) conducted on sill plate assemblies by Mahaney and Kehoe (2002). In this experimental study, a lateral load was placed at the top of 8' x 8' shear walls to include the effects of overturning and the plywood sheathing was nailed at a reduced spacing of 3" on center along the panel edges to insure failure in the sill plates or holdowns. The fragility curves for sill plates without holdowns would apply typically to the first level of a building. The fragility curves for sill plates with holdowns could apply to upper levels if holdowns are installed at the end of wall piers in these levels.

The shear walls that were considering in the development of the fragility curves for sill plates were constructed using:

- Walls 8' tall by 8' in length
- Grade No. 2 or 2x4 better Hem-Fir/Douglas-Fir studs
- 2x4, 2x6, 3x4 or 3x6 sill plates
- 5/8" diameter anchor bolts
- Anchor bolt are hand tight plus ¼ turn
- Sill plate face nailed to studs with 2-16d nails

- HTT22 Holdown from Simpson Strong Tie
- 4”x4” end posts

Considering that the base shear force required for failing a sill plate is significantly below the shear capacity of an anchor bolt, the authors recommend using the same fragility curves for sill plates anchored to a concrete foundation with ½” diameter anchor bolts, which is typical of residential construction.

8.1 Definition of Damage States for Sill Plates without Holdowns

For the development of the fragility curves for sill plates without holdowns, only one damage state, DS_1, failure of the sill plates, is considered. This singled damage state is associated with complete splitting of the sill plates, as shown in Fig. 17. The repair for the sill plate splitting would be to replace the entire wall. In most cases the sill plates failed due to the overturning moment, which causes the sill plate to uplift, bend and split due to tension perpendicular to grain.

Figure 17 - Damage State 1 for Sill Plates without Holdowns: Replacement of Entire Wall (from Mahaney and Kehoe 2002).

8.1.1 Development of Fragility Curves for 2x Sill Plates without Holdowns

The fragility curves shown in Fig. 18 for 2x sill plates without holdowns contain three different types of bolt washers (2.5” square by 0.25” thick washer, standard 1.5” round washer and 3” square by 0.5” thick washer). The fragility curve for the 2.5” square washer by 0.25” thick washer was based on experimental data. While the median for both the standard round and 3” square washer are from experimental data, the dispersion factor (β) was increased to 0.40 based on the judgment of the authors to reflect the limited experimental data available. These median and dispersion values are shown in Table 13.

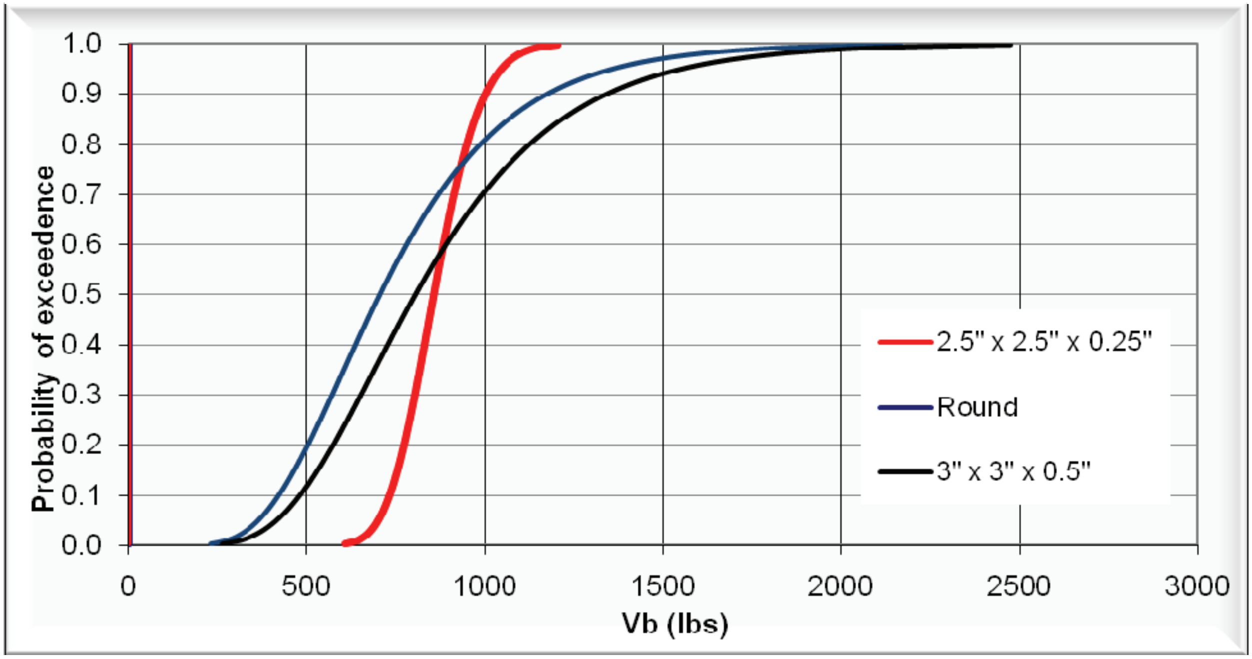

Figure 18 - Fragility curves for 2x Sill Plates without Holdowns and with Various Types of Bolt Washers.

Table 13 - Median and Dispersion Values for Sill Plates without Holdowns.

Washer Type	Demand Parameter (DP)	Median (θ)	Dispersion (β)
2.5”x2.5”x0.25”	Shear Force per Anchor Bolt VB (lbs)	855	0.12
Standard Round 1.5” dia.		704	0.40
3”x3”x0.5”		805	0.40

8.1.2 Development of Fragility Curves for 3x Sill Plates without Holdowns

The fragility curve shown in Fig. 19 is for 3x sill plates, without holdowns, and connected to a concrete foundation with 5/8” diameter anchor bolts incorporating 2.5”square x 0.25” thick washers. Because of the limited experimental data available (i.e two tests), the dispersion parameter (β) was increased to 0.4. The median and dispersion for this fragility curve is shown in Table 14. Note that the median value for 3x sill plates is 37% higher than the median for 2x sill plates (1174 lbs vs 855 lbs) indicating the beneficial effect of using 3x sill plates when holdowns are not incorporated.

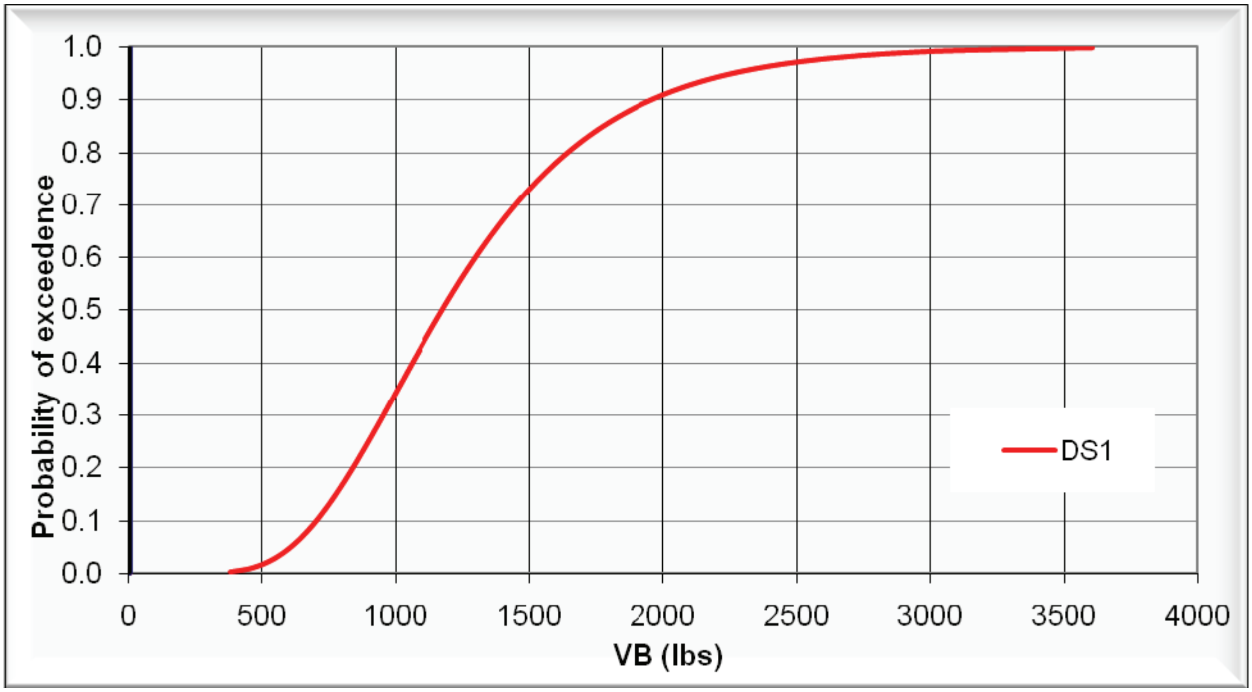

Figure 19 - Fragility Function for 3x Sill Plates without Holdowns.

Table 14 - Median and Dispersion Values for 3x Sill Plates without Holdowns

Damage State	Demand Parameter (DP)	Median (θ)	Dispersion (β)
DS_1	Shear Force per Anchor Bolt VB (lbs)	1174	0.40

8.2 Definition of Damage States for Sill Plates with Holdowns

For the development of the fragility curves for sill plates incorporating holdowns at the end of the wall piers, only one damage state, DS_1, complete failure of the sill plates and/or of the holdowns. This damage state is illustrated by a photograph in Fig. 20. Both types of failures (sill plates and holdowns) are grouped together since it is the opinion of the author that failure of the holdown controls the behavior and when the holdown fails the sill plate will fail soon after. This could be shown by comparing the median values of the fragility curves for sill plates with and without holdowns; the sill plates with holdowns can withstand a force about three times that without holdowns.

All test data reviewed in this document incorporated a particular type of holdown (HTT22 from Simpson Strong Tie) with an allowable uplift load of 5260 lbs. In the absence of test data incorporating other types of holdown, the authors recommend in the interim multiplying the median values developed herein for the HTT22 Simpson Strong Tie holdown by T/5260, where T is the allowable uplift load of the holdown considered in lbs. For this case, the dispersion factor (β) should be increased to a value of 0.40 to recognize the higher uncertainty associated with this fragility curve. Also, it is the judgment of the authors that when holdowns are incorporated, the effect of different types of bolt washers on the anchor bolts should be secondary. Therefore, the authors recommend using the same fragility curves for sill plates with holdowns for any types of washers applied to the anchor bolts.

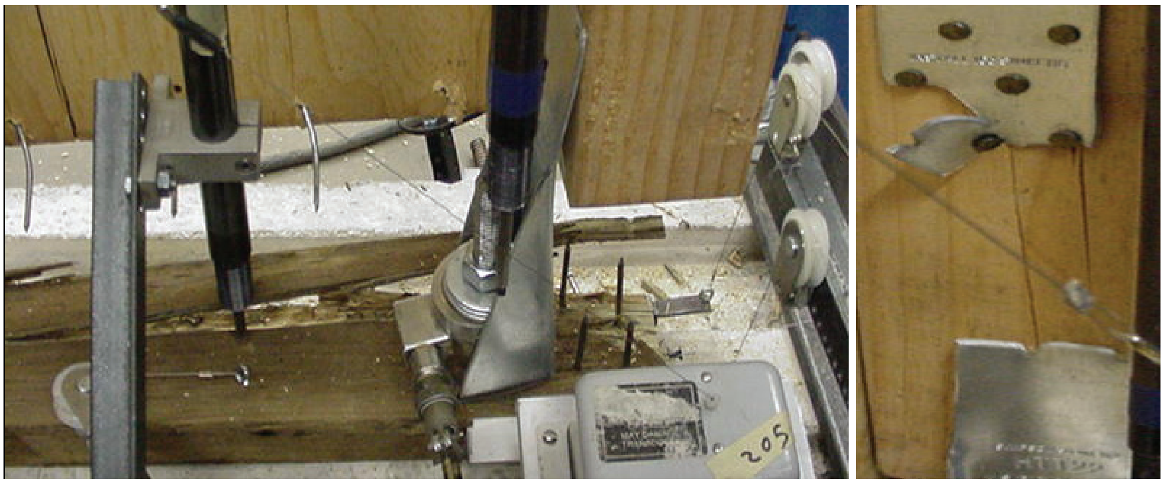

Figure 20 - Damage State 1 for Sill Plates with Holdowns: Replacement of Entire Wall (from Mahaney and Kehoe 2002).

8.2.1 Development of Fragility Curves for 2x Sill Plates with Holdowns

The fragility curves shown in Fig. 21 for 2x sill plates with holdowns contain two different types of bolt washers (standard 1.5” round washer and 3” square by 0.5” thick washer). The fragility curve for the 3” square washer by 0.5” thick washer was based on experimental data. While the median for the standard round are from experimental data, the dispersion factor (β) was increased to 0.40 based on the judgment of the authors to reflect the limited experimental data available. These median and dispersion values are shown in Table 15. Note that the median values are similar for both types of washers indicating that the types and sizes of washers are not important parameter governing the failure capacity of sill plates with holdown.

Table 15 - Median and Dispersion Values for 2x Sill Plates with Holdowns

Washer Type	Demand Parameter (DP)	Median (θ)	Dispersion (β)
Standard Round 1.5” dia.	Shear Force per Anchor Bolt VB (lbs)	2790	0.40
3”x3”x0.5”		2620	0.26

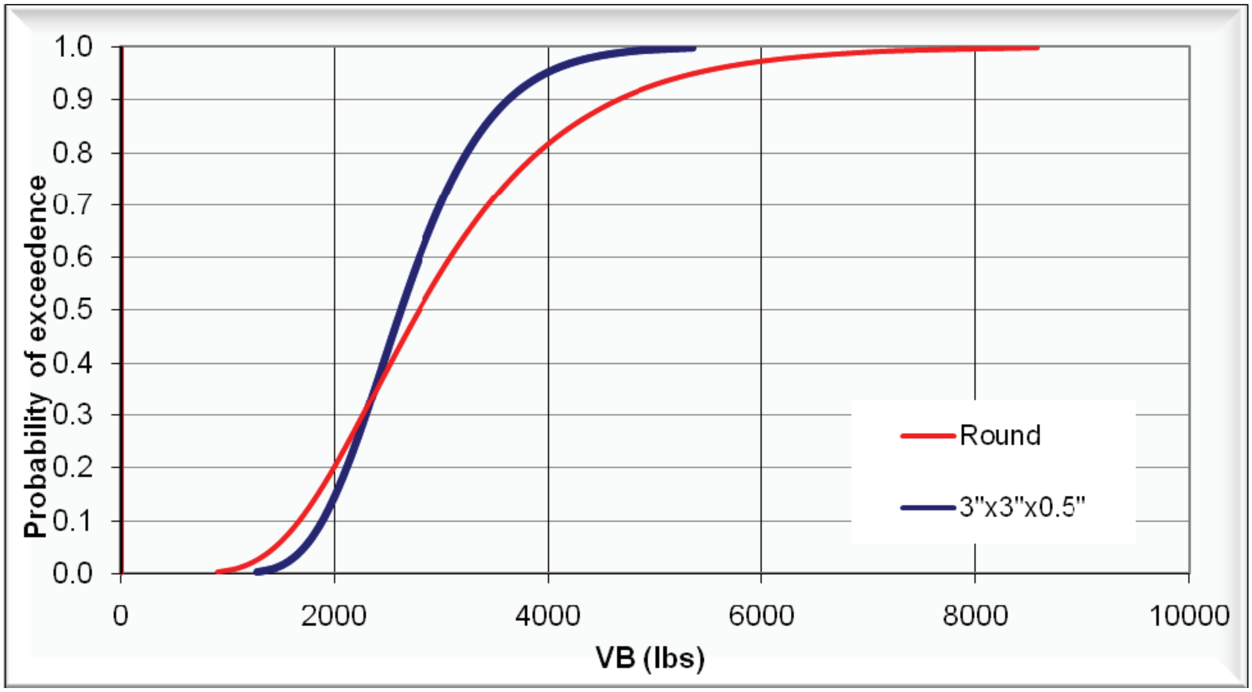

Figure 21 - Fragility Curves for 2x Sill Plates with Holdowns and with Various Types of Bolt Washers.

8.2.2 Development of Fragility Curves for 3x Sill Plates with Holdowns

The fragility curve shown in Fig. 22 is for 3x sill plates, with holdowns, and connected to a concrete foundation with 5/8" diameter anchor bolts incorporating 2.5"square"x 0.25" thick washers. Because of the limited experimental data available (i.e two tests), the dispersion parameter (β) was increased to 0.4. The median and dispersion for this fragility curve is shown in Table 16. Note that the median value for 3x sill plates is similar (actually slightly lower) than the median values for 2x sill plates indicating that the size of the sill plate is not an important parameter governing the failure capacity of sill plates with holdowns.

Table 16 - Median and Dispersion Values for 3x Sill Plates with Holdowns.

Damage State	Demand Parameter (DP)	Median (θ)	Dispersion (β)
DS_1	Shear Force per Anchor Bolt VB (lbs)	2324	0.40

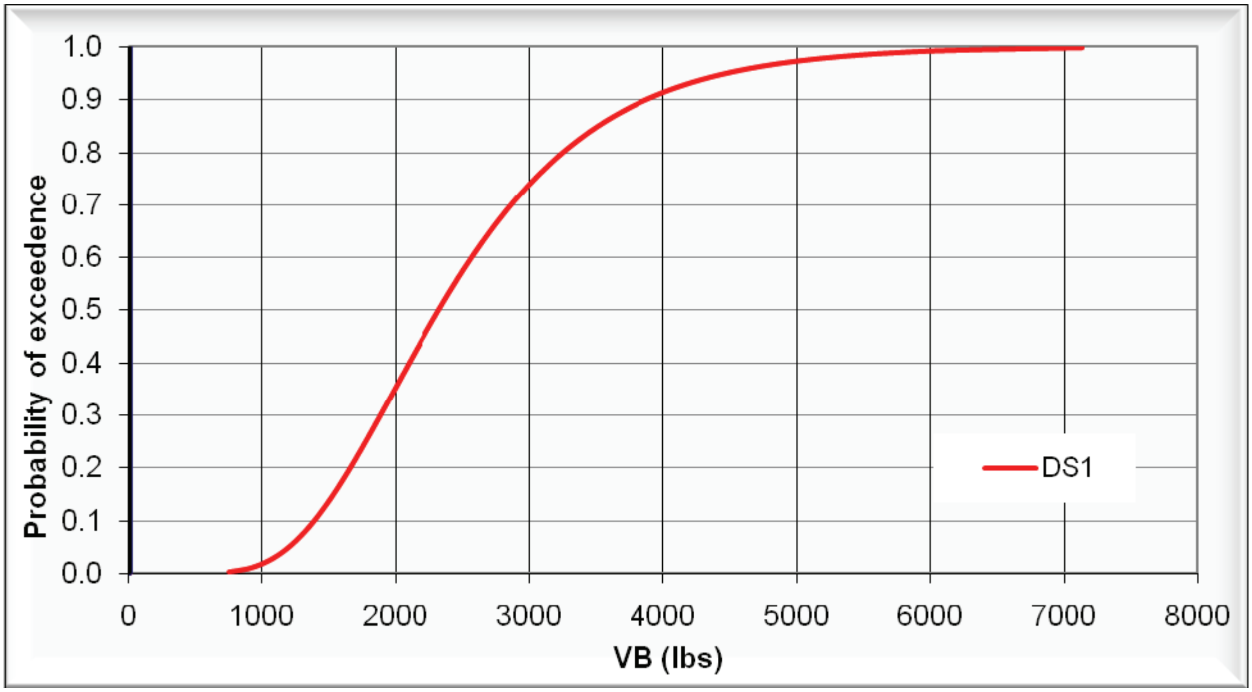

Figure 22 - Fragility Function for 3x Sill Plates with Holdowns.

9. Damage State Interactions

In this section, the interactions between the various damage states, DS_i, defined for wood light-frame systems considered in this document are defined. Three possible interactions are defined between pairs of damage states part of the same or different systems.

The first damage state interaction is defined as an Independent (I) interaction. This means that a given pair of damage states can occur independently of each other. An example would be the independent occurrence of a damage state to the gypsum wallboard on the interior surface of a shear wall and the damage state to the wood sheathing (OSB or Plywood) on the exterior surface of the wall. Therefore, independent fragility curves would be used to define these two damage states.

The second damage state interaction is defined as a Sequential (S) interaction. This means that a given damage state can not occur before a preceding damage state has occurred. An example of this would be the sequence of damages states (e.g. DS_1, DS_2 and DS_3) defined for a given system. Obviously, damage state DS_1 must occur before damage state DS_2 and damage state DS_2 must occur before damage state DS_3. Therefore, sequential fragility curves must be used to define these damage states.

The third damage state interaction is defined as a Mutually Exclusive (ME) interaction. This means that a pair of independent damage states can not occur simultaneously. An example would be the complete failure of a sill plate, requiring the replacement of an entire shear wall, before a given damage to the other components of the wall occur. Therefore for this case, the set of damage states for the wall components (wood sheathing and gypsum wallboard) would not be considered once the sill plate has failed.

These three types of damage state interactions for wood light-frame systems are shown in a matrix format in Table 17.

Table 17 – Damage State Interactions for Wood Light-Frame Systems.

		Gypsum Wallboard		**Shear Wall Systems #50 and #47**			**Shear Wall Systems #51 and #48**			**Braced Wall System #52**	**2x and 3x Sill Plates with and without holdowns**
		DS_1	DS_2	DS_1	DS_2	DS_3	DS_1	DS_2	DS_3	DS_1	DS_1
Gypsum Wallboard	DS_1		S_{12}	I	I	I	I	I	I	I	ME
	DS_2			I	I	I	I	I	I	I	ME
Shear Wall Systems #50 and #47	DS_1				S_{12}	S_{13}	I	I	I	I	ME
	DS_2					S_{23}	I	I	I	I	ME
	DS_3						I	I	I	I	ME
Shear Wall Systems #51 and #48	DS_1							S_{12}	S_{13}	I	ME
	DS_2								S_{23}	I	ME
	DS_3									I	ME
Braced Wall System #52	DS_1										ME

S_{ij} – Sequential (DS_i occurs before DS_j), I – Independent, ME – Mutually Exclusive

10. Summary of Fragilities Curves for Wood Light-Frame Systems

Table 18 summarizes the demand parameters, medians and dispersions for the fragility curves developed in this document for wood light-frame systems.

Table 18 – Summary of Fragilities for Wood Light-Frame Systems

System Number/Type		Demand Parameter	Median % (θ)			Dispersion (β)			Data Type[*]
			DS_1	DS_2	DS_3	DS_1	DS_2	DS_3	
Gypsum Wallboard[***]		Inter-Story Drift ISD (%)	0.33	0.56	-	0.55	0.56	-	A,A
Wall System #50[***]			1.50	2.62	3.69	0.40	0.16	0.17	E,A,A
Wall System #47[***]			1.00	1.75	2.50	0.40	0.40	0.40	E,E,E
Wall System #51[***]			0.25	0.52	2.52	0.43	0.28	0.12	A,A, A
Wall System #48[***]			0.17	0.35	1.70	0.50	0.40	0.40	E,E,E
Braced Wall System #52			1.00	-	-	0.30	-	-	E
2x Sill Plates without Holdowns	2.5"x2.5"x0.25" washers	Shear Force per Anchor Bolt VB (lbs)	855	-	-	0.12	-	-	A
	Standard Round 1.5" diameter washers		704	-	-	0.40	-	-	E
	3"x3"x0.5" washers		805	-	-	0.40	-	-	E
3x Sill Plates without Holdowns			1174	-	-	0.40	-	-	E
2x Sill Plates with Holdowns[**]	Standard Round 1.5" diameter washers		2790	-	-	0.40	-	-	E
	3"x3"x0.5" washers		2620	-	-	0.26	-	-	A
3x Sill Plates with Holdowns[**]			2324	-	-	0.40	-	-	E

[*]A – Actual Data (Method A), E – Expert Judgment (Method E)

[**]For holdowns other than HTT22 Simpson Strong Tie, the median should be multiplied by T/5260, where T is the allowable uplift load of the holdown considered. The dispersion (β) should also be increased to 0.40.

[***]For wall piers with aspect ratios between 2:1 and 3.5:1, median value should be multiplied by $2b_s/h$.

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12. Acknowledgements

The work described in this report was conducted as part of the ATC-58 Project "Guidelines for Seismic Performance Assessment of Buildings," pursuant to a contract with the Federal Emergency Management Agency. The substance of such work is dedicated to the public. The author(s) are solely responsible for the accuracy of statements or interpretations contained in this publication. No warranty is offered with regard to the results, findings and recommendations contained herein, either by the Federal Emergency Management Agency, the Applied Technology Council (ATC), its directors, members or employees. The authors acknowledge Mr. Andy Merovich and Dr. Andrew Whittaker who reviewed and provided useful comments on the various drafts of this report.

Appendix A – Data and Lognormal Fragility Curves

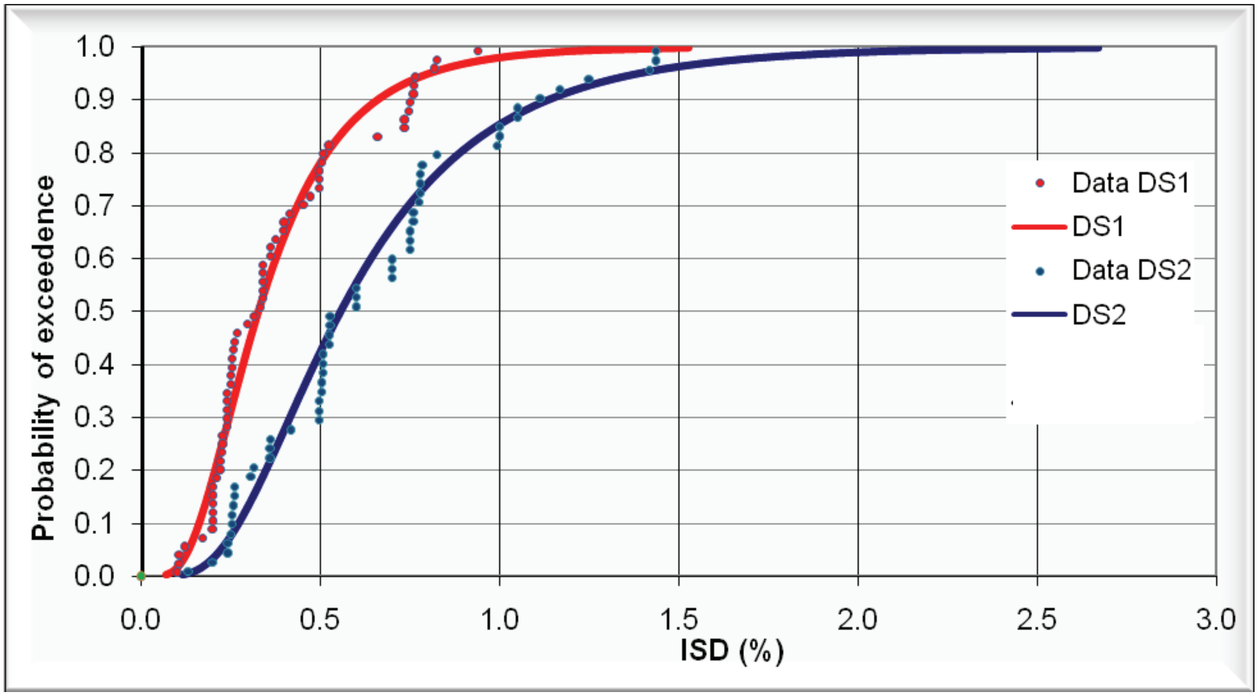

Figure A1 - Fragility Function for Walls with Gypsum Wallboard.

Table A1 - Medians and Dispersions for Walls with Gypsum Wallboard.

	Median θ	Dispersion β	Number of Samples	Lilliefors Test
DS1	0.33	0.55	62	Fails
DS2	0.56	0.56	56	Passes

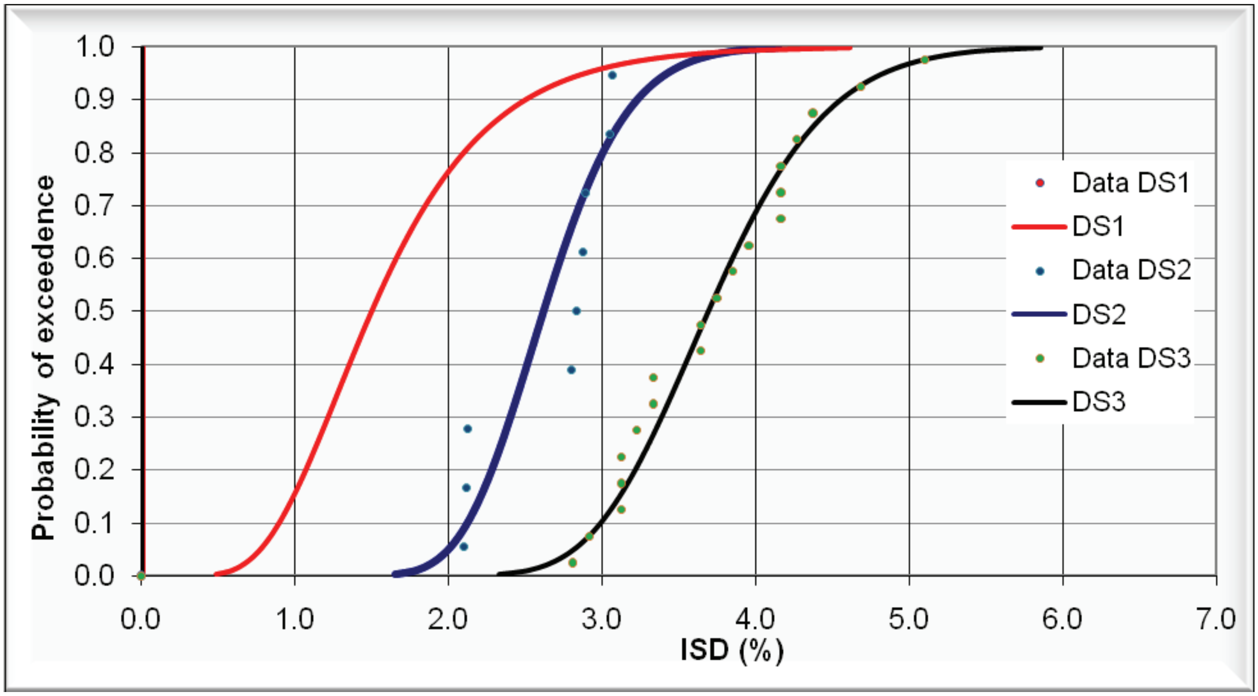

Figure A2 - Fragility Function for Walls with OSB/Plywood Sheathing (System #50).

Table A2 - Median and Dispersion Values for Walls with OSB/Plywood Sheathing (System #50).

	Median θ	Dispersion β	Number of Samples	Lilliefors Test
DS1	1.50	0.40	N/A	N/A
DS2	2.62	0.16	9	Passes
DS3	3.69	0.17	20	Passes

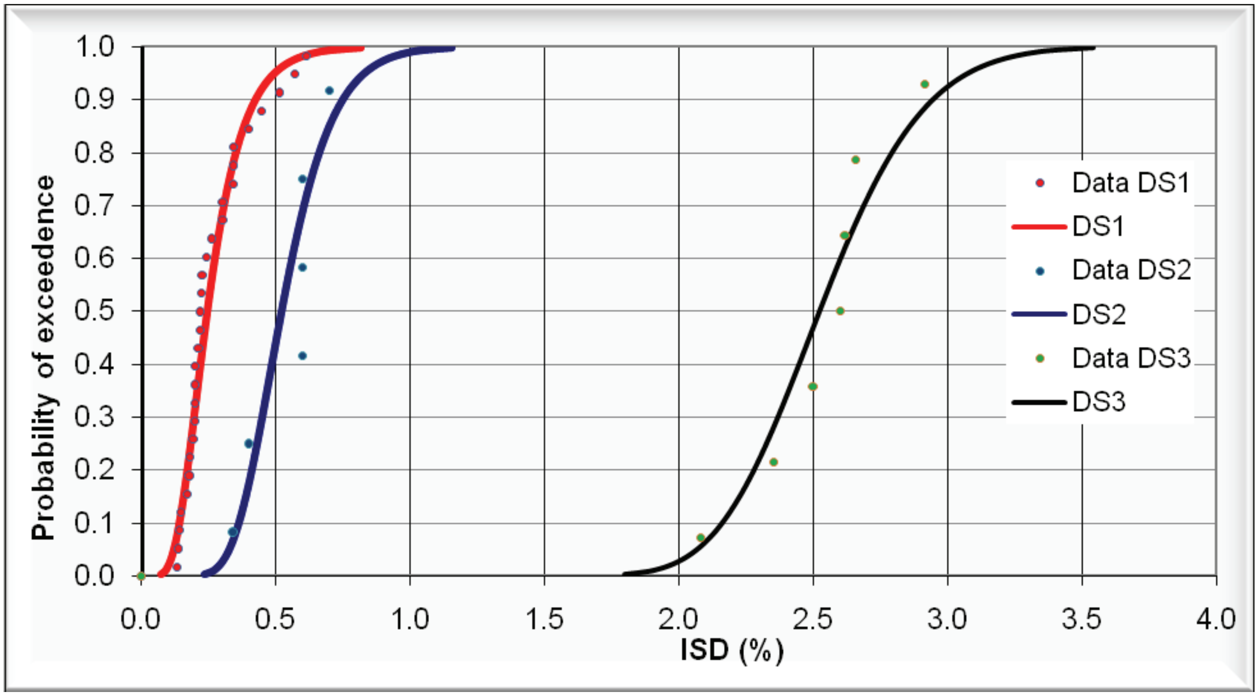

Figure A3 - Fragility Function for Walls with OSB/Plywood Sheathing and Stucco Exterior Finish (System #51).

Table A3 - Median and Dispersion Values for Walls with OSB/Plywood Sheathing and Stucco Exterior Finish (System #51).

	Median θ	Dispersion β	Number of Samples	Lilliefors Test
DS1	0.246	0.427	29	Fails
DS2	0.523	0.282	6	Passes
DS3	2.522	0.121	7	Passes

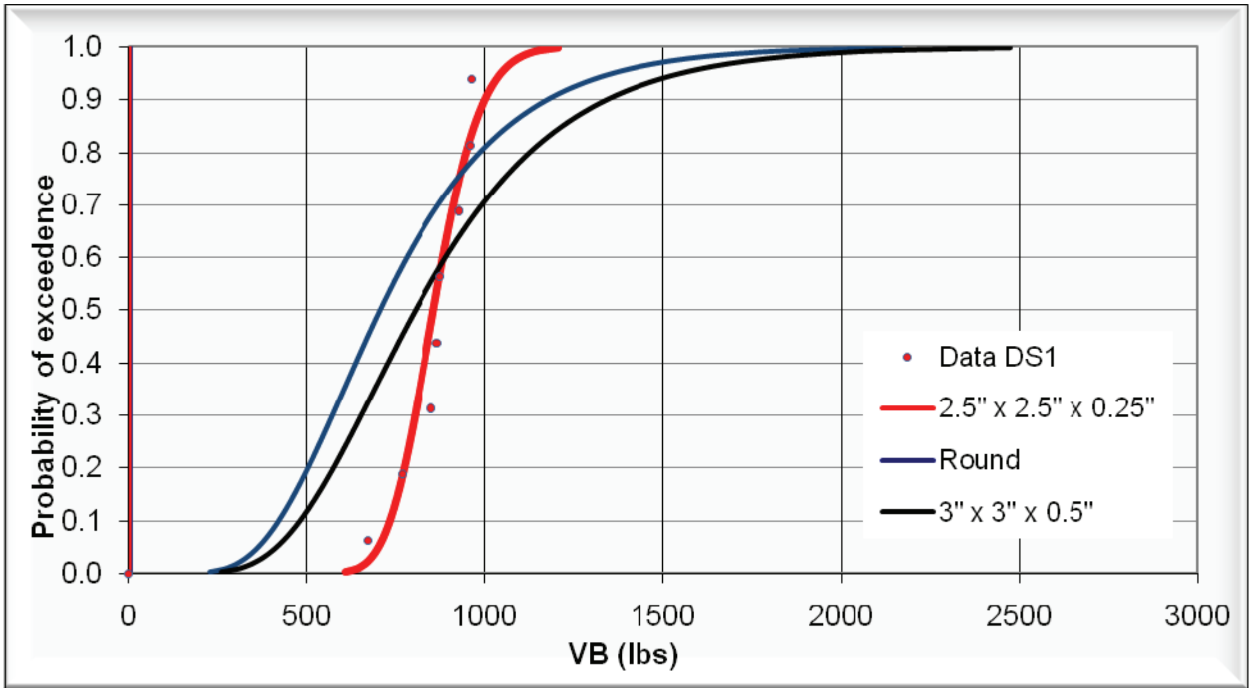

Figure A4 - Fragility Function for 2x Sill Plates without Holdowns.

Table A4 - Median and Dispersion Values for Sill Plates without Holdowns.

Washer Type	Median θ	Dispersion β	Number of Samples	Lilliefors Test
2.5”x2.5”x0.25”	855.05	0.12	8	Passes
Standard Round 1.5” diameter	704.25	0.40	N/A	N/A
3”x3”x0.5”	805.25	0.40	N/A	N/A

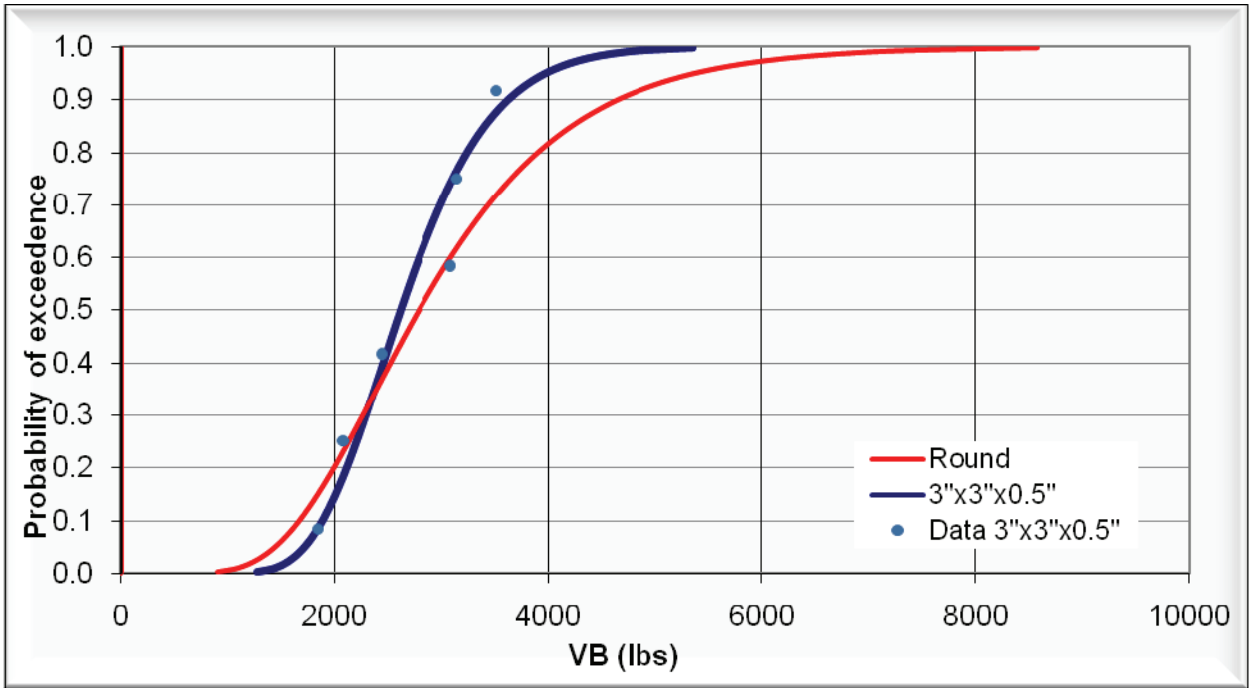

Figure A5 - Fragility Function for 2x Sill Plates with Holdowns.

Table A5 - Median and Dispersion Values for 2x Sill Plates with Holdowns Fragility Curves.

Washer Type	Median θ	Dispersion β	Number of Samples	Lilliefors Test
Standard Round 1.5” diameter	2789.5	0.40	N/A	N/A
3”x3”x0.5”	2619.70	0.26	6	Passes

Appendix B – Fragility Data for Gypsum Wallboard Partitions

Test Data from McMullin and el al (2001).

Table B1 - Monotonic Test Data.

Damage State	Test 1 Front	Test 1 Back	Test 2 Front	Test 2 Back	Test 3 Front	Test 3 Back	Test 4 Front	Test 4 Back	Test 5 Front	Test 5 Back	Test 10 Front	Test 10 Back
Cracking of paint over fastener	0.254	0.254	0.503	0.374	0.939	1.008	0.735	0.735	0.498	0.498	1.018	1.247
Cracking of wallboard at wall penetration	0.24	0.76	0.2	0.2	0.227	0.262	0.24	0.24	0.22	0.22	0.267	0.508
Crushing of wallboard at perimeter	1.758	0.254	1.05	1.05	0.778	0.778	0.498	0.751	0.498	0.751	2.991	1.508
Cracking of joint at out-of-plane wall	0.76	0.76	0.503	0.503	0.778	-	1.521	0.994	0.498	-	-	0.508
Cracking of vertical butt joint	-	-	-	-	-	-	-	0.761	-	-	0.746	1.018
Cracking of horizontal wall joint	-	-	-	-	-	-	-	4.063	-	-	-	-
Local buckling of panel at wall penetration	0.525	0.254	0.241	0.241	0.262	0.262	0.527	0.527	1.001	1.001	0.508	0.508
Global buckling of panel	-	-	-	-	-	-	2.039	1.437	2.039	1.437	2.017	-
Misc.-Cracking of panel not at opening	-	-	-	-	-	-	-	-	-	-	-	-

Table B2 - Cyclic Test Data.

Damage State	Test 6 Front	Test 6 Back	Test 7 Front	Test 7 Back	Test 11 Front	Test 11 Back	Test 12 Front	Test 12 Back	Test 13 Front	Test 13 Back
Cracking of paint over fastener	0.34	0.18	0.25	0.25	0.524	0.472	0.17	0.227	0.451	0.764
	0.34	0.24	0.25	0.25	0.524	0.472	0.226	0.227	0.541	0.764
Average pos. and neg drift	0.34	0.21	0.25	0.25	0.524	0.472	0.198	0.227	0.496	0.764
Cracking of wallboard at wall penetration	0.24	0.24	0.09	0.09	0.121	0.258	0.117	0.826	0.085	0.226
	0.24	0.24	0.12	0.12	0.121	0.258	0.226	0.826	0.113	0.226
Average pos. and neg drift	0.24	0.24	0.105	0.105	0.121	0.258	0.1715	0.826	0.099	0.226
Crushing of wallboard at perimeter	2	1.25	0.777	NR	2.376	N/A	1.114	1.42	N/A	N/A
	2	1.25	0.777	-	2.376	-	1.114	1.42	-	-
Average pos. and neg drift	2	1.25	0.777	-	2.376	-	1.114	1.42	-	-
Cracking of vertical butt joint	N/A	0.75	0.301	0.301	0.357	0.268	0.345	0.341	0.254	0.339
	-	0.75	0.419	0.419	0.472	0.394	0.452	0.452	0.339	0.339
Average pos. and neg drift		0.75	0.36	0.36	0.4145	0.331	0.3985	0.3965	0.2965	0.339
Cracking of horizontal wall joint	N/A	N/A	N/A	N/A	0.66	N/A	0.818	1.42	0.452	0.278
	-	-	-	-	0.66	-	0.818	1.42	0.452	0.349
Average pos. and neg drift	-	-	-	-	0.66	-	0.818	1.42	0.452	0.3135
Cracking of vertical joint at out-of-plane wall	0.25	0.25	0.301	0.359	0.785	N/A	1.746	0.826	0.278	NR
	0.36	0.25	0.419	0.359	0.785	-	1.746	0.826	0.349	-
Average pos. and neg drift	0.305	0.25	0.36	0.359	0.785	-	1.746	0.826	0.3135	-
Local buckling of panel at wall penetration	0.75	N/A	0.419	0.359	0.13	0.258	0.17	0.525	1.169	NR
	0.75	-	0.419	0.359	0.13	0.258	0.226	0.525	1.169	-
Average pos. and neg drift	0.75	-	0.419	0.359	0.13	0.258	0.198	0.525	1.169	-
Global buckling of panel	1.94	4.17	N/A	1.71	N/A	N/A	N/A	1.746	N/A	2.825
	1.94	4.17	-	1.71	-	-	-	1.746	-	2.825
Average pos. and neg drift	1.94	4.17	-	1.71	-	-	-	1.746	-	2.825

Gypsum Wallboard Test data from Arnold, A. et al. (2005)

Wall number	Damage at 0.20%	Damage at 0.34%	Damage at 0.40%	Damage at 0.60%	Damage at 0.70%	Damage at 0.90%
5	1	-	1	-	2	-
6	-	1	-	2	-	2
7	1	-	1	-	2	-
8	-	1	-	2	-	2
11	1	-	1	-	2	-
12	-	1	-	2	-	-

Appendix C – Fragility Data Walls with OSB/Plywood and Stucco

Table C1 - Test Data from Gatto and el al. (2001).

Specimen ID	Test Specimen	Test Protocol		Test type	Displacement (in)	%DRIFT Disp/H*100	Nail tear out	Nail fracture	Sheathing buckling	Sheathing separation	Sill plate Tie down damage
Test 1	OSB	Mono	East	M	3.8	3.96	x			x	
			West	M	4.2	4.38	x				
Test 2	OSB	CUREE	East	C	4	4.17	x			x	x
			West	C	4	4.17	x			x	
Test 5	PWD	Mono	East	M	4.1	4.27	x			x	
			West	M	4	4.17	x				
Test 6	PWD	CUREE	East	C	4.9	5.10	x	x	x	x	
			West	C	4.5	4.69	x			x	
Test 9	OSB	Near-fault	East	C	3	3.13	x	x			
			West	C	3	3.13	x			x	
Test 10	PWD	Near-fault	East	C	3.6	3.75	x				x
			West	C	3.5	3.65	x				
Test 13	OSB+GWB	CUREE	East	C	2.8	2.92	x	x			x
			West	C	2.7	2.81	x			x	
Test 14	PWD+GWB	CUREE	East	C	3.7	3.85	x				
			West	C	3.5	3.65	x		x	x	x
Test 15	OSB+GWB	CUREE (D)	East	C	3.2	3.33	x	x	x	x	
			West	C	3.2	3.33	x			x	
Test 16	PWD+GWB	CUREE (D)	East	C	3	3.13	x	x			x
			West	C	3.1	3.23	x	x		x	
Test 17	OSB+Stucco	CUREE (D)	East	C	2	2.08	x				
			West	C	2.8	2.92	x	x			
Test 18	PWD+Stucco	CUREE (D)	East	C	2.5	2.60	x	x			
			West	C	3.7	3.85	x				

Specimen ID	Test Specimen	Sill plate damage	Tie down stud damage	Top plate damage/separation	Stud separation	Stud Breaking/splitting	GWB loose/fell off	screw tear out	Stucco Cracking	Stucco Separation
Test 1	OSB	x	x		x					
				x						
Test 2	OSB		x		x					
Test 5	PWD									
			x	x	x	x				
Test 6	PWD			x	x	x				
Test 9	OSB		x	x	x	x				
				x	x					
Test 10	PWD			x						
			x		x	x				
Test 13	OSB+GWB	x	x					x		
				x						
Test 14	PWD+GWB									
		x		x	x					
Test 15	OSB+GWB				x	x				
			x		x	x				
Test 16	PWD+GWB	x			x		x			
				x	x		x	x		
Test 17	OSB+Stucco		x		x	x				x
			x	x	x	x				
Test 18	PWD+Stucco		x		x	x			x	x
			x	x	x	x				

Table C2 - Test Data from Gatto et al. (2001).

Test ID	Test Specimen	Test Protocol	Displacement (in)	%Drift (Disp/96")*100	Nail tear out	Nail fracture	Frame Split	Partial withdrawal	GWB Cracking	GWB Separation	Stucco Cracking	Stucco Separation	sill plate split
4B	OSB	CUREE	2.01	2.09									
	FS		2.02	2.10									
			2.015	2.10	x			x					
6A	OSB	CUREE	2.43	2.53									
	PD		2.94	3.06									
			2.685	2.80	x		x	x					
6B	OSB	CUREE	2.93	3.05									
	PD		2.95	3.07									
			2.94	3.06	x			x					
11A	OSB	CUREE	2.01	2.09									
	FS		2.07	2.16									
	Staples		2.04	2.13	x	x		x					
11B	OSB	CUREE	2.03	2.11									
	FS		2.03	2.11									
	Staples		2.03	2.11	x	x		x					
13A	OSB	CUREE	2.21	2.30									
	Stucco		2.9	3.02									
	GWB		2.555	2.66	x			x	x	x	x	x	
13B	OSB	CUREE	2.39	2.49									
	Stucco		2.13	2.22									
	GWB		2.26	2.35	x			x	x	x	x	x	
21A	OSB	CUREE	2.08	2.17									
	PD		2.95	3.07									
	Stucco		2.515	2.62	x			x			x	x	
21B	OSB	CUREE	2.12	2.21									
	PD		2.68	2.79									
	Stucco		2.4	2.50	x	x	x	x			x	x	

Test ID	Test Specimen	Test Protocol	Displacement (in)	%Drift (Disp/96")*100	Nail Tear out	Nail fracture	Frame Split	Partial withdrawal	GWB Cracking	GWB Separation	Stucco Cracking	Stucco Separation	sill plate split
23A	OSB	CUREE	2.89	3.01									
	PD		2.55	2.66									
	GWB		2.72	2.83	x			x	x	x			
23B	OSB	CUREE	2.92	3.04									
	PD		2.93	3.05									
	GWB		2.925	3.05	x			x	x	x			
24A	OSB	CUREE	2.86	2.98									
	PD		2.4	2.50									
	Hard/GWB		2.63	2.74	x		x	x	x	x			x
24B	OSB	CUREE	2.55	2.66									
	PD		2.49	2.59									
	Hard/GWB		2.52	2.63	x		x	x	x				
26A	OSB	CUREE	2.87	2.99									
	PD		2.64	2.75									
	Loose HD		2.755	2.87	x			x					
26B	OSB	CUREE	2.56	2.67									
	PD		2.99	3.11									
	Loose HD		2.775	2.89	x			x					

Table C3 - Test Data from Pardoen et al. (2002).

Story Level	Test Specimen	Test Phase	% Drift	Stucco Cracking	Nail Pops
1	Front	2	0.219	x	
1	Back	2	0.611	x	
1	East	2	0.262	x	
1	West	2	0.224	x	
2	Front	2	0.21	x	
2	Back	2	0.177	x	
2	East	2	0.301	x	
2	West	2	0.397	x	
3	Front	2	0.17	x	
3	Back	2	0.145	x	
3	East	2	0.2	x	
3	West	2	0.225	x	
1	Front	3	0.512	x	x
1	Back	3	1.507	x	x
1	East	3	0.444	x	x
1	West	3	0.301	x	x
2	Front	3	0.243	x	
2	Back	3	0.136	x	
2	East	3	0.181	x	
2	West	3	0.569	x	
3	Front	3	0.143	x	
3	Back	3	0.131	x	
3	East	3	0.219	x	
3	West	3	0.191	x	

Table C4 - Test data from Arnold, A. et al. (2005)

wall number	Damage at 0.20%	Damage at 0.34%	Damage at 0.40%	Damage at 0.60%	Damage at 0.70%	Damage at 0.90%
5	1	-	1	-	2	-
6	-	2	-	2	-	2
7	1	-	1	-	2	-
8	-	1	-	2	-	2
11	1	-	2	-	-	-
12	-	1	-	2	-	-

Appendix D - Fragility Data for Sill Plates

Table D1 – Test data from Mahaney and Kehoe (2002) for Sill Plates without hold downs

Test No.	Date tested	Wood Species	Nominal Sill Plate Size	Bolt Dia.	Nut/Washer	Vertical Load	Ultimate Load (lbs)	Ultimate Load (plf)	Sill Failure
21	11/10/2000	Hem Fir	2x4	5/8	2-1/2 inch square by 1/4 inch plate washer	100 lb/ft	3840	480	X
29	11/13/2000	Hem Fir	2x4	5/8	2-1/2 inch square by 1/4 inch plate washer	100 lb/ft	3857	482	X
30	11/15/2000	Hem Fir	2x4	5/8	2-1/2 inch square by 1/4 inch plate washer	100 lb/ft	3715	464	X
26	11/10/2000	Hem Fir	2x4	5/8	2-1/2 inch square by 1/4 inch plate washer	100 lb/ft	3496	437	X
27	11/15/2000	Hem Fir	2x4	5/8	2-1/2 inch square by 1/4 inch plate washer	100 lb/ft	3401	425	X
38x	11/14/2000	Douglas Fir	2x4	5/8	2-1/2 inch square by 1/4 inch plate washer	100 lb/ft	3464	433	X
40x	11/1/2000	Douglas Fir	2x6	5/8	2-1/2 inch square by 1/4 inch plate washer	100 lb/ft	3074	384	X
25	11/6/2000	Hem Fir	2x6	5/8	2-1/2 inch square by 1/4 inch plate washer	100 lb/ft	2688	336	X
28	11/17/2000	Hem Fir	2x4	5/8	Round	100 lb/ft	2819	352	X
33	11/8/2000	Hem Fir	2x4	5/8	Special 3 inch square by 1/2 inch slotted plate	100 lb/ft	3221	403	X
40	11/21/2000	Douglas Fir	3x6	5/8	2-1/2 inch square by 1/4 inch plate washer	100 lb/ft	4236	530	X
40m	10/30/2000	Douglas Fir	3x6	5/8	2-1/2 inch square by 1/4 inch plate washer	100 lb/ft	3892	487	X

Table D2 – Test data from Mahaney and Kehoe (2002) for Sill Plates with hold downs

Test No.	Date tested	Wood Species	Nominal Sill Plate Size	Bolt Dia.	Distance from end of wall	Nut/Washer	Vertical Load	Ultimate Load (lbs)	Ultimate Load (plf)	Sill Failure	Plywood nail failure	Other Failures
41-4x4.3	12/8/2000	Hem Fir	2x4	5/8	20 inches	Special 3 inch square by 1/2 inch plate w/ slot	100 lb/ft	12606	1576		X	
42	12/28/2000	Hem Fir	2x4	5/8	8 inches	Special 3 inch square by 1/2 inch plate w/ slot	100 lb/ft	12362	1545			
50	12/28/2000	Hem Fir	2x4	5/8	20 inches	Special 3 inch square by 1/2 inch plate w/ slot	100 lb/ft	9778	1222			HTT22 failed at lower row of nails
41-4x4.2	12/7/2000	Hem Fir	2x4	5/8	20 inches	Special 3 inch square by 1/2 inch plate w/ slot	100 lb/ft	8330	1041			Stud at plywood joint at center
41-4x4.1	12/6/2000	Hem Fir	2x4	5/8	20 inches	Special 3 inch square by 1/2 inch plate w/ slot	100 lb/ft	14061	1758			Stud at plywood joint at center
41b	12/6/2000	Hem Fir	2x4	5/8	20 inches	Special 3 inch square by 1/2 inch plate w/ slot	100 lb/ft	7418	927			Double 2x end post split
43	12/28/2000	Hem Fir	2x4	5/8	20 inches	Round	100 lb/ft	11158	1395	X		
37	1/4/2001	Douglas Fir	3x4	5/8	8 inches	2-1/2 inch square by 1/4 inch washer	100 lb/ft	9296	1162			End post split

Appendix E – Summary of Fragility Data

Table E1 - Fragility Data for Gypsum Wallboard.

Specimen		DS1	Specimen		DS2
Reference	ID	Δ/h (θ)	Reference	ID	Δ/h (θ)
McMullin	1	0.25	McMullin	1	1.76
McMullin	1	0.24	McMullin	1	0.76
McMullin	1	0.25	McMullin	1	0.25
McMullin	1	0.76	McMullin	1	0.76
McMullin	2	0.50	McMullin	2	1.05
McMullin	2	0.20	McMullin	2	0.50
McMullin	2	0.37	McMullin	2	1.05
McMullin	2	0.20	McMullin	2	0.50
McMullin	3	0.94	McMullin	3	0.78
McMullin	3	0.23	McMullin	3	0.78
McMullin	3	1.01	McMullin	3	0.78
McMullin	3	0.26	McMullin	4	0.50
McMullin	4	0.74	McMullin	4	1.52
McMullin	4	0.24	McMullin	4	0.75
McMullin	4	0.74	McMullin	4	0.99
McMullin	4	0.24	McMullin	5	0.50
McMullin	5	0.50	McMullin	5	0.50
McMullin	5	0.22	McMullin	5	0.75
McMullin	5	0.50	McMullin	10	2.99
McMullin	5	0.22	McMullin	10	1.51
McMullin	10	1.02	McMullin	10	0.51
McMullin	10	0.27	McMullin	1	0.53
McMullin	10	1.25	McMullin	1	0.25
McMullin	10	0.51	McMullin	2	0.24
McMullin	4	0.76	McMullin	2	0.24
McMullin	10	0.75	McMullin	3	0.26
McMullin	10	1.02	McMullin	3	0.26
McMullin	6	0.34	McMullin	4	0.53
McMullin	6	0.21	McMullin	4	2.04
McMullin	7	0.25	McMullin	4	0.53
McMullin	7	0.25	McMullin	4	1.44
McMullin	11	0.52	McMullin	5	1.00
McMullin	11	0.47	McMullin	5	2.04
McMullin	12	0.20	McMullin	5	1.00
McMullin	12	0.23	McMullin	5	1.44
McMullin	13	0.50	McMullin	10	0.51
McMullin	13	0.76	McMullin	10	2.02
McMullin	6	0.24	McMullin	10	0.51
McMullin	6	0.24	McMullin	6	2.00
McMullin	7	0.11	McMullin	6	1.25
McMullin	7	0.11	McMullin	7	0.78
McMullin	11	0.12	McMullin	11	2.38

Specimen		DS1	Specimen		DS2
Reference	ID	Δ/h (θ)	Reference	ID	Δ/h (θ)
McMullin	11	0.26	McMullin	12	1.11
McMullin	12	0.17	McMullin	12	1.42
McMullin	12	0.83	McMullin	6	0.31
McMullin	13	0.10	McMullin	6	0.75
McMullin	13	0.23	McMullin	6	1.94
McMullin	6	0.75	McMullin	6	0.25
McMullin	7	0.36	McMullin	6	4.17
McMullin	7	0.36	McMullin	7	0.36
McMullin	11	0.41	McMullin	7	0.42
McMullin	11	0.33	McMullin	7	0.36
McMullin	12	0.40	McMullin	7	0.36
McMullin	12	0.40	McMullin	7	1.71
McMullin	13	0.30	McMullin	11	0.79
McMullin	13	0.34	McMullin	11	0.13
McMullin	11	0.66	McMullin	11	0.26
McMullin	12	0.82	McMullin	12	1.75
McMullin	12	1.42	McMullin	12	0.20
McMullin	13	0.45	McMullin	12	0.83
McMullin	13	0.31	McMullin	12	0.53
EDA07	5	0.2	McMullin	12	1.75
EDA07	7	0.2	McMullin	13	0.31
EDA07	11	0.2	McMullin	13	1.17
EDA07	6	0.34	McMullin	13	2.83
EDA07	8	0.34	EDA07	5	0.6
EDA07	12	0.34	EDA07	7	0.6
			EDA07	11	0.7
			EDA07	6	0.7
			EDA07	8	0.6
			EDA07	12	0.7

Tables E2 - Fragility Data for OSB/Plywood with GWB and Non-Structural Siding.

Specimen		DS1	Specimen		DS2	Specimen		DS3
Reference	ID	Δ/h (θ)	Reference	ID	Δ/h (θ)	Reference	ID	Δ/h (θ)
Engineering Judgment			Pardoen	4B	2.098958	Gatto	Test 1	3.96
			Pardoen	6A	2.796875			4.38
			Pardoen	6B	3.0625	Gatto	Test 2	4.17
			Pardoen	11A	2.125			4.17
			Pardoen	11B	2.114583	Gatto	Test 5	4.27
			Pardoen	23A	2.833333			4.17
			Pardoen	23B	3.046875	Gatto	Test 6	5.10
			Pardoen	26A	2.869792			4.69
			Pardoen	26B	2.890625	Gatto	Test 9	3.13
								3.13
						Gatto	Test 10	3.75
								3.65
						Gatto	Test 13	2.92
								2.81
						Gatto	Test 14	3.85
								3.65
						Gatto	Test 15	3.33
								3.33
						Gatto	Test 16	3.13
								3.23

Table E3 – Fragility Data for OSB/Plywood with GWB and Stucco.

Reference	Specimen Location	Specimen ID	DS1 Δ/h (θ)
W19	Back	2	0.219
W19	Front	2	0.611
W19	East	2	0.262
W19	West	2	0.224
W19	Back	2	0.21
W19	Front	2	0.177
W19	East	2	0.301
W19	West	2	0.397
W19	Back	2	0.17
W19	Front	2	0.145
W19	East	2	0.2
W19	West	2	0.225
W19	Back	3	0.512
W19	Front	3	1.507
W19	East	3	0.444
W19	West	3	0.301
W19	Back	3	0.243
W19	Front	3	0.136
W19	East	3	0.181
W19	West	3	0.569
W19	Back	3	0.143
W19	Front	3	0.131
W19	East	3	0.219
W19	West	3	0.191
EDA07	5		0.2
EDA07	7		0.2
EDA07	11		0.2
EDA07	6		0.34
EDA07	8		0.34
EDA07	12		0.34

Specimen Reference	Specimen ID	DS2 Δ/h (θ)
EDA07	5	0.34
EDA07	7	0.4
EDA07	11	0.6
EDA07	6	0.6
EDA07	8	0.6
EDA07	12	0.7

Specimen Reference	Specimen ID	DS3 Δ/h (θ)
Pardoen	13A	2.661458
Pardoen	13B	2.354167
Pardoen	21A	2.619792
Pardoen	21B	2.5
Gatto	Test 17	2.083333
		2.916667
Gatto	Test 18	2.604167
		3.854167

Table E4 - Fragility Data for Sill Plates

2x Sill Plates without holdowns

2-1/2 inch square by 1/4 inch plate washer			
Reference	Specimen ID	PLF	lb/Anchor bolt
Mahaney	21	480	960
Mahaney	29	482	964.25
Mahaney	30	464	928.75
Mahaney	26	437	874
Mahaney	27	425	850.25
Mahaney	38x	433	866
Mahaney	40x	384	768.5
Mahaney	25	336	672
Standard 1.5" dia round wahser			
Reference	Specimen ID	PLF	lb/Anchor bolt
Mahaney	28	352	704.75
Special 3 inch square by 1/2 inch slotted plate			
Reference	Specimen ID	PLF	lb/Anchor bolt
Mahaney	33	403	805.25

2x Sill Plates with holdowns

2-1/2 inch square by 1/4 inch washer			
Reference	Specimen ID	PLF	lb/Anchor bolt
Mahaney	37	1162	2324
Standard 1.5" dia round washer			
Reference	Specimen ID	PLF	lb/Anchor bolt
Mahaney	43	1395	2789.5
Special 3 inch square by 1/2 inch plate w/ slot			
Reference	Specimen ID	PLF	lb/Anchor bolt
Mahaney	41-4x4.3	1576	3151.5
Mahaney	42	1545	3090.5
Mahaney	50	1222.25	2444.5
Mahaney	41-4x4.2	1041.25	2082.5
Mahaney	41-4x4.1	1757.625	3515.25
Mahaney	41b	927.25	1854.5

3x Sill Plates without holdowns

2-1/2 inch square by 1/4 inch plate washer			
Reference	Specimen ID	PLF	lb/Anchor bolt
Mahaney	38	645	1289.25
Mahaney	40	530	1059

3x Sill Plates with holdowns

2-1/2 inch square by 1/4 inch washer			
Reference	Specimen ID	PLF	lb/Anchor bolt
Mahaney	37	1162	2324