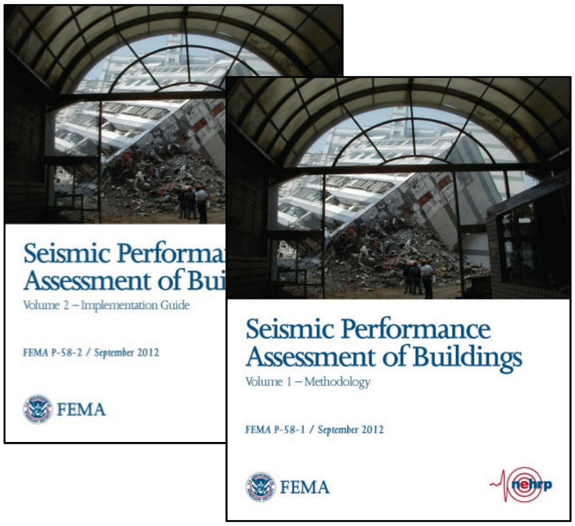

Background Document

FEMA P-58/BD-3.9.2

Seismic Fragility of Building Interior Cold-Formed Steel Framed Gypsum Partition Walls

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Submitted to

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Prepared for

FEDERAL EMERGENCY MANAGEMENT AGENCY
U.S. Department of Homeland Security
500 C Street, SW
Washington, D.C. 20472

June 15, 2011

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contained herein has not been independently verified for accuracy as a stand-alone document, and may have been superseded in its final implementation within the methodology. Specifically in the case of certain nonstructural component fragilities, the NISTIR fragility classification numbering scheme was modified over the course of the project, and the fragility classification number assigned in this document might be different from numbers assigned in the final fragility database. 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*.

SEISMIC FRAGILITY OF BUILDING INTERIOR COLD-FORMED STEEL FRAMED GYPSUM PARTITION WALLS

Prepared for ATC-58 by
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Introduction

The objective of this document is to summarize the development of fragility functions for interior non-load-bearing gypsum wallboard partitions commonly used in building construction. The partition assembly consists of C-shaped cold formed metal studs (the most commonly used are gage 20 and gage 25 with a web depth of 3-5/8 in.), U shaped horizontal cold-formed metal tracks in the top and bottom and gypsum wallboard as facing material. Typically one layer of gypsum wallboard is used on each side of the steel framing with the two most commonly used thickness being 1/2 inch and 5/8 inch, however many other configurations exist depending on the desired fire rating and sound isolation requirements. The fragility functions developed here are intended to be representative of those using gypsum wallboards satisfying ASTM C36 Specification for Gypsum Wallboard or the more recent ASTM C 1396 Specification for Gypsum Board and Section 2205 of the 2000 International Building Code (IBC), and ASTM C 645, Specification for Non-Load (Axial) Bearing Steel Studs, Runners (Track), and Rigid Furring Channels for Screw Application of Gypsum Board. An example of typical framing of an interior gypsum wall partition is shown in Figure 1. As shown in this photograph studs typically have punched holes (with geometry varying from manufacturer to manufacturer) to accommodate plumbing, electrical, telecommunication (e.g., telephone, internet, etc.) or other types of installations. Figure 2 shows examples of electrical and plumbing installations inside of building partitions.

Although standards exist for the materials, thicknesses, stud and track geometry, stud separation, height limitations, etc., there is a wide variety of detailing and installation practices which are primarily based on recommendations from different manufacturers and local building trade practices. Some manufacturers recommend screwing the studs to the horizontal tracks while others only recommend this at certain locations. ASTM C754 requires that studs located adjacent to door and window frames, partition intersections, and corners be anchored to runner flanges by screws, or by crimping at each stud and runner flange. In California the studs are typically screwed to the bottom and top tracks. Often, but not always, the top track has vertically slotted holes of the flanges, in what is commercially referred to as "slip track", to accommodate vertical deflections of the floor system without introducing vertical deformation/loads to the partition. Examples of typical connections between studs and upper and horizontal tracks (sometimes referred to as runners) are shown in Figure 3, Figure 4 and Figure 5.

The term "slip-track" is also sometimes used within the earthquake engineering community to describe a friction only connection to the top track that allows horizontal in-plane movement of the top track relative to the studs and gypsum board. Details for the friction connection allowing horizontal sliding are compared to a full-connection in Figure 6. The main difference in the friction connection is that the studs are not directly screwed to the upper track and the top row of screws connecting the gypsum fall below the top track flange. During racking motions, the top track slides relative to the remainder of the wall imposing minimal deformations on the studs and gypsum (only friction force transfers). While the friction connection detail does not transfer drift deformation directly into the partitions, the end of the partition are often restrained by transverse walls, thus a distinction is made for walls with and without returns. As will be shown later, this does not necessarily improve the seismic performance of partitions as damage still occurs at low levels of deformation and concentrates at the intersection of partition walls. In California, the studs are typically screwed to the upper track as is recommended by manufactures in the attached appendix.

Another variation to installation practice is *partial height walls*, which typically extend to the suspended ceiling level. The top track in the framing resides at the ceiling level and braced to the top slab with diagonal studs as shown in Figure 7. In some cases, the framing is installed along the full story height and only the gypsum is placed to the ceiling level. This type of partial height walls have framing details identical to full-height walls and are expected to behave in a similar fashion.

Fragility functions developed herein are based entirely on experimental results of racking tests. These tests are primarily static racking tests although results from a few dynamic tests are also includes. Most specimens are 8 ft (2.4m) by 8 ft (2.4m) or 11.5 ft (3.5 m h) by 12 ft (3.7 m w), however some of the experimental tests include specimens with return walls and one investigation included two full room specimens with corners and other conditions commonly found in buildings. Many of the specimens include doors. As explained in the next section only specimens representative of typical cold-formed steel framing construction were considered. Four different categories of walls are considered for grouping the data based on their expected behavior under seismic loading: (i) full-connection, (ii) seismic slip track with no returns, (iii) slip track with returns, and (iv) partial height walls.

Figure 1: Framing of typical interior partition (photo by E. Miranda).

Figure 2: Examples of plumbing and electrical installation in gypsum wallboard partitions (photos by E. Miranda).

Figure 3: Photo of typical connection between stud and lower track (photo by E. Miranda).

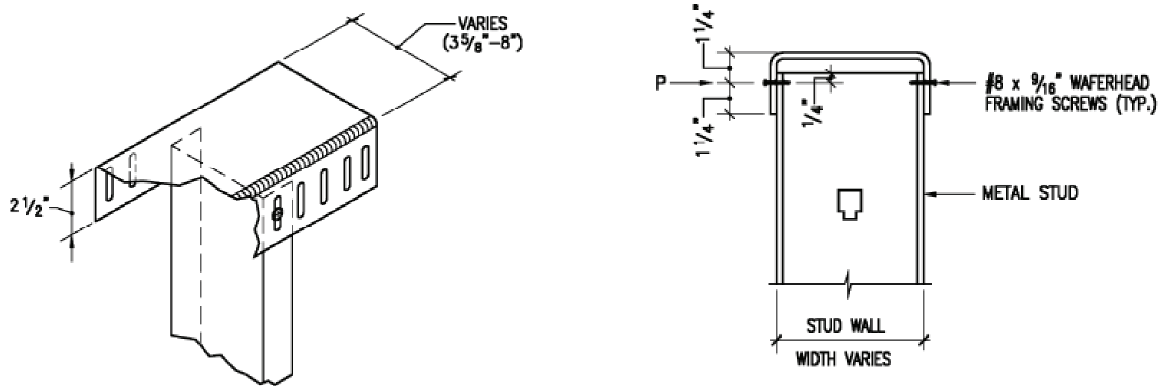


Figure 4: Typical connection between studs and vertically-slotted top tracks (source: http://www.sliptrack.com)

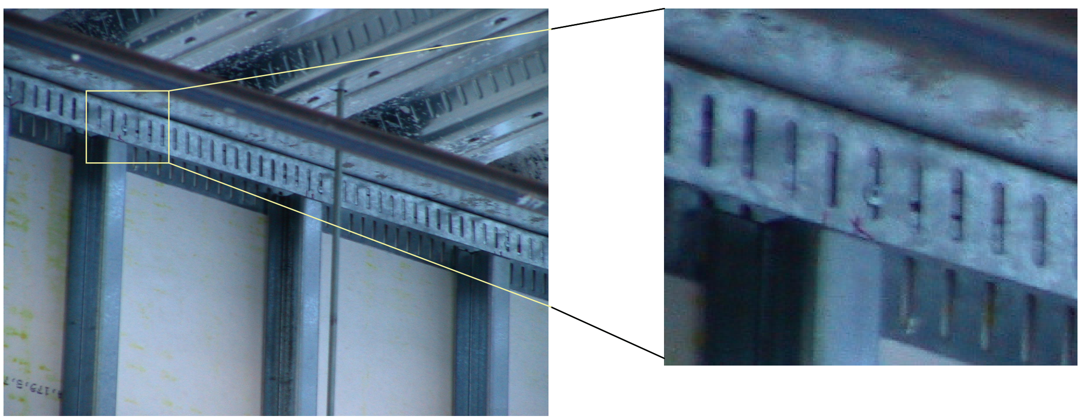
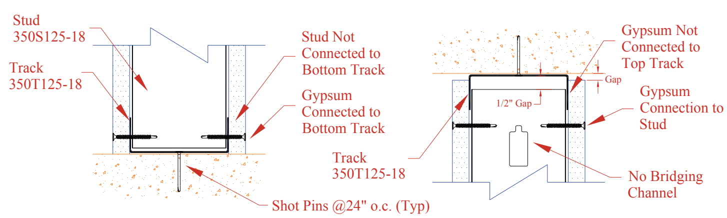
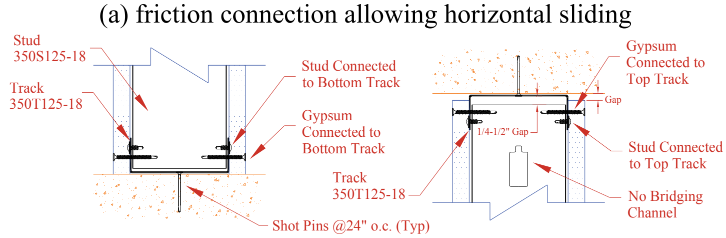


Figure 5: Photo of typical connection between stud and upper track (photo by E. Miranda).



(a) friction connection allowing horizontal sliding



(b) Full connection

Figure 6: Typical framing and sheathing details (from Retamales et al. 2010)

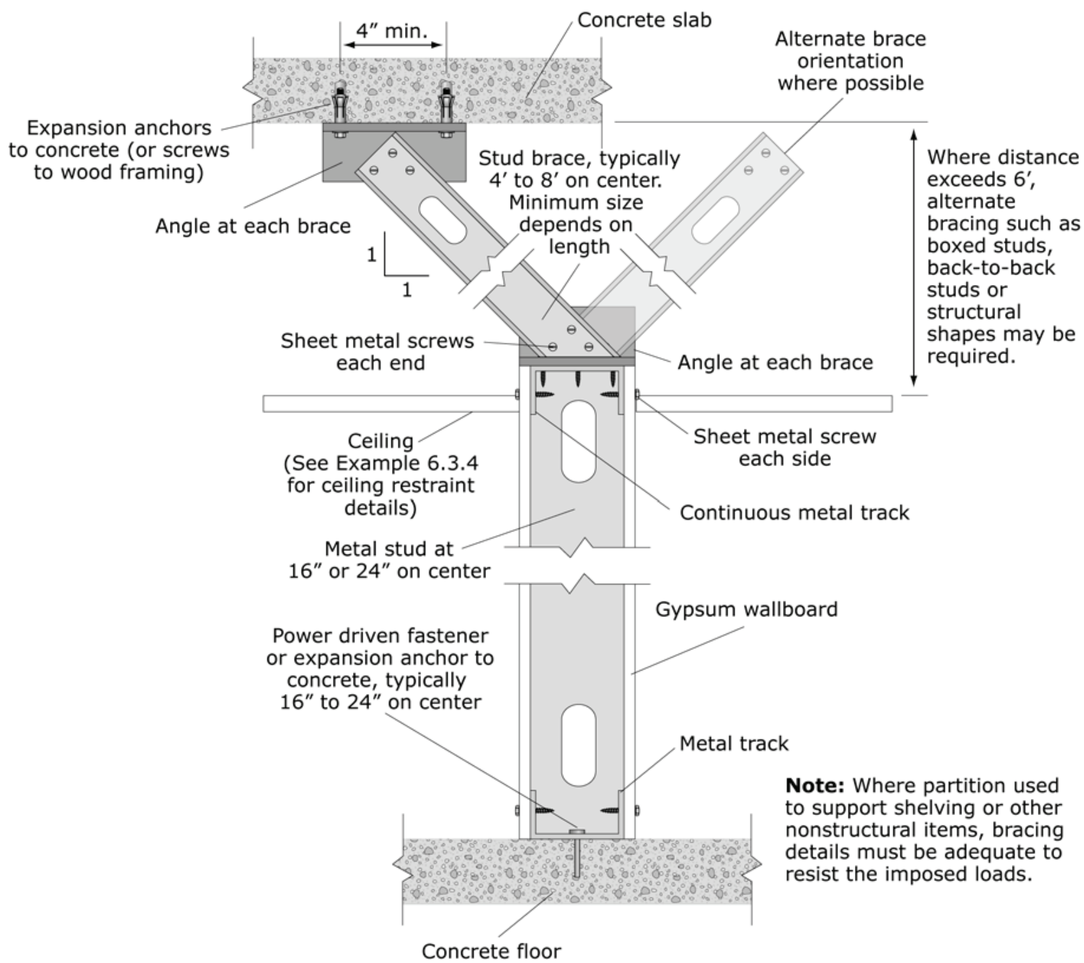


Figure 7: Non-load bearing partial height wall (from FEMA-74, 2011)

Sources of Information

Data from a total of 74 experimental tests from six different research investigations spanning over 40 years were considered for developing the fragility functions. The following paragraphs briefly summarize each of the six research investigations considered.

Between 1966 and 1974 John A. Blume and Associates (John A. Blume and Associates 1966, 1968, Freeman 1971, 1974, 1979) tested fifty-four interior wall panel specimens. Thirty-four were gypsum wallboard, seven were plaster, nine were plywood, and four were combinations of plywood and gypsum wall board. All specimens were 8 ft (2.4m) wide by 8 ft (2.4m) high. Some of the wall panels had metal studs while other had wood studs. Only specimens with gypsum wallboard on metal studs were considered in the development of the fragility functions since those are the most commonly used in commercial building construction. Furthermore, their gypsum wallboard panels had several construction detail variations of the connections of metal studs and gypsum wallboard to the top and bottom metal tracks. Of the thirteen types of wall panels studied in their investigation only five were gypsum wallboard with metal studs. However, of those five, types 1 and 2 connected the studs to the top and bottom tracks only by friction and are considered as seismic slip-track with no returns. Types 3, 4 and 9 for a total of 13 specimens were considered as having full-connections. They all use one layer of 1/2 inch layer of gypsum wallboard on each side and 3-5/8 inch deep metal studs with 0.018 inch thickness (also referred to as 18 mils or 25 gauge). In all three types the studs were connected to the tracks (runners) by pop-rivets. Types 3 and 9 wall panels had no openings while type 4 wall panels had one door. Type 9 wall panels are similar to type 3 wall panels except for the fact that in type 9 wall panels the gypsum wallboard is attached to the horizontal tracks with screws, while in type 3 the wallboard in only attached to the studs.

All wall panels tested by John A. Blume and Associates were subjected to cyclic loading consisting of equal displacement on both loading directions, starting at small displacements and progressively increasing the amplitude. At least four full cycles of each peak displacement amplitude were completed before increasing to a larger displacement, starting at 1/32 inch (0.8 mm) and progressing to more than 1 inch. Some specimens were loaded pseudo-statically (10 sec per cycle) while others were tested dynamically at 0.7 Hz, 1 Hz and 2 Hz.

Prof. Rihal (Rihal, 1982; Rihal, and Granneman, 1984), tested fourteen 8 ft (2.4m) by 8 ft (2.4m) interior wall partition specimens. One of the specimens was a control specimen made of 2x4 inch wood studs and 3/8 inch plywood as facing material of both sides of the partition while the remaining thirteen specimens had 18 mils metal studs with a single layer of 5/8 inch gypsum wallboards as facing material on each side of the partition. Eleven of the gypsum wall partitions used 3-5/8 inch deep metal studs and two specimens used 2-1/2 inch deep studs. The fasteners used to attach the gypsum wallboard to the partition framing were one inch type S drywall screws. Four of the specimens had openings and one was partial height. However, only the gypsum was partial height with the studs spanning slab to slab and directly connected to the top and bottom track. These partial gypsum height walls were considered with the full-connection group since the framing is similar. Connection details at the top varied from specimen to specimen. In two of the specimens (specimens P2 and P3) the studs were only connected to the top runner by friction only and therefore were considered as slip tracks with no returns, while all other metal stud partitions were included to represent a variety of connection details that may be found in various buildings. All specimens were subjected to cyclic loading in their plane using a pinned frame similar to the one used by Freeman. All specimens were subjected to two complete cycles of loading for each increasing level of lateral deformation with increments starting at 1/16 in and increasing to 1/8 inch, 1/4 inch, 3/8 inch, 1/2 inch and then loaded to failure.

As part of the U.S.-Japan Cooperative Research Project a full-scale seven story reinforced concrete building was tested at the Building Research Institute (BRI) in Tsukuba, Japan (Kaminosono et al, 1984). The building had a height of 21.75 m (71.4 ft) with plan dimensions of 16 m (52.5 ft) by 17 m (55.5 ft) in plan. The story height was 3.75 m for the first story and 3.0 m for the second through seventh stories. The lateral resisting system consisted of a dual system of a shear wall and moment resisting frames. After pseudo-dynamic testing of the structure and subsequent repair, nonstructural components were added to the building which included gypsum wallboard partitions with fully connected framing (Nakata et al., 1984). Damage was documented as various stages of subsequent pseudo-dynamic testing.

Bersofsky, A.M, (2004) recently tested sixteen specimens gypsum wallboard partitions in the Powell Laboratory at the University of California, San Diego. The specimens were constructed using 18 or 30-mil 3-5/8 inch steel studs, and 1/2 or 5/8-inch gypsum wallboard. Each specimen was 16-feet long, and 8-feet tall. Return walls were installed perpendicular to the plane of the main wall at opposite ends, creating an I-wall cross section.

Eight tests were conducted in total. Each test consisted of in-plane shear testing of two wall specimens simultaneously. For six of the eight tests, Wall-A and Wall-B were designed and built in an identical manner. This was to check for any variability in the test results. Only in tests 2 and 5 did the walls A and B vary slightly. Test 5 included only partial height gypsum, but the framing was similar to full height walls. Testing consisted of quasi-static reversed cyclic loading in plane according to a predefined loading protocol. The loading protocol was developed by the PEER advisory committee specifically for this project which was partly based on the CUREE loading protocol for the testing of wood-frame structures. Two of the specimens had vertical slip-track while the rest had conventional (non-slotted) tracks. Most of the specimens used 5/8 inch gypsum wallboards in combination with 18 mil metal studs spaced 24 inch. Typical screw spacing for attaching the wallboards to the metal frames was 8 inches. In the first test an uplift was observed in the specimen due to a reduced number of hold downs, therefore results from this test were not included here. This problem was corrected in all subsequent tests.

Lang (Land and Restrepo 2006, Lang 2007), tested two identical specimens that were constructed in accordance with current practice including mudding and taping of the gypsum finish wallboard. The specimens represented full scale office rooms which were approximately 15 feet long, 12 feet wide, and 14 feet high. The specimen configuration included several characteristics common to partition wall construction including return walls, T-walls, a structural column wrap, utility cut-out, and door with a sidelight. Metal framing was erected in accordance with current construction practice, including 3-⅝ inch 30 mil studs spaced every 16 inches. Vertically slotted tracks (slip tracks) were used at the top of the walls; this is an industry standard to allow only for vertical deflections. The studs were fastened to the tracks at the flanges with No. 8 by 9/16 inch self-tapping screws. Gypsum wallboard panel with a thickness of 5/8 inch were used as facing material on each side of the partitions. The wallboard was fastened with No. 8 self-tapping screws placed at 8 inches on center to the bottom track and every 8 to 10 inches (12 inch minimum) to the studs and were not screwed to the top track.

The two specimens were subjected to different loading protocols developed as part of the ATC-58 project. Bi-directional lateral displacements were imposed on the specimens in a crossshaped manner, with decoupled strong and weak axes. There was no bi-axial movement. The specimens were first loaded in the strong axis for two cycles, returned to zero displacement, loaded in the weak axis for two cycles, and then returned to zero displacement. The weak to strong axis ratio was 0.5. The loading history consists of step-wise, exponentially increasing drift ratio amplitudes. Two cycles per amplitude were performed. In the first test fasteners that attached the tracks to the concrete slabs fracture due to low cycle fatigue apparently due to the large number of cycles in the loading protocol, so the second specimen was subjected to a modified protocol with significantly smaller number of cycles (approximately one third).

Lee et al. (2006, 2007) tested various configurations of interior partitions with metal studs. The partitions tested were built without screwing studs to the horizontal tracks as in the seismic slip-track. One test included returns, but these were not properly braced to restrict the motion at the intersection of the sliding walls.

As part of the NEES Grand Challenge project, a comprehensive experimental program was carried out to evaluate the seismic response, failure mechanisms, and fragilities of steel-stud gypsum partition walls at the University at Buffalo. In total, thirty-six partition wall specimens corresponding to sixteen different wall configurations were constructed following standard and proposed construction techniques (Retamales et al. 2010). An additional fourteen wall were tested out of plane and not reported here. In-plane quasi-static and dynamic cyclic tests were carried out to assess the seismic performance of the walls under both story drifts and floor accelerations when additional mass such as bookshelves are installed. The Practice Committee and Advisory Board of the NEES Nonstructural project provided input into the proper selection of the most common construction details for commercial and institutional buildings at the initial stages of the experimental program. The variables considered in the selection of the wall configurations included:

- (i) Connectivity of sheathing and studs to tracks and spacing of track fasteners to slab (12 or 24" o.c.)
- (ii) Presence of transverse (return) walls
- (iii) Detail of wall intersection
- (iv) Attachment of weights such as bookshelves or equivalent unbraced rigid ceiling
- (v) Height of the partition wall (full or partial height)
- (vi) Stud and track wall thickness (18 or 30 mil)
- (vii) Spacing of steel framing system (16 or 24" o.c.)
- (viii) Direction of testing (in-plane or out-of-plane) and type of test (dynamic or quasi-static)

For the in-plane tests, a new cyclic protocol was used that considers the number and sequence of "rain flow cycles" applied to the specimen, following a similar procedure to FEMA 461. The advantage to this protocol is that when applied dynamically, it can also match a desired floor or ground response spectrum. While many cycles were applied, observations were only made at drifts of: 0.2, 0.4, 0.62, 0.81, 1.0, 1.16, 1.35, 1.57, 1.84, 1.99, 2.15, 2.32, 2.66, 2.82, 3.0%

The previously mentioned experimental studies were used to gather data from past laboratory testing of gypsum partition walls on light gate steel studs and to develop fragility functions for four different groups of walls:

1) Full-connection between the tracks and stud framing
2) Seismic slip-track connection with only friction between the top track and/or bottom track to the studs and gypsum and including return walls
3) Seismic slip-track connection without returns
4) Partial height walls with diagonal bracing connecting the top track to the slab above

Figure 8: Examples of damage stage 1 (left, center: Tests by R. Retamales et al. 2007, photos by E. Miranda, right: NEES Nonstructural Test).

Damage States

Three damage states were selected for the development of the fragility functions. Consistent with the approach developed by the Pacific Earthquake Engineering Research Center (Krawinkler and Miranda, 2004) damage states well selected in accordance to repair methods. The three damage states are the same previously proposed by Taghavi and Miranda (2003).

The first damage state, DS-1, consists of minor damage which can be repaired by patching, re-taping, sanding and painting of the gypsum wallboard. Examples of this type of damage include minor cracking of the gypsum wallboards or the tape, warping of the tape, minor damage around the screw heads, etc. For partial height walls, DS-1 can also include buckling or local failure of the braces. Photos illustrating DS-1 damage are shown in Figure 8.

DS-2 consists of severe cracking, crushing or out of plane buckling of the gypsum wallboards such that replacement of the wallboards becomes necessary. Repair would involve removing the damage wallboards and subsequent taping, pasting, sanding and painting. DS-2 also includes damage to boundary studs that can be easily replaced. Figure 9 shows photos that illustrate this kind of damage.

DS-3 involves severe damage to the partition including not only severe damage to the gypsum wallboards and the screws connecting them to the studs and tracks but also damage to the steel framing such that replacement of the partition becomes necessary. This type of damage typically involves local buckling and/or fracture of the metal studs. Figure 10 shows a couple of photos that illustrate this damage state.

Figure 9: Examples of damage stage 2 (tests by R. Retamales et al. 2007, photos by E. Miranda).

Figure 10: Example of damage stage 3 (photos by A. Bersofsky).

Fragility Functions: Full Connections

Fragility functions were developed by first identifying the level of lateral deformation imposed in the partition at which each damage level was first reported to occur. Table 1 summarizes this information for all full-height specimens. For each of the tests by Berosvky listed in this table there are two specimens.

First a lognormal probability distribution was fitted on the ascending sorted data by using moment matching in which the median is computed as the geometric mean and the dispersion (β) is computed as the logarithmic standard deviation. Empirical cumulative distribution functions were also plotted using Hazen's plotting position given as

$$p_i = \frac{i - 0.5}{n}$$

where i is the rank of the sorted data and n is the sample size corresponding to each damage state.

Figure 11 shows the empirical cumulative distribution function corresponding to DS-1. As shown in this figure visible damage occurred in some specimens at very low values of interstory drift (less than 0.001) while in others this damage state was not reported to occur until drift ratios reached half a percent. Also shown in the figure is the fitted lognormal distribution. In some cases, the counted median was used as opposed to the geometric mean if the former provided a better fit to the data. The values actually used in the plots are discussed later in the presentation of the fragility results in tabular form.

Figure 12 shows cumulative distribution functions corresponding to DS-2. The figure shows both the empirical cumulative distribution function and the fitted lognormal distribution. As shown in this figure this second damage state was reported to occur for interstory drift ratios ranging from 0.003 to five times this value.

Figure 13 shows the empirical and fitted lognormal cumulative distribution functions corresponding to DS-3. It can be seen that this damage state, in which replacement of the partition becomes necessary, occurs at interstory drift ratios between 0.008 and 0.03.

Parameters of the fitted lognormal probability distribution functions are shown in Table 2. The geometric mean X_m, is reported except where indicate in the table footer that the counted *Median* was used as it resulted in a better fit to the data. In can be seen that contrary to the belief that the dispersion of different damage states is approximately constant or that it increases for larger values of damage, here the variability in the deformation from specimen-to-specimen (the logarithmic standard deviation) decreases from DS-1 to DS-2 and DS-3.

Table 1: Interstory drifts ratios in which each damage state was reported to have occurred, and modified data observed in between cycles.

Research Investigation	Specimen	Interstory Drift Ratio at DS			Modified data -considers DS observed in between cycles		
		DS1	DS2	DS3	DS1	DS2	DS3
JAB	A-4	0.0026	0.0078	-	0.0025	0.0077	-
	A-12	0.0026	0.0052	-	0.0025	0.0051	-
	A-12R	0.0026	0.0052	-	0.0025	0.0051	-
	A-30	0.0052	0.0078	-	0.0051	0.0077	-
	X-33	0.0026	-	-	0.0025	-	-
	A-5	0.0052	0.0104	-	0.0051	0.0103	-
	A-15	0.0026	0.0052	-	0.0025	0.0051	-
	A-15R	-	0.0052	-	-	0.0051	-
	A-31	0.0026	0.0052	-	0.0025	0.0051	-
	A-31R	0.0007	0.0026	-	0.0007	0.0025	-
	A-11	0.0026	0.0052	-	0.0025	0.0051	-
	A-11R	0.0013	0.0052	-	0.0013	0.0051	-
	A-27	0.0026	0.0052	-	0.0025	0.0051	-
Rihal	P2A	0.0039	0.0083	-	0.0033	0.0083	-
	P3A	0.0039	0.0063	-	0.0033	0.0063	-
	P4	0.0026	0.0104	-	0.0023	0.0104	-
	P5	0.0046	0.0110	-	0.0040	0.0110	-
	P6	0.0052	0.0078	-	0.0046	0.0078	-
	P7	0.0046	0.0104	-	0.0040	0.0104	-
	P8	0.0039	-	-	0.0033	-	-
	P8A	0.0033	0.0063	-	0.0027	0.0063	-
	P9	0.0039	0.0111	-	0.0033	0.0111	-
	P10	0.0039	0.0073	-	0.0033	0.0073	-
	P11	0.0039	0.0073	-	0.0033	0.0073	-

AMB	2A	0.0030	0.0150	0.0300	0.0020	0.0125	0.0250
	2B	0.0030	0.0150	0.0300	0.0020	0.0125	0.0250
	3A	0.0005	-	0.0150	0.0005	-	0.0125
	3B	0.0005	-	0.0150	0.0005	-	0.0125
	4A	0.0030	-	0.0150	0.0020	-	0.0125
	4B	0.0030	-	0.0150	0.0020	-	0.0125
	5A	0.0050	-	0.0150	0.0040	-	0.0125
	5B	0.0050	-	0.0150	0.0040	-	0.0125
	6A	0.0010	-	0.0150	0.0010	-	0.0125
	6B	0.0010	-	0.0150	0.0010	-	0.0125
	7A	0.0010	0.0100	0.0200	0.0010	0.0075	0.0175
	7B	0.0010	0.0100	0.0200	0.0010	0.0075	0.0175
	8A	0.0010	0.0150	0.0200	0.0010	0.0125	0.0175
	8B	0.0010	0.0150	0.0200	0.0010	0.0125	0.0175
Lang	1	0.0025	-	0.0082	0.0024	-	0.0077
	2	0.0028	-	0.0077	0.0027	-	0.0072
Jap	GBM-2	0.0020	0.0080	-	0.0015	0.0075	-
NEESR	4	0.0040	0.0062	0.0116	0.0030	0.0051	0.0108
	5	0.0020	0.0040	0.0232	0.0010	0.0030	0.0224
	6	0.0040	0.0062	0.0266	0.0030	0.0051	0.0249
	7	0.0020	0.0062	0.0100	0.0010	0.0051	0.0091
	8	0.0040	0.0100	0.0100	0.0030	0.0091	0.0091
	9	0.0020	0.0040	0.0062	0.0010	0.0030	0.0051
	10	0.0020	0.0081	0.0081	0.0010	0.0072	0.0072
	23	0.0040	0.0081	0.0100	0.0030	0.0072	0.0091
	24	0.0040	0.0040	0.0116	0.0030	0.0030	0.0108
	25	0.0040	0.0040	0.0062	0.0030	0.0030	0.0051
	26	0.0040	0.0100	0.0100	0.0030	0.0091	0.0091
	27	0.0040	0.0062	0.0081	0.0030	0.0051	0.0072
	28	0.0040	0.0081	0.0081	0.0030	0.0072	0.0072

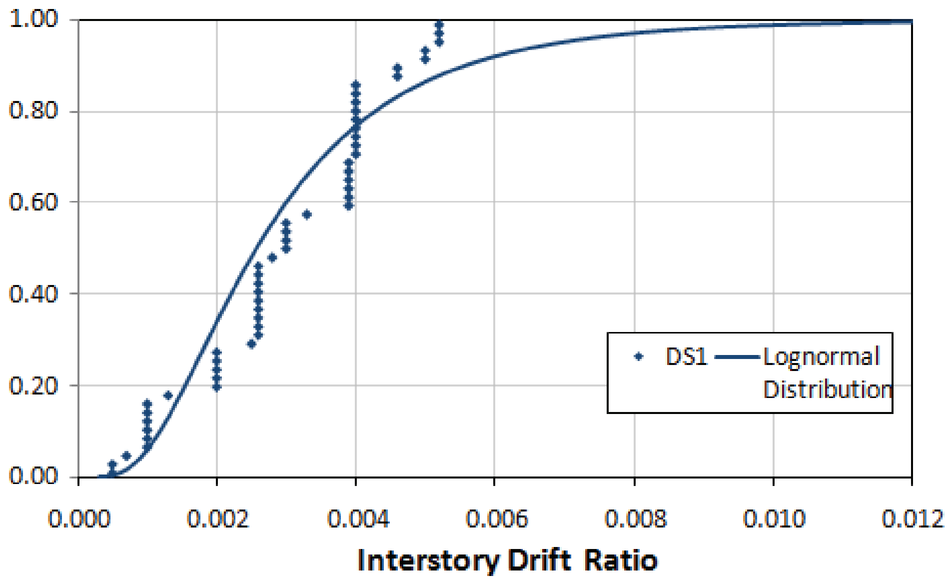


Figure 11: Cumulative distribution function corresponding to damage state 1.

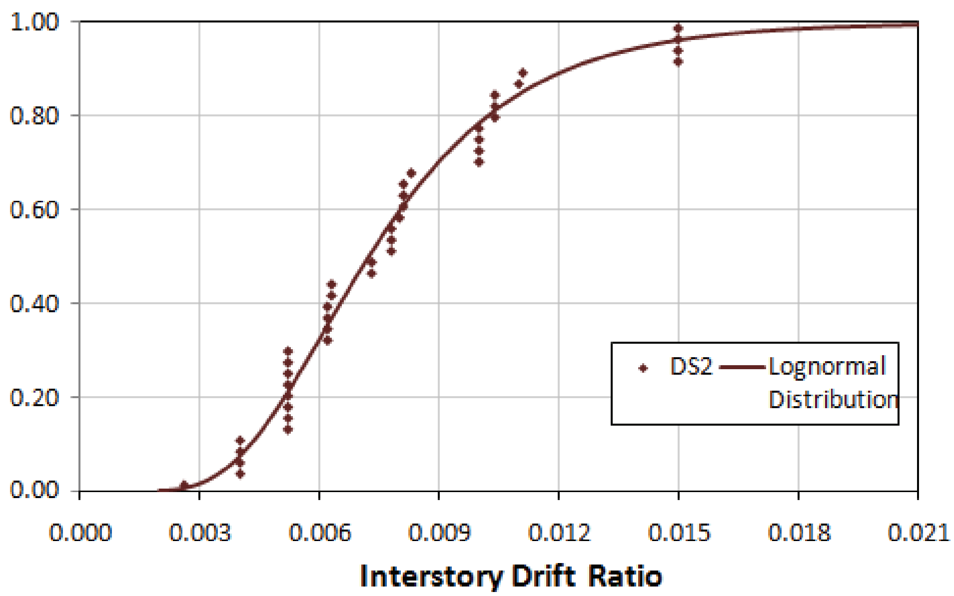


Figure 12: Cumulative distribution function corresponding to damage state 2.

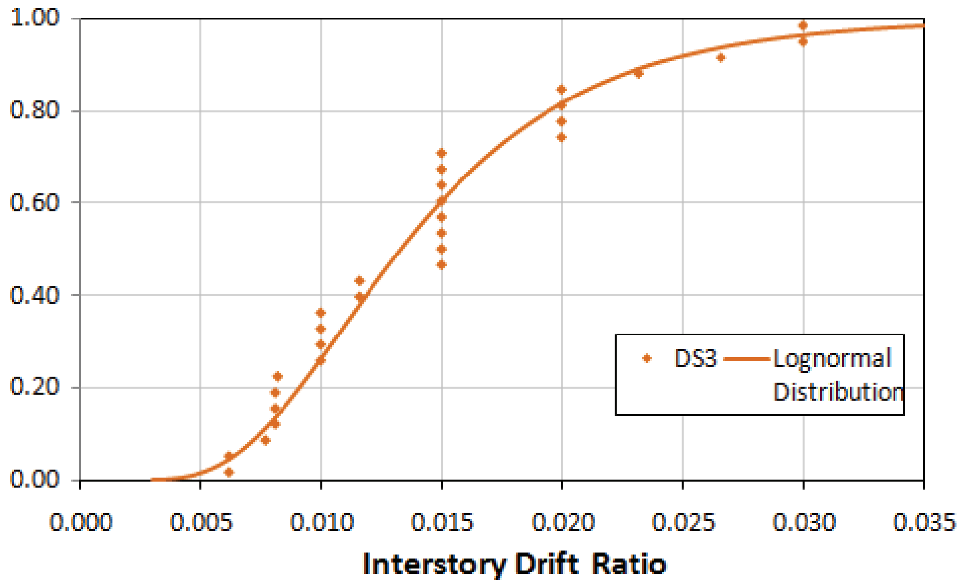


Figure 13: Cumulative distribution function corresponding to damage state 3.

Table 2: Parameters of lognormal distributions fitted to data in Table 1 without correction.

Damage State	Description	IDR x_m	Dispersion
DS1	First visible damage, ligth cracking requiring pasting, taping and repaint	0.0026	0.61
DS2	Significant cracking and crushing in gypsum boards requiring wallboard replacement	0.0072	0.41
DS3	Severe damage to board and frame requiring partition replacement	0.0133	0.45

However, some modifications are needed to the values reported in table 1. First, one must take into account that the occurrence of damage is typically only reported at the end of each loading cycle and therefore values reported in table 1 correspond to values at the end of the loading cycle in which damage states 1, 2 and 3 were reported to occur. This means that the damage actually occurred somewhere between the deformation corresponding to the previous loading cycle and the value reported in Table 1. Therefore, if one neglects this, a small bias toward overestimating the deformation at which the damage state is reached is produced which results in an underestimation of damage. Aslani and Miranda (2005) proposed to take into account this uncertainty by subtracting one half of the deformation increment at the cycle in which each damage state was reported to have occurred. This is equivalent to assuming the additional deformation between the two loading cycles as a random variable with a uniform probability distribution. This correction is applied to the data with drifts greater than 0.0012 since this correction can significantly reduce these smaller values. Figure 14 shows shifted empirical distribution functions with their corresponding fitted lognormal distributions. The final data corrected for the last half cycle is included the right three columns of Table 1.

Additionally one must take into account that values in Table 1 are not necessarily equal to those that would be obtained for the population, and that there is an additional source of uncertainty from the fact of being based on a relatively small samples. It can be shown that the geometric mean is normally distributed with a standard deviation equal to the logarithmic standard deviation divided by the square root of the sample size. To account for this statistical uncertainty the logarithmic variance was increased by the square of the standard error (σ^2/n). Parameters recommended for the fragility functions are shown in table 3.

Table 3: Recommended parameters for the fragility functions based on corrected data shown in Table 1.

Damage State	Description	IDR x_m	Dispersion
DS1	First visible damage, ligth cracking requiring pasting, taping and repaint	0.0021	0.58
DS2	Significant cracking and crushing in gypsum boards requiring wallboard replacement	0.0065	0.43
DS3	Severe damage to board and frame requiring partition replacement	0.0116	0.45

(Counted median used for DS-2)

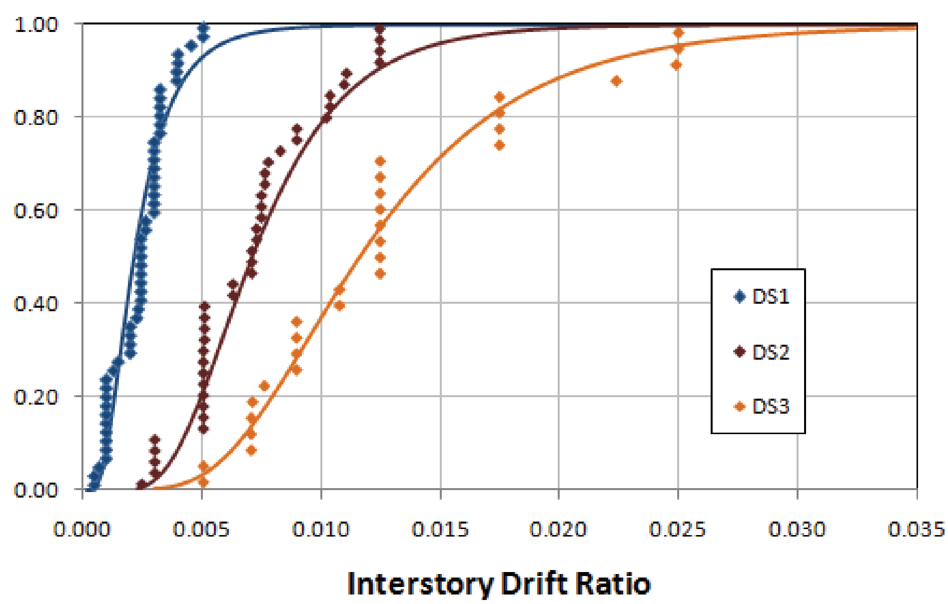


Figure 14: Comparison of shifted empirical cumulative distribution functions and lognormal distributions.

Fragility functions: Friction Connections with Returns

A similar procedure is applied to derive fragility functions for the friction connection detail to the top track allowing for horizontal sliding. Only walls tested with returns are included here –all specimens correspond to wall tested as part of the NEESR Grand Challenge project. It is expected that in most standard installations, wall will intersect into other transverse walls. In these cases, damage to the walls is expected to be concentrated in the corners of the intersection due to crushing and does not typically spread through the entire wall surface as for full-connections. Note that because all the wall are from the same test series, the dispersion value is adjusted by β_u=0.25. For this data, the counted median values are used in the final fragility functions for DS-2 and DS-3 to avoid crossing of the fragility curves. Table 4 through Table 6 and Figure 15 present the data and fragility analysis using a format similar to the full-connections group.

Table 4: Interstory drifts ratios in which each damage state was reported to have occurred, and modified data observed in between cycles.

Research Investigation	Specimen	Interstory Drift Ratio at DS			Modified data -considers DS observed in between cycles		
		DS1	DS2	DS3	DS1	DS2	DS3
NEESR	1	0.0020	0.0062	0.0062	0.0010	0.0051	0.0051
	2	0.0020	0.0062	0.0100	0.0010	0.0051	0.0091
	3	0.0040	0.0062	0.0062	0.0030	0.0051	0.0051
	20	0.0020	0.0100	0.0232	0.0010	0.0091	0.0224
	21	0.0040	0.0081	-	0.0030	0.0072	-
	22	0.0062	0.0062	0.0100	0.0051	0.0051	0.0091
	31	0.0020	0.0062	0.0062	0.0010	0.0051	0.0051
	32	0.0040	0.0100	0.0100	0.0030	0.0091	0.0091

Table 5: Parameters of lognormal distributions fitted to data in Table 5 without correction.

Damage State	Description	Median x_m	Dispersion
DS1	First visible damage, ligth cracking requiring pasting, taping and repaint	0.0030	0.52
DS2	Significant cracking and crushing in gypsum boards requiring wallboard replacement. Damaged boundary studs	0.0072	0.33
DS3	Severe damage to board and frame requiring partition replacement	0.0092	0.54

(Counted median used for DS-2 and DS-3)

Table 6: Recommended parameters for the fragility functions based on corrected data shown in Table 5.

Damage State	Description	Median x_m	Dispersion
DS1	First visible damage, ligth cracking requiring pasting, taping and repaint	0.0019	0.73
DS2	Significant cracking and crushing in gypsum boards requiring wallboard replacement. Damaged boundary studs	0.0061	0.37
DS3	Severe damage to board and frame requiring partition replacement	0.0081	0.59

(Counted median used for DS-2 and DS-3)

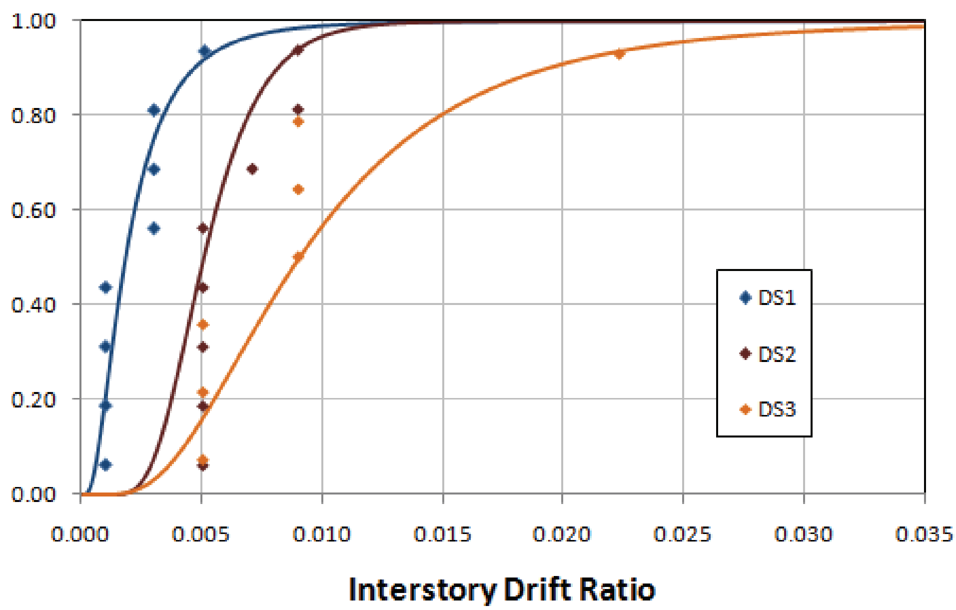


Figure 15: Comparison of shifted empirical cumulative distribution functions and lognormal distributions.

Fragility Functions: Friction Connection with no Returns

Testing of seismic slip track or friction only connection to the top and/or bottom track been considered in various studies. However, with the exception of the NEESR Grand Challenge project, all previous studies did not include return. While slip tracks perform well when not considering edges, these walls are expected to run into transverse walls in most typical installations. The NEESR Grand Challenge project confirmed the difference in behavior between these two conditions with only a slight increase to DS1, this damage mainly results because the end studs are bolted to the track. However, one advantage to the seismic slip track is that DS3 was not observed even at 0.03 drift. Note that Lee et al. (2007) tested seismic slip tracks with a return, but a gap was left between the intersecting walls and are considered in this group. It should also be noted that some of the data for this group was not corrected for the last half cycle. This data corresponds to dynamic testing where video was used to identify the instant at which failure corresponding to a DS occurred.

Table 7: Interstory drifts ratios in which each damage state was reported to have occurred, and modified data observed in between cycles.

Research Investigation	Specimen	Interstory Drift Ratio at DS			Modified data -considers DS observed in between cycles		
		DS1	DS2	DS3	DS1	DS2	DS3
NEESR	14	0.0013	0.0130	-	0.0013	0.0130	-
	15	0.0056	0.0245	-	0.0056	0.0245	-
	16	0.0027	0.0104	-	0.0027	0.0104	-
LEE	1	-	0.0150	-	-	0.0125	-
	2	0.0050	0.0100	-	0.0038	0.0075	-
	4	-	0.0100	-	-	0.0100	-
JAB	A-3	0.0078	0.0104	-	0.0077	0.0103	-
	A-19	-	0.0078	-	-	0.0077	-
	A-29	0.0104	0.0104	-	0.0104	0.0104	-
	A-2	0.0039	0.0052	-	0.0038	0.0051	-
	A-14	0.0039	-	-	0.0038	-	-
	A-23	0.0039	0.0078	-	0.0038	0.0077	-
	A-23R	0.0039	0.0052	-	0.0038	0.0051	-
	A-28	0.0026	-	-	0.0026	-	-
	A-28R	0.0007	0.0078	-	0.0007	0.0078	-

Table 8: Parameters of lognormal distributions fitted to data in Table 7 without correction.

Damage State	Description	Median xm	Dispersion
DS1	First visible damage, ligth cracking requiring pasting, taping and repaint	0.0035	0.74
DS2	Significant cracking and crushing in gypsum boards requiring wallboard replacement. Damaged boundary studs	0.0097	0.42
DS3	Severe damage to board and frame requiring partition replacement	-	-

Table 9: Recommended parameters for the fragility functions based on corrected data shown in Table 10.

Damage State	Description	Median xm	Dispersion
DS1	First visible damage, ligth cracking requiring pasting, taping and repaint	0.0034	0.72
DS2	Significant cracking and crushing in gypsum boards requiring wallboard replacement. Damaged boundary studs	0.0093	0.42
DS3	Severe damage to board and frame requiring partition replacement	-	-

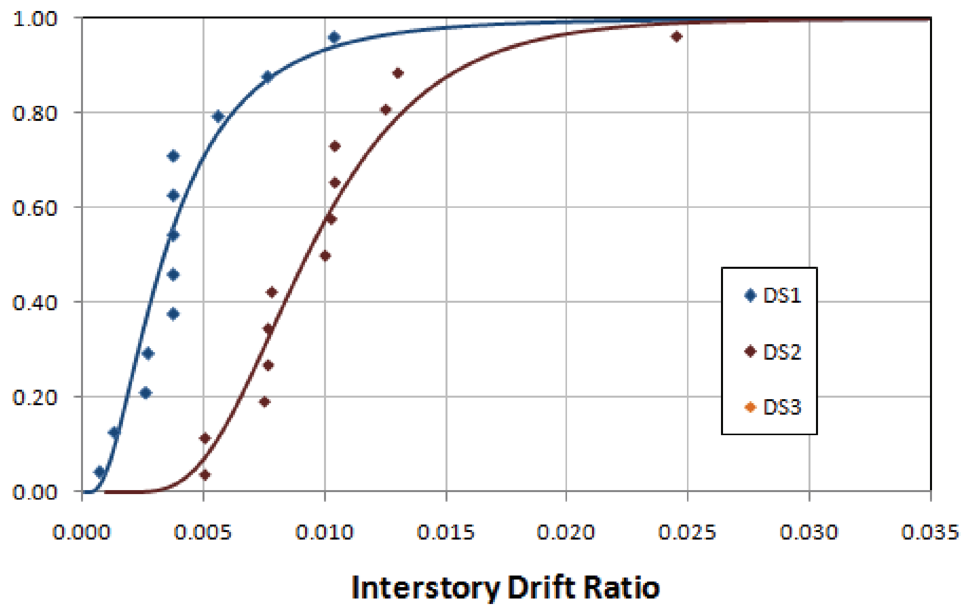


Figure 16: Comparison of shifted empirical cumulative distribution functions and lognormal distributions.

Fragility Functions: Partial Height Walls

Testing of partial height walls with diagonal bracing between the top track and top slab have only been reported as part of the NEESR Grand Challenge project. In previous tests identifying partial height walls, the framing was installed as in the full-connection walls, with only the gypsum installed to a partial height. This type of walls are reported with the full connection group since a similar behavior is expected as confirmed by examining the damage state data from these walls in previous testing by Rihal and Bersofsky. The braced partial height walls as considered here typically have the first sign of damage associated to the diagonal bracing by buckling or at the connection to the top track or slab. However, since the braces are exposed above the ceiling panels, this should be a relatively simple repair and damage to bracing is considered as DS-1. The flexibility associated with the braces significantly increases the initiation of damage and is largely depended on the braced height. The particular walls considered were 8 ft (2.4m) high with additional 3.5 ft (1m) of diagonal bracing. Note that because there are only three specimens and all walls are from the same test series, the dispersion value is adjusted by β_u=0.25. Table 10 through Table 12 and Figure 17 present the data and fragility analysis using a format similar to the full-connections group.

Table 10: Interstory drifts ratios in which each damage state was reported to have occurred, and modified data observed in between cycles.

Research Investigation	Specimen	Interstory Drift Ratio at DS			Modified data -considers DS observed in between cycles		
		DS1	DS2	DS3	DS1	DS2	DS3
NEESR	17	0.0081	0.0135	0.0184	0.0072	0.0126	0.0171
	18	0.0081	0.0116	0.0184	0.0072	0.0108	0.0171
	19	0.0062	0.0100	0.0199	0.0051	0.0091	0.0192

Table 11: Parameters of lognormal distributions fitted to data in Table 10 without correction.

Damage State	Description	Median x_m	Dispersion
DS1	First visible damage, ligth cracking requiring pasting, taping and repaint. Damaged or buckled braces.	0.0074	0.29
DS2	Significant cracking and crushing in gypsum boards requiring wallboard replacement. Damaged boundary studs or track.	0.0116	0.29
DS3	Severe damage to board and frame requiring partition replacement	0.0189	0.25

Table 12: Recommended parameters for the fragility functions based on corrected data shown in Table 10.

Damage State	Description	Median x_m	Dispersion
DS1	First visible damage, ligth cracking requiring pasting, taping and repaint. Damaged or buckled braces.	0.0064	0.32
DS2	Significant cracking and crushing in gypsum boards requiring wallboard replacement. Damaged boundary studs or track.	0.0107	0.30
DS3	Severe damage to board and frame requiring partition replacement	0.0177	0.26

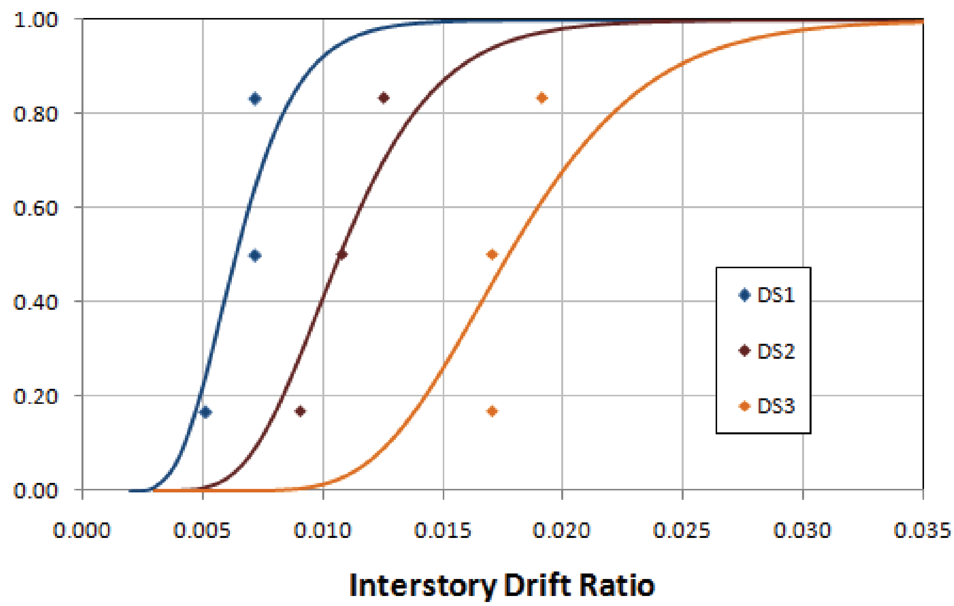


Figure 17: Comparison of shifted empirical cumulative distribution functions and lognormal distributions.

Summary of Recommend Values

The final recommended fragility parameters are reported here and plotted against available data. The values are rounded to two significant figures for the median and to the nearest 5/100 for the dispersion.

Full Connections

Table 13: Final recommended parameters for the fragility functions.

Damage State	Description	IDR x_m	Dispersion
DS1	First visible damage, ligth cracking requiring pasting, taping and repaint	0.0021	0.60
DS2	Significant cracking and crushing in gypsum boards requiring wallboard replacement	0.0071	0.45
DS3	Severe damage to board and frame requiring partition replacement	0.0120	0.45

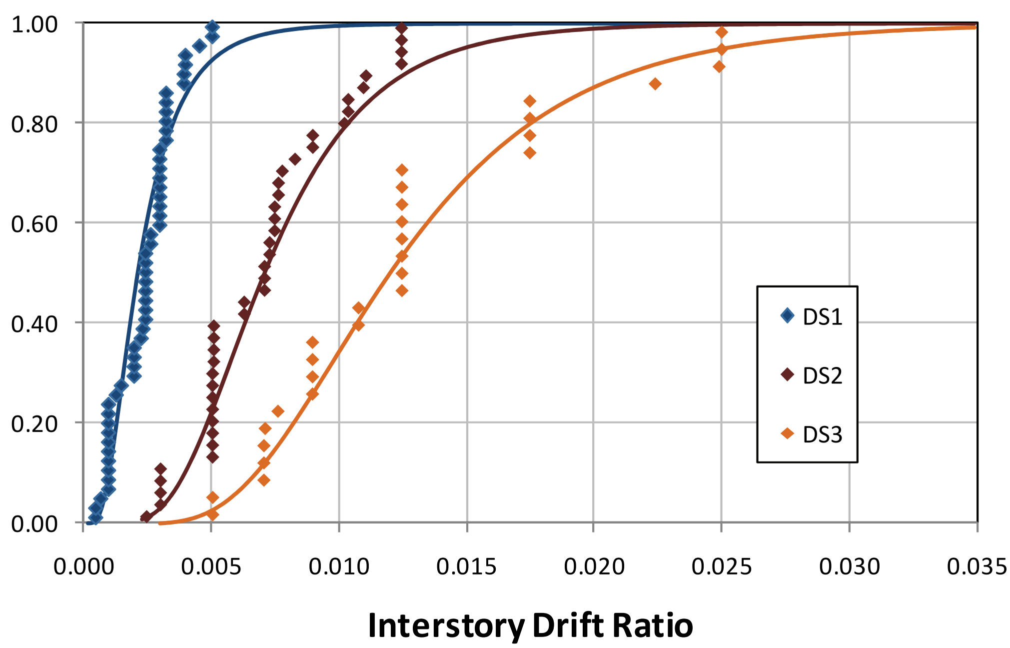


Figure 18: Comparison of shifted empirical cumulative distribution functions and lognormal distributions.

Friction Connections with Returns

Table 14: Final recommended parameters for the fragility functions.

Damage State	Description	Median x_m	Dispersion
DS1	First visible damage, ligth cracking requiring pasting, taping and repaint	0.0020	0.70
DS2	Significant cracking and crushing in gypsum boards requiring wallboard replacement. Damaged boundary studs	0.0050	0.40
DS3	Severe damage to board and frame requiring partition replacement	0.0090	0.60

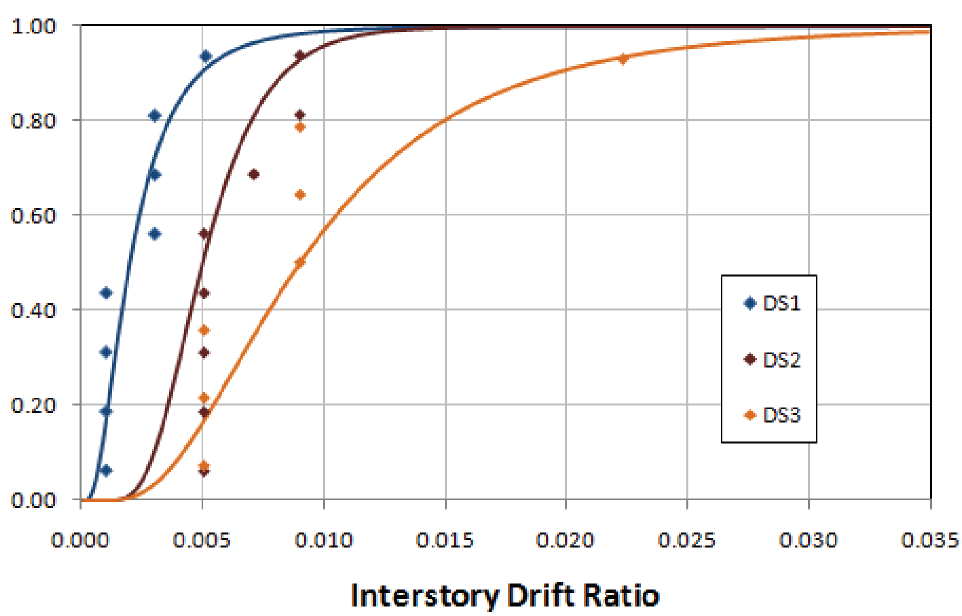


Figure 19: Comparison of shifted empirical cumulative distribution functions and lognormal distributions.

Friction Conneciton with no Returns

Table 15: Final recommended parameters for the fragility functions.

Damage State	Description	Median xm	Dispersion
DS1	First visible damage, ligth cracking requiring pasting, taping and repaint	0.0035	0.70
DS2	Significant cracking and crushing in gypsum boards requiring wallboard replacement. Damaged boundary studs	0.0093	0.45
DS3	Severe damage to board and frame requiring partition replacement	-	-

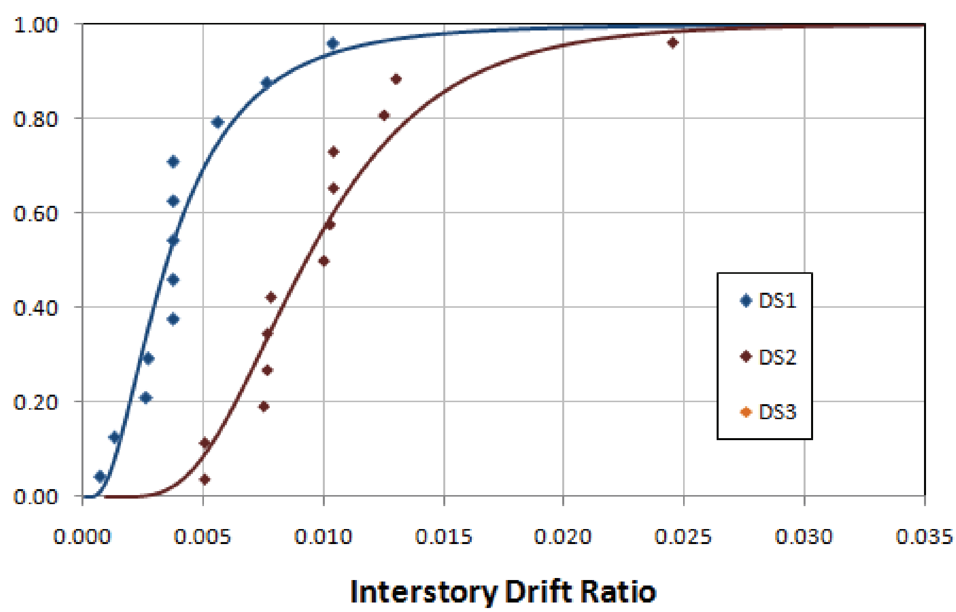


Figure 20: Comparison of shifted empirical cumulative distribution functions and lognormal distributions.

Partial Height Walls

Table 16: Final recommended parameters for the fragility functions.

Damage State	Description	Median x_m	Dispersion
DS1	First visible damage, ligth cracking requiring pasting, taping and repaint. Damaged or buckled braces.	0.0064	0.30
DS2	Significant cracking and crushing in gypsum boards requiring wallboard replacement. Damaged boundary studs or track.	0.0110	0.30
DS3	Severe damage to board and frame requiring partition replacement	0.0180	0.30

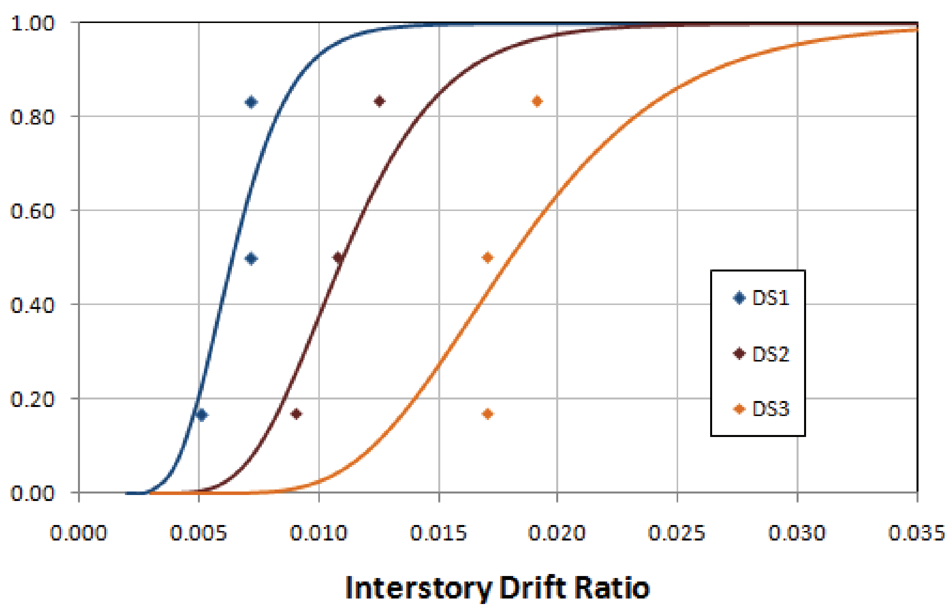


Figure 21: Comparison of shifted empirical cumulative distribution functions and lognormal distributions.

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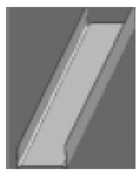
APPENDIX A – Example of construction recommendation by a manufacturer.

Big "D" metal framing products are highly suited for prefabricated panel construction which provides additional economy in today's highly competitive construction industry. Dietrich Metal Framing's structural product line consists of:

Structural Studs are available in web sizes ranging from 2-1/2", 3-5/8" 4", 6", 8", 10", 12", 14" and 16"

- Equal flanges of 1 3/8", 1-5/8" 2", 2-1/2", 3" and 3-1/2"
- Returns (lips) of 1/2", 5/8" and 1"
- 33 and 50 KSI yield strengths
- 20, 18, 16, 14 and 12 gage.

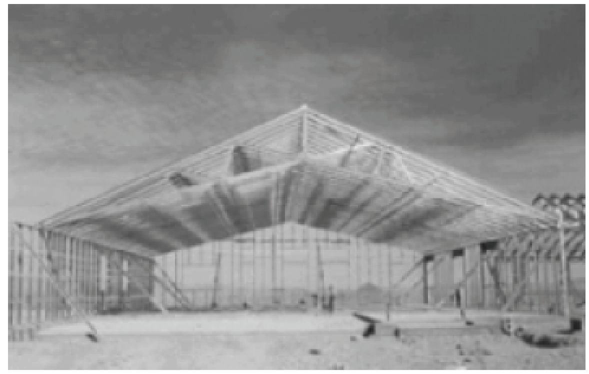


Structural Track (TSB) is available in matching Web sizes ranging from 2-1/2" to 16"

- Standard leg heights of 1-1/4" (unequal and equal leg heights up to 3" are available upon request)
- Standard 10' lengths (other lengths are available upon request) 33 and 50 KSI yield strengths 20, 18, 16, 14 and 12 gage
- Other sizes and gages can be custom rolled as required. Contact your nearest Dietrich facility for additional information and pricing.

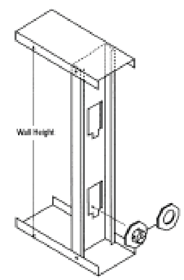
Metal Trusses

Prefabricated, non-combustible light gage trusses are available through Dietrich's joint venture company AEGIS Metal Framing. A nationwide network of truss fabricators will engineer, design and factory build trusses to your specifications. Metal trusses are the ideal, cost effective alternative to structural steel, pressure treated wood trusses, bar joist, and site assembled cold formed trusses. If you have a customer who is looking for non-combustible, metal trusses, call Dietrich Metal Framing



Drywall Framing

For Non-load Bearing Interior Walls



Drywall or interior framing is a non-load bearing wall system that supports gypsum panel construction. Most non-load bearing walls are constructed using 25-gage (0.018" thick) or 20-gage (0.033" thick) material. 22-gage (0,027" thick) studs also are available. Wall height, stud spacing and wind load will determine the gage.

Metal studs are twisted into top and bottom track and screw attached using 7/16" pan head framing screws. Studs may be spaced at either 12", 16" or 24" on-center spacing based on wall height.

Studs and track are C-shaped channels, roll-formed from corrosion-resistant, galvanized steel. Together, they provide efficient, low-cost framing for partition walls, ceilings and column fireproofing.

All interior studs are designed for quick screw attachment of drywall or plaster facing materials, and can be cut to length. Track aligns and secures studs to floors and ceilings, and is also used in conjuction with studs for constructing openings, headers and sills.

Step By Step

1. Cut studs and track to required lengths as you install using aviator snips or circular saw with abrasive, metal cutting blade.

2. Attach ceiling track. Use drywall screws to attach to joists. For parallel joists, bridge two joists with track spaced 24"o.c. or less and install ceiling runner across bridges.

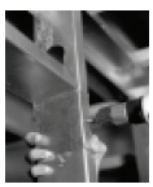
3. Plumb to position floor runner directly below ceiling track.

4. Attach floor track. Use power-actuated fasteners for concrete floor. Use drywall screws for wood sub-floor. Same fastener spacing as ceiling track. Then mark stud locations 16"o.c. or 24"o.c. top and bottom starting from the same end.

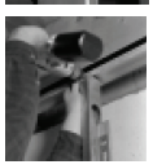
5. Insert stud at slight angle into tracks – then twist into place. Be sure all studs are pointed the same way for easier drywall attachment and punchouts are oriented the same way for easy plumbing or electrical installation.

6. Screw – attach stud to ceiling track and floor track with 7/16" pan or wafer-head screws. Hold stud flange to runner for easier screw attachment.

7. For door and window openings, cut track 4" longer than opening. Notch legs and bend web 90° to attach to jamb stud.



8. Attach C-runner bracing across studs to support cabinet attachment. C-runner must be notched to fit between studs.

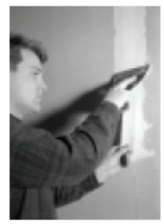


9. Insert grommets or pieces of pipe insulation into prepunched holes whenever you pass through wiring or plumbing.

10. Screw-attach drywall to framing using drywall screws. Board should be attached to the open end of the studs first.

11. Install corner beads and trim with screws or staples.

12. Tape and finish with joint compound.



Helpful Hints

Most wood trim can be adhesively attached and may require temporary screws while adhesive sets. If mechanical attachment is required, consider inserting sections of wood 2x4 inside track for nailing.

Door frames can be attached directly to steel framing, but many installers prefer wood 2x4 framing around the rough opening. If this option is chosen, frame rough opening 3" wider to allow for wood studs.

If framing is used to support insulation blankets, the insulation will have to be ordered to the full 16" or 24" width dimension.

Hanging pictures or artwork can be handled easily with standard hanging attachment except drywall screws are recommended where studs are located.

Extremely heavy shelving and other heavy objects should be anticipated. Cross bracing with C-runners is recommended.

LIMITATION: 25-gage steel studs are designed for use in non-load bearing construction only. Check building codes before beginning construction.