Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 1376

EXPERIMENTAL SEISMIC FRAGILITY ASSESSMENT OF LIGHT GAUGE STEEL STUDDED GYPSUM PARTITION WALLS

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ABSTRACT

Partition wall subsystems constitute a significant portion of the total investment in building infrastructure. Past earthquakes have demonstrated that damage to these nonstructural subsystems can cause substantial earthquake losses and degrade the overall functionality of buildings. Nevertheless, the data obtained from field observations, previous experimentations, and numerical simulations are insufficient to fully characterize their mechanical response under seismic actions and to develop effective solutions to improve their seismic performance. As part of the NEES Nonstructural Grand Challenge Project entitled: *Simulation of the Seismic Performance of Nonstructural Systems,* a comprehensive experimental program evaluated the seismic performance of light gage steel studded gypsum partition walls. Fifty partition wall specimens, corresponding to twenty two different wall configurations, were constructed following standard construction techniques. Quasi-static and dynamic tests were carried out to assess the in-plane and out-of-plane seismic performance of the walls under both story drifts and floor accelerations. This paper describes the failure mechanisms observed in the walls and develops, based on the methodology developed by the ATC-58 Project, a seismic fragility database for gypsum partition walls.

Introduction

The NEES Nonstructural Grand Challenge Project entitled: *Simulation of the Seismic Performance of Nonstructural Systems* (http://www.nees-nonstructural.org) integrates multidisciplinary system-level studies that develop, for the first time, the simulation capabilities and implementation process for enhancing the seismic performance of Ceiling-Piping-Partition (CPP) nonstructural systems. This project is led by the University of Nevada, Reno in

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collaboration with the Consortium of Universities for Research in Earthquake Engineering (CUREE), Cornell University, Georgia Institute of Technology, North Carolina Agricultural and Technical State University, North Carolina State University, Rutherford & Chekene, State University of New York at Buffalo, and University of California, San Diego. In the first experimental phase of the project, a comprehensive testing program is using the University at Buffalo and the University of Nevada, Reno NEES Equipment Sites to conduct full-scale subsystem and system-level experiments, respectively. The main objective of the subsystem level test series is to characterize the seismic performance of CPP systems and to provide the input for the design and execution of system-level experiments at the University of Nevada, Reno. This paper reports on a comprehensive test program on light gage steel studded gypsum partition wall subsystems conducted at the University at Buffalo and on the seismic fragility analysis performed from the resulting data.

Seismic Performance of Partition Wall Subsystems

The first experimental phase of the project evaluated the seismic performance of twenty two different configurations of light gauge steel studded gypsum partition walls, constructed following standard construction practices. The subsystem-level tests were performed using the University at Buffalo Nonstructural Component Simulator (UB-NCS), subjecting full-scale specimens to both dynamic and quasi-static test protocols. The main objective of the partition wall subsystem-level test series was to evaluate the seismic fragility of several configurations of light gauge steel studded gypsum partition walls.

The University at Buffalo Nonstructural Component Simulator (UB-NCS)

The UB-NCS, shown in Figure 1, provides the unique capability to replicate, under controlled laboratory conditions, the effects of strong seismic shaking on distributed nonstructural systems located at the upper levels of multistory buildings. Furthermore, this testing equipment allows for assessing the seismic interactions between displacement and acceleration sensitive nonstructural subsystems. The UB-NCS testing facility can subject full-scale nonstructural specimens to accelerations of up to 3g, peak velocities of 100 in/s and displacements in the range of ±40 in, enveloping the peak seismic responses recorded at the upper levels of multistory buildings during historical earthquakes. A more detailed description of the UB-NCS testing frame and its capabilities can be found in Mosqueda *et al*. (2007).

Testing Protocols for the UB-NCS

Testing protocols currently used for the seismic performance assessment of nonstructural components and equipment, such as FEMA 461 (FEMA 2006) and AC156 (ICC-ES 2007), focus either on displacement or acceleration sensitive components, through quasi-static racking or shake table protocols. However, many nonstructural systems, like the CPP systems studied in this project, are composed of subsystems that individually may be either acceleration or displacement sensitive, but when combined with other subsystems may become sensitive to both accelerations and interstory drifts. To this end, an innovative testing protocol has been developed for assessing the seismic fragility of combined nonstructural systems, taking full advantage of the UB-NCS capabilities. The UB-NCS testing protocol consists of a pair of displacement histories for the bottom and top testing platforms that simultaneously match: (i) a target Floor Response Spectrum (FRS), and (ii) either a target Generalized Interstory Drift (GID) or a maximum interstory drift, Δ_{Max}, based on the anticipated specimen deformation capacity. The input variables for the protocol are the local seismic hazard, in terms of the spectral coordinates defined in ASCE/SEI 7-05 (ASCE 2005), the normalized building height above grade where the nonstructural system is located, and optionally, the maximum drift Δ_{Max} to be imposed. For fragility assessment, this test series considered a generic site with spectral coordinates S_{DS}=1g and S_{D1}=0.6g, a generic nonstructural system located at a roof building level, and a maximum drift Δ_{Max}=3%. Figure 2 shows the platform motions used as input for the UB-NCS during dynamic tests. Furthermore, the quasi-static testing protocol shown in Figure 3 was developed for evaluating the seismic fragility of primarily drift-sensitive components. Both the dynamic and quasi-static fragility testing protocols impose a similar number of damaging cycles (ASTM 1997) on drift sensitive components. Further details on these testing protocols can be found in Retamales *et al*. (2008).

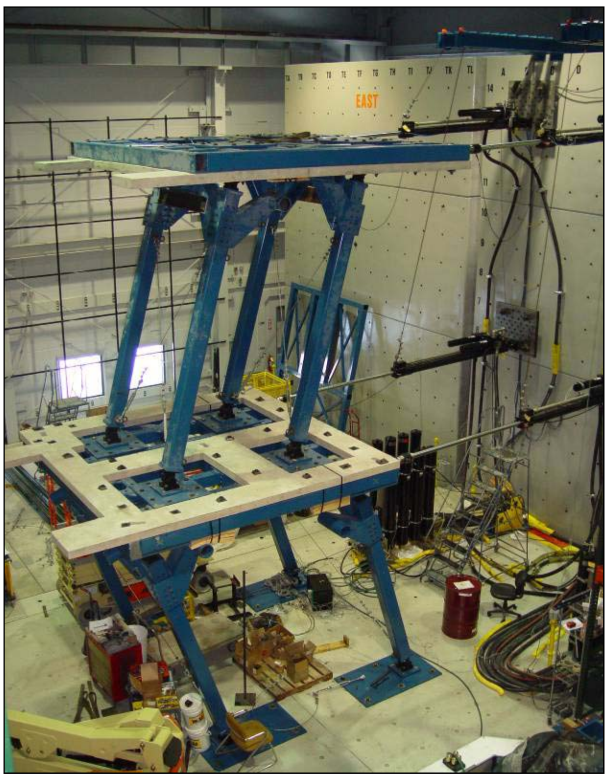


Figure 1. Photograph of the UB-NCS

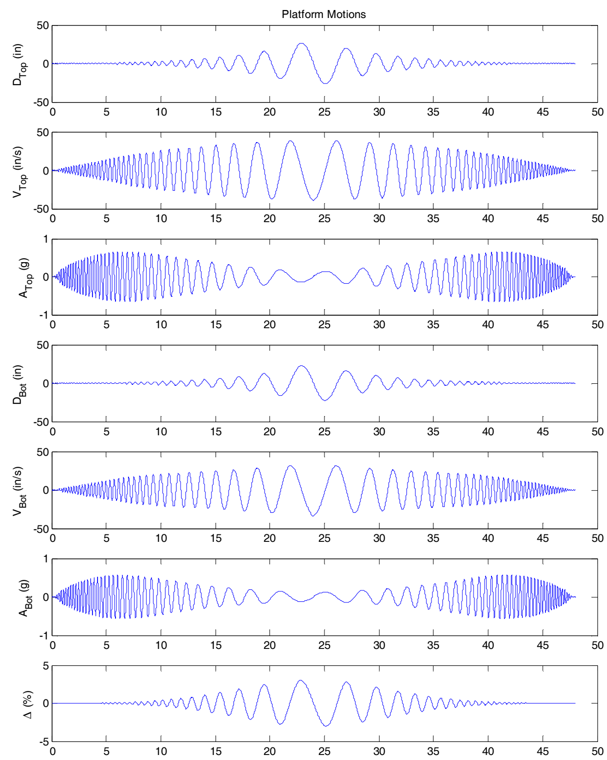


Figure 2. Dynamic fragility testing protocol

Description of Partition Wall Specimens

In this test program, 50 specimens of light gauge steel studded gypsum partition walls were tested. The partition walls were installed parallel (36 specimens) and perpendicular (14 specimens) to the direction of the input motions, to study their in-plane and out-of-plane seismic performance, respectively. The partition wall specimens were approximately 12 ft long by 11.5 ft tall. Figure 4 shows the most typical configuration used for in-plane testing. The Practice Committee and the 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 bottom and top tracks, as illustrated in Figure 5
(ii) Spacing of track fasteners (12 or 24" o.c.)
(iii) Presence of transverse (return) walls
(iv) Detail of wall intersection, as illustrated in Figure 6
(v) Attachment of weights such as bookshelves or equivalent unbraced rigid ceiling
(vi) Height of the partition wall (total or partial height)
(vii) Stud and track wall thickness (25 or 20 ga)
(viii) Spacing of steel framing system (16 or 24" o.c.)
(ix) Direction of testing (in-plane or out-of-plane) and type of test (dynamic or quasi-static)

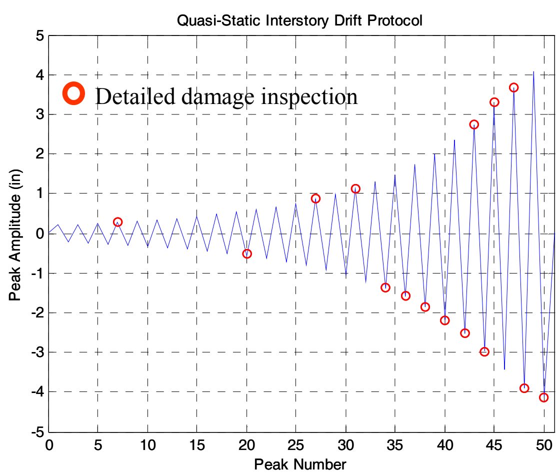


Figure 3. Quasi-static fragility testing protocol

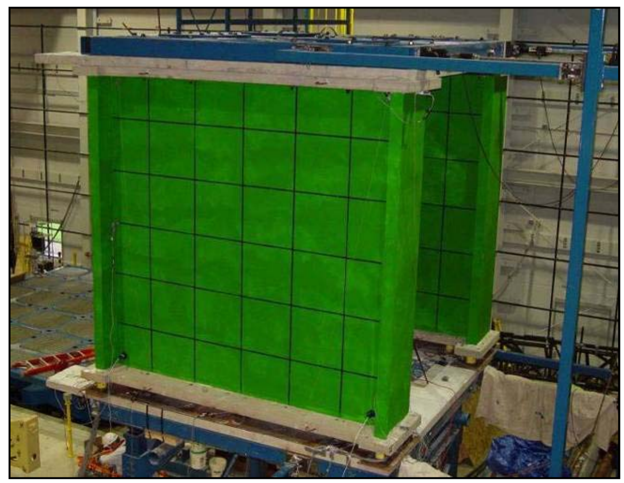
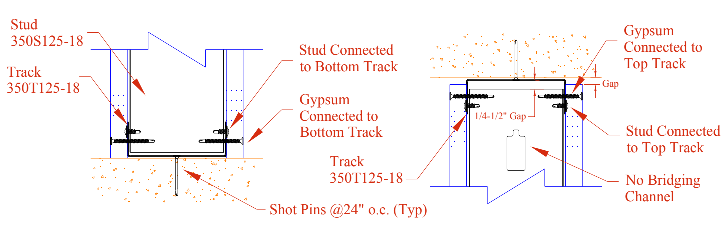
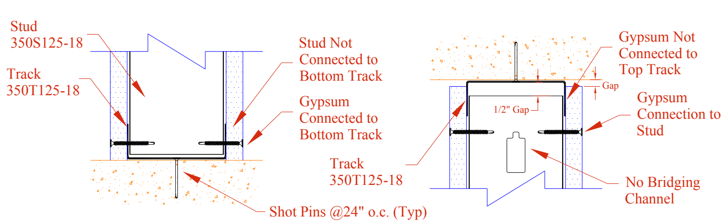


Figure 4. Photo typical test specimen

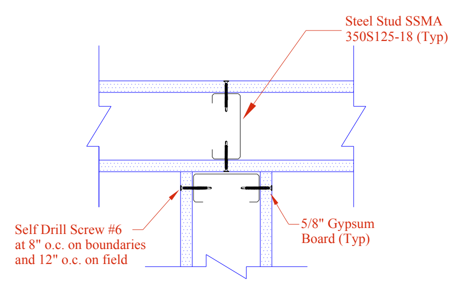


(a) Basic connection (slip track)

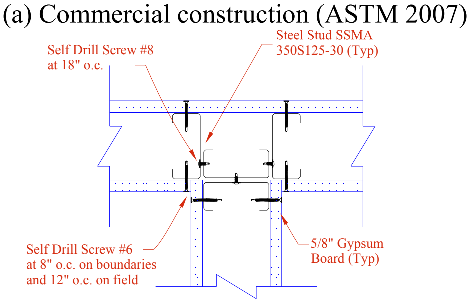


(b) Full connection

Figure 5. Typical framing and sheathing details



(a) Commercial construction (ASTM 2007)



(b) Institutional construction (SSMA 2001)

Figure 6. Typical wall intersection details

Testing Program

The 22 wall configurations listed in Table 1 were considered in the test program. In general, slight variations in the configurations were progressively introduced between consecutive tests. For fragility assessment purposes, 3 tests were conducted for each wall configuration, unless the observed damage was similar to specimens already tested. All specimens without attached mass tested in-plane, except for configuration 11, were tested using the quasi-static testing protocol shown in Figure 3. During the quasi-static tests, detailed inspections of the specimen's damage were performed at the peak drifts indicated in Figure 3. Particularly, the specimen damage states triggered at each inspection and the damage progression were carefully monitored. All other specimens were tested using the dynamic testing protocol shown in Figure 2. During dynamic testing, the seismic demands triggering the damage states were estimated by tracking the time-stamped high-definition videos and the data recorded during the tests.

Table 1. Summary of gypsum partition wall configurations

Config	Specimen ID	Specimen Description	Loading Direction/Rate	Steel Stud Type	Steel Frame and Sheathing Connectivity						
					Stud to Bottom Track	Stud to Top Track	Gypsum to Bottom Track	Gypsum to Top Track	Return Walls	Attached Mass	Ceiling Connected
1	1, 2 & 3	Basic (slip track)	In Plane/Static	350S125-18	No	No	Yes	No	Yes	No	No
2	4	Gypsum connected to top track	In Plane/Static	350S125-18	No	No	Yes	Yes	Yes	No	No
3	5, 6 & 10	No Return	In Plane/Static	350S125-18	No	No	Yes	Yes	No	No	No
4	7, 8 & 9	Full connection	In Plane/Static	350S125-18	Yes	Yes	Yes	Yes	Yes	No	No
5	11, 12 & 13	Bookshelf	In Plane/Dynamic	350S125-18	No	No	Yes	No	No	Yes	No
6	14, 15, & 16	Equivalent Ceiling	In Plane/Dynamic	350S125-18	Yes	No	Yes	No	No	Yes	Yes
7	17, 18 & 19	Partial height braced wall	In Plane/Static	350S125-18	Yes	Yes	Yes	Yes	Yes	No	No
8	20, 21 & 22	Institutional const./slip track	In Plane/Static	350S125-30	Yes	No	Yes	No	Yes	No	No
9	23, 24 & 26	Institutional const./Full Connection@24"	In Plane/Static	350S125-30	Yes	Yes	Yes	Yes	Yes	No	No
10	25, 27 & 28	Institutional const./Full Connection@12"	In Plane/static	350S125-30	Yes	Yes	Yes	Yes	Yes	No	No
11	29 & 30	No Return/Dynamic	In Plane/Dynamic	350S125-18	No	No	Yes	No	No	Yes	No
12	31 & 32	C-Shaped Walls	In Plane/Static	350S125-18	Yes	No	Yes	No	Yes	No	No
13	33	Solution to T corner damage/corner gaps	In Plane/Static	350S125-18	Yes	No	Yes	No	Yes	No	No
14	34	Solution to T corner damage/double slip track	In Plane/Static	350S125-18	No	No	No	No	Yes	No	No
15	35	Solution to L corner damage/corner gaps	In Plane/Static	350S125-18	Yes	No	Yes	No	Yes	No	No
16	36	Solution to T corner damage/slip track	In Plane/Static	350S125-18	Yes	No	Yes	No	Yes	No	No
17	37	Unloaded Wall w/ Returns	Out of Plane/Dynamic	350S125-18	No	No	Yes	No	Yes	No	No
18	38	Unloaded Wall w/o Returns	Out of Plane/Dynamic	350S125-18	No	No	Yes	No	No	No	No
19	39, 45 & 47	Bookshelf wall w/ returns	Out of Plane/Dynamic	350S125-18	No	No	Yes	No	Yes	Yes	No
20	40, 41 & 43	Bookshelf wall w/o returns	Out of Plane/Dynamic	350S125-18	No	No	Yes	No	No	Yes	No
21	42, 44 & 46	Equivalent Ceiling wall w/ returns	Out of Plane/Dynamic	350S125-18	Yes	No	Yes	No	Yes	Yes	Yes
22	48, 49 & 50	Partial height braced wall	Out of Plane/Dynamic	350S125-18	Yes	Yes	Yes	Yes	Yes	No	No

Performance Assessment

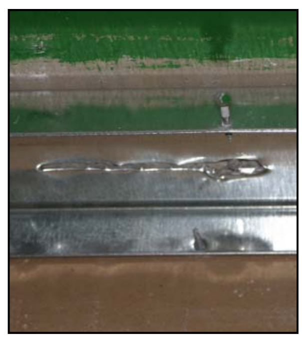
Table 2 and Figure 7 summarize the main damage observed and the failure mechanisms of all test specimens. In particular, Specimens 33 through 36 considered four different details specifically developed for reducing damage at wall intersections and corners. Examples of the improved construction details are shown in Figure 8. The improved details substantially reduced the forces transferred to the partitions and increased the drift levels at which initial damage occurred, as demonstrated later by the fragility analysis. Most of the damage was concentrated in sacrificial cornerbeads elements. It was noted that all specimens with bookshelves (weighting 510 lb approximately) that failed during out-of-plane dynamic testing corresponded to specimens previously used for other tests. After the first use, all visible damage (including replacement of nails connecting tracks to concrete slabs, damaged studs, pulled out screws, damaged joint paper tape and mud, etc.) was repaired. These observations indicate that partition walls with attached masses located in zones of high seismicity, and that may experience more than one strong earthquake during their lifetime, may be highly vulnerable to collapse.

Table 2. Summary of damage and failure mechanisms of test specimens

Config	Specimen ID	Main Damage/Failure Observed	Photo
1	1, 2 & 3	Damage concentrated in transverse walls top tracks: Tearing of track web, nails pulled out from concrete, and bending of track flanges. Damage was also observed in the transverse walls top gypsum panels. Longitudinal walls exhibited limited crushing at wall corners.	a
2	4	Crushing of gypsum boards around all screws connecting sheathing to top track, at a relatively low drift level (~0.4%). Then, a similar damage to specimens 1, 2 & 3 was observed.	a
3	5, 6 & 10	Damage along steel cornerbeads. Crushing of gypsum boards at wall corners. Nails in connections of tracks to concrete passing thru the track webs. In specimen 10, tearing of the top track was observed.	b & c
4	7, 8 & 9	Specimen 7 & 9: Top and bottom tracks slipped after track tearing around all nailed connections. Specimen 8: Moment hinges were observed in all studs, approximately 1 ft under top end connection.	c & d
5	11, 12 & 13	Damage concentrated in top 4 feet of wall end: Boundary stud bent after being pulled from gypsum boards and top track. Limited rocking of screws attaching gypsum board to bottom track. Books were protected against fallings in order to keep the mass attached to the walls during the test. However, for Specimen 12, the safety device was removed and books fell down from the bookshelf.	b
6	14, 15, & 16	Damage Similar to specimens 11, 12 &13 was observed. Limited popout of screws was observed in the steel angle connecting equivalent "ceiling" to walls (Specimen 16).	b
7	17, 18 & 19	Damage in seismic braces due to buckling. Failure in braces to top track connections. In specimen 18, the connection between the top tracks of longitudinal and transverse walls failed. Failure in some of the track to concrete connections were observed.	e & f
8	20, 21 & 22	Failure of bottom and top tracks of transverse walls. Severe damage of the studs in wall intersections. Severe damage of sheetrock in transverse wall due to out-of-plane bending. Bending of transverse wall top track flanges observed. Damage along vertical edges of sheathing of longitudinal wall.	g
9	23, 24 & 26	Specimen 23: Track fasteners passing thru the top track. Hinges formed 1' under top end of studs. Failure of top track in transverse wall. Slight crushing of wall corners. Specimen 24: Track fasteners passing thru the bottom track. Failure of bottom tracks of transverse walls. Damage in gypsum panel joints. Specimen 26: Tears along all bottom track connections and global wall slip.	c, d & h
10	25, 27 & 28	Crushing of gypsum around screws connecting to top track and plastic hinge forming on studs due to bending.	i & j
11	29 & 30	Damage in the upper 4' of the steel cornerbeads and wall boundary studs. Nails at the end of the tracks passing thru the track webs.	b
12	31 & 32	Wall corners totally opened. Damage along conerbeads. Studs in transverse walls pulled out from transverse wall top track.	k
13	33	Joint cornerbead detached from walls at drifts levels as low as 0.2-0.4%. Damage does not progresses in the specimen at larger drift levels.	l
14	34	Damage was observed for the fist time at a drift level of 1.2%. Then joint paper tape detached from wall intersection (1.2-1.4% drift), vertical cracks in gypsum of transverse walls (1.6% drift), and failure of fasteners in transverse wall track connections (1.8% drift) were observed.	g
15	35	Exterior joint cornerbead detached from walls at drifts levels close to 0.6%. Damage does not progresses in the specimen at larger drift levels.	m
16	36	Joint paper tape detached from wall intersection (0.4-0.6% drift), failure of fasteners in transverse wall track connections (0.6% drift), and vertical cracks in gypsum of transverse walls (1.4% drift), were observed.	g
17	37	Minor damage observed at top end of cornerbeads and crushing of corners of return walls. Screws pulled out from wallboards to stud connections.	n
18	38	Most of the screws in the connection of the top row of gypsum boards to studs completely pulled out.	n
19	39, 45 & 47	Screws pulled out from gypsum to stud connections. Bookshelf connectors needed to be tighten after the test. Damage along top end of cornerbeads. Specimen 47 collapsed.	b & o
20	40, 41 & 43	Screws pulled out from gypsum to stud connections. Bookshelf connectors needed to be tighten after the test. Horizontal cracks along gypsumboard joints. Damage along top end of cornerbeads. Specimens 40 and 43b collapsed.	n, p & q
21	42, 44 & 46	Screws pulled out from gypsum to stud connections. Damage at the top and bottom ends of cornerbeads. In specimens 42 and 44, crushing of gypsumboards around fence staples connectors was observed. In specimens 44b and 46, the equivalent ceiling got completely detached from the partition wall.	b, n & r
22	48, 49 & 50	Screws in connections of braces to walls' top tracks pulled out. Buckling of seismic braces. Buckling of top tracks around seismic brace connections.	e, f & s


(a) Damage in transverse wall top track


(b) Damage of corner beads/boundary studs


(c) Tearing along top track fastener


(d) Hinges in studs (commercial const.)


(e) Buckling of braces


(f) Damage in brace connections


(g) Damage transverse walls

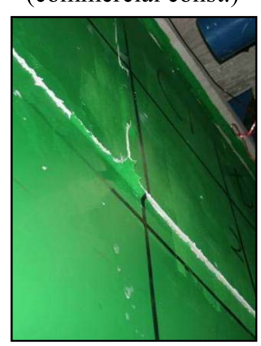

(h) Damage between wallboards

Figure 7. Photos of damage observed during in-plane and out-of-plane testing


(i) Hinges forming in studs institutional const.

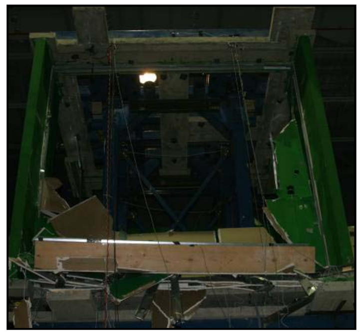

(j) Crushing and shearing of gypsum around screws in top track connection

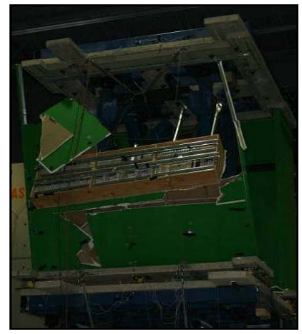

(k) Damage at wall corner, cornerbeads and boundary stud


(l) Damage along sacrificial cornerbeads at wall intersection


(m) Damage at sacrificial cornerbeads


(n) Screws pulled out from steel studs


(o) Collapse of partition wall with returns


(p) Collapse of partition wall without returns


(q) Crack along partition wall


(r) Crushing of gypsum around fence staple connector


(s) Deformation of top track around brace connection

Figure 7. Photos of damage observed during in-plane and out-of-plane testing (Cont'd)

Seismic Fragility Analysis

The experimental results described in the previous section were processed to populate a comprehensive seismic fragility database for light gauge steel studded gypsum partition walls. Table 3 presents the drift levels at which each damage observation was triggered for all drift sensitive specimens. The damage observations in Table 3 were sorted in ascending order of the median drift level triggering each damage observation, and then grouped and assigned to one of the Damage States (DS's) defined in Table 4. These DS's were defined in terms of the nature of the damage observed and the characteristics of the required repair actions. It is assumed that the drift level triggering a specific DS for a given specimen corresponds to the minimum drift level triggering one of the damage observations associated to that DS. Furthermore, the fragility data was grouped according to the taxonomy of the specimens tested, as shown in Table 5. In a similar fashion, the seismic fragility of the acceleration sensitive partition walls (specimens with attached weights) was assessed. In particular, the damage state DS_2, consisting of failure of the connectors (1-¼” fence staples) attaching the equivalent unbraced rigid ceiling to the partition walls, and the damage state DS_3, consisting of the collapse of walls with attached bookshelves, were evaluated. The damage state DS_1 could not be evaluated from the recorded time stamped videos because the exact occurrence of the associated damage could not be identified. Table 6 shows a set of Engineering Demand Parameters (EDP’s) associated to the occurrence of damage states DS_2 and DS_3.

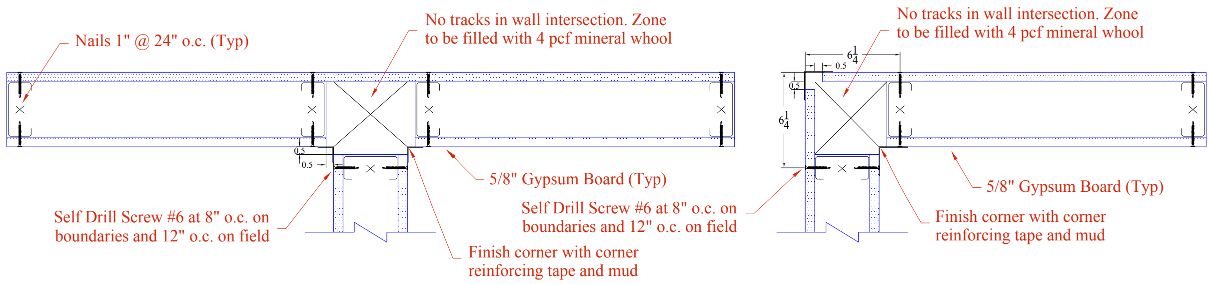


Figure 8. Details proposed for reducing seismic damage

Table 3. Drifts levels triggering several damage states in displacement sensitive walls

			Specimen ID																																			
Damage State			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	31	32	33	34	35	36	48	49	50
DS_1	Damage Observation	Cracks along longitudinal wall corner beads	-	-	-	-	0.20	0.40	-	-	-	0.20	0.28	0.10	0.48	0.13	0.56	0.27	-	-	-	-	-	-	-	-	-	-	-	-	-	0.40	0.20	-	0.20	-	-	-	-
		Crack along tape/pulled tape/crushing wall vertical edges	0.20	0.20	0.40	0.62	-	-	0.20	0.40	0.20	-	-	-	-	-	-	-	1.00	1.16	2.66	0.20	0.40	1.00	0.40	0.62	0.40	0.62	0.40	0.40	0.20	0.62	0.20	1.00	-	0.40	-	-	-
		Gypsumboard screw popout/rocking (top track)	-	-	-	0.62	0.40	0.40	0.40	0.40	0.40	0.40	-	-	-	-	-	-	-	-	0.62	-	-	-	0.40	0.40	0.40	0.40	0.62	0.40	-	-	-	-	-	-	-	-	-
		Gypsumboard screw popout/rocking (bottom track)	0.62	0.62	-	0.40	0.62	0.81	0.40	0.62	0.40	1.84	-	-	-	-	-	-	-	-	-	-	-	-	0.62	1.00	0.40	0.40	0.40	0.40	-	-	-	1.16	-	-	-	-	-
		Minimum Drift Level Triggering DS_1	0.20	0.20	0.40	0.40	0.20	0.40	0.20	0.40	0.20	0.20	0.28	0.10	0.48	0.13	0.56	0.27	1.00	1.16	0.62	0.20	0.40	1.00	0.40	0.40	0.40	0.40	0.40	0.40	0.20	0.40	0.20	1.00	0.20	0.40	-	-	-
DS_2	Damage Observation	Damage in gypsumboard transverse wall	0.62	0.62	0.62	1.16	-	-	1.99	1.99	-	-	-	-	-	-	-	-	-	-	-	1.35	0.81	0.62	-	1.16	1.00	1.00	1.35	1.16	1.84	1.84	-	1.57	-	1.35	-	-	-
		Crushing partition wall corners	2.82	3.00	0.62	0.62	0.40	0.62	0.62	2.32	0.40	1.00	-	-	-	-	-	-	-	-	-	1.16	-	-	0.81	1.35	0.40	-	0.62	0.81	-	-	-	-	-	-	-	-	-
		Boundary stud detached from gypsum/bending	0.62	0.62	1.00	1.16	1.00	1.00	1.99	1.00	0.81	1.84	2.23	1.73	1.66	1.30	2.45	1.04	-	-	-	2.15	1.00	2.15	1.35	2.15	1.99	2.15	1.00	1.35	1.99	1.99	-	1.99	-	1.00	-	-	-
		Damage along gypsumboads edges	-	-	-	-	-	-	-	2.32	-	-	-	-	-	-	-	-	-	-	-	1.35	-	-	1.16	0.40	0.40	1.57	1.00	-	1.99	-	-	-	-	-	-	-	-
		Brace buckling/top track bending (partial height walls)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.81	0.81	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.26	0.93	1.34
		Failure of seismic braces connectors (partial height walls)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2.15	2.66	2.15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3.05	3.03	3.03
		Failure stud connectors at walls intersection (inst. const.)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.00	1.16	-	-	0.81	-	-	1.35	1.99	-	-	-	1.35	-	1.99	-	-	-
		Minimum Drift Level Triggering DS_2	0.62	0.62	0.62	0.62	0.40	0.62	0.62	1.00	0.40	1.00	2.23	1.73	1.66	1.30	2.45	1.04	0.81	0.81	1.00	1.00	0.81	0.62	0.81	0.40	0.40	1.00	0.62	0.81	1.84	1.84	-	1.35	-	1.00	1.26	0.93	1.34
DS_3	Damage Obs.	Damage transverse wall track fasteners/bending flanges	0.62	1.00	0.62	1.16	-	-	1.00	1.00	0.81	-	-	-	-	-	-	-	-	-	0.81	2.32	-	1.00	3.00	1.35	-	1.00	1.99	2.32	0.62	1.00	-	1.84	-	0.62	-	-	-
		Longitudinal wall track fastening failure	-	-	-	-	2.32	2.66	1.84	-	0.62	0.81	-	-	-	-	-	-	1.99	-	-	-	-	1.99	2.15	1.16	0.81	1.84	-	-	1.00	-	-	-	-	-	-	-	-
		Failure connection between walls (partial height)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.84	1.57	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		Field screw popout/rocking (hinge forming in field stud)	-	-	-	-	-	-	-	1.16	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.00	1.35	0.62	-	0.81	0.81	-	-	-	1.99	-	-	-	-	-
		Minimum Drift Level Triggering DS_3	0.62	1.00	0.62	1.16	2.32	2.66	1.00	1.00	0.62	0.81	-	-	-	-	-	-	1.99	1.84	0.81	2.32	-	1.00	1.00	1.16	0.62	1.00	0.81	0.81	0.62	1.00	-	1.84	-	0.62	-	-	-

Table 4. Definition of damage states

Damage State		Description of Damage Associated	Repair Actions
DS_1	Superficial damage to the walls	Cracks along cornerbeads, cracks along joint paper tape, screws pulled out from connections of gypsum boards to steel framing	Cosmetic repairs, including: replacement of cornerbeads, replacement of screws pulled out, replacement of joint paper tape, application of joint compound, sanding, and painting
DS_2	Local damage of gypsum wallboards and/or steel frame components	Crushing of wall corners, out-of-plane bending and cracking of gypsum wallboards at wall intersections, damage of screws connecting wallboards to boundary studs, bending of boundary studs, buckling of diagonal braces (partial height partition walls), damage of gypsum wallboards around ceiling connectors or damage induced by ceiling impact	Local repairs, including: repair or replacement of gypsum wallboards, replacement of boundary studs, replacement of seismic braces, replacement of ceiling connectors
DS_3	Severe damage to walls	Tears in steel tracks around connectors of track to concrete slab, track fasteners passing thru track webs, track flanges bent at wall intersections, hinges forming in studs, partition wall collapse	Replacement of partition wall (Steel framing and gypsum wallboards)

Table 5. Seismic fragility groups

Group	Sub Group	Description
0	0	All specimen data
1	1a	Full-height specimens. Commercial construction practice and slip tracks
	1b	Full-height specimens. Commercial construction practice and partial/full connections
	1c	Full-height specimens. Commercial construction practice (slip tracks and full connection)
2	2a	Full-height specimens. Institutional construction practice and slip tracks
	2b	Full-height specimens. Institutional construction practice and partial/full connections
	2c	Full-height specimens. Institutional construction practice (slip tracks and full connection)
3	3	Partial-height specimens
4	4	Specimens including improved corner details

In Table 6, the values in bold correspond to either damaged or collapsed specimens. In Table 6 it is observed that all collapses of specimens with bookshelves occurred after imposing the peak floor accelerations and peak spectral demands. As previously mentioned, the partition walls that collapsed during testing corresponded to refurbished specimens. Using the ATC-58 framework (Porter *et al*. 2007), experimental fragility curves for displacement and acceleration sensitive partition walls in groups 0 thru 4 were determined. Table 7 summarizes the median, x_m, and logarithmic standard deviation, β, values obtained for all specimen groups. The β values in Table 7 were calculated as $\beta = \sqrt{\beta_r^2 + \beta_u^2}$, where β_r denotes the logarithmic standard deviation of the fragility data, and $\beta_u = 0.25$ accounts for the fact that all specimens experienced the same loading history (Porter *et al*. 2007). Figure 9 shows the final fragility curves calculated from the experimental data, which satisfy the Lilliefors goodness-of-fit test at the 5% significance level.

Table 6. EDP's triggering several damage states in acceleration sensitive walls

Damage State				Specimen ID 37	38	39	40	41	42	43	43b	44	44b	45	46	47
Damage State	DS_1	-	Damage associated to DS_1 could not be identified from the recorded videos and response histories	-	-	-	-	-	-	-	-	-	-	-	-	-
			EDP Triggering DS_1 (N/A)	-	-	-	-	-	-	-	-	-	-	-	-	-
	DS_2	Repairable	Peak Floor Acceleration (average bottom and top platform peak accelerations) (g)	-	-	-	-	-	0.80	-	-	0.81	**0.81**	-	**0.72**	-
			Peak Spectral Acceleration (g)	-	-	-	-	-	4.74	-	-	4.75	**4.73**	-	**4.60**	-
			Peak Specimen Acceleration (g)	-	-	-	-	-	2.06	-	-	1.44	**2.00**	-	**1.73**	-
			Peak Interstory Drift (%)	-	-	-	-	-	3.14	-	-	3.15	**3.15**	-	**0.24**	-
			EDP Triggering DS_2 (Peak Floor Acceleration)	-	-	-	-	-	0.80	-	-	0.81	**0.81**	-	**0.72**	-
	DS_3	Collapse	Peak Floor Acceleration (average bottom and top platform peak accelerations) (g)	0.82	0.81	0.81	**0.80**	0.81	-	0.81	**0.80**	-	-	0.79	-	**0.78**
			Peak Spectral Acceleration (g)	4.72	4.73	4.72	**4.76**	4.72	-	4.72	**4.70**	-	-	4.72	-	**4.71**
			Peak Specimen Acceleration (g)	2.50	2.86	4.11	**2.71**	2.60	-	2.04	**1.39**	-	-	1.72	-	**2.09**
			Peak Interstory Drift (%)	3.19	3.19	3.22	**0.43**	3.14	-	3.15	**0.36**	-	-	3.16	-	**0.39**
			EDP Triggering DS_3 (Peak Floor Acceleration)	0.82	0.81	0.81	**0.80**	0.81	-	0.81	**0.80**	-	-	0.79	-	**0.78**

Table 7. Summary parameters fragility curves

Fragility parameters in terms of imposed interstory drift (%)								
Group	**Sub Group**	**Description**	**DS_1**		**DS_2**		**DS_3**	
			x_m (%)	β	x_m (%)	β	x_m (%)	β
0	0	All specimen data	0.35	0.56	0.69	0.39	1.04	0.55
1	1a	Full-height specimens. Commercial construction practice and slip tracks	0.26	0.45	0.68	0.35	0.75	0.36
	1b	Full-height specimens. Commercial construction practice and partial/full connections	0.27	0.44	0.61	0.41	1.18	0.59
	1c	Full-height specimens. Commercial construction practice (slip tracks and full connection)	0.27	0.43	0.64	0.38	0.96	0.61
2	2a	Full-height specimens. Institutional construction practice and slip tracks	0.36	0.55	0.79	0.34	-	-
	2b	Full-height specimens. Institutional construction practice and partial/full connections	0.40	0.25	0.63	0.43	0.88	0.33
	2c	Full-height specimens. Institutional construction practice (slip tracks and full connection)	0.42	0.31	0.69	0.40	0.98	0.52
3	3	Partial-height specimens	0.74	0.29	1.00	0.33	1.79	0.28
4	4	Specimens including improved corner details	0.34	0.77	-	-	-	-
Fragility parameters in terms of imposed floor acceleration (g)								
Group	**Sub Group**	**Description**	**DS_1**		**DS_2**		**DS_3**	
			x_m (g)	β	x_m (g)	β	x_m (g)	β
0	0	All acceleration sensitive walls tested out-of-plane	-	-	0.70	0.25	0.80	0.25

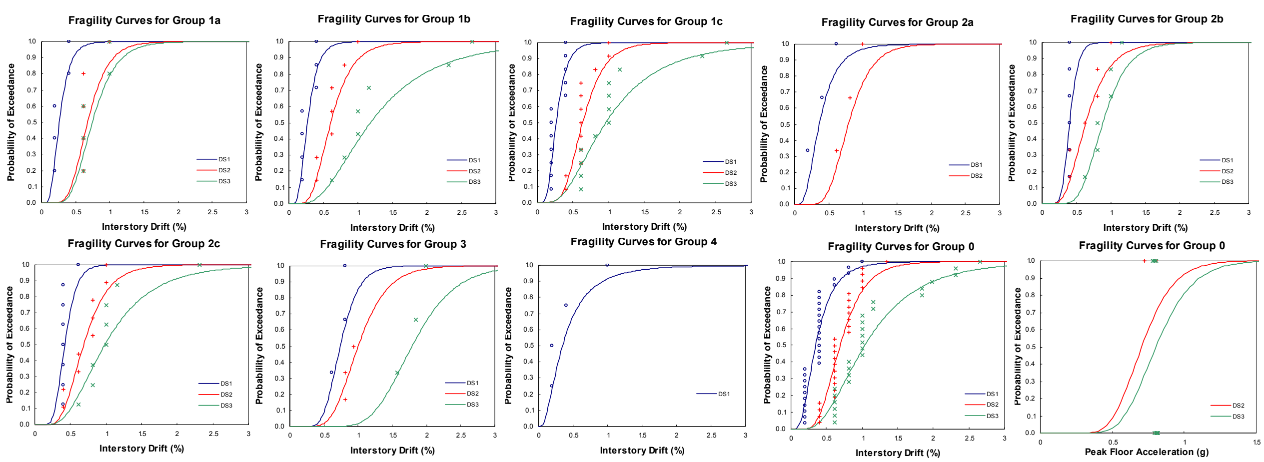


Figure 9. Example fragility curves for partition walls

Conclusions

Partition wall subsystem experiments were performed at the University at Buffalo as part of the NEES Nonstructural Grand Challenge project. The test plan and construction details were selected with close collaboration with the Practice Committee and Advisory Board of NEES Nonstructural. The results of the experiments were used to populate a comprehensive seismic fragility database, to provide input for the design and execution of the system-level experiments to be performed at the University of Nevada, Reno, and to generate the data required for developing analysis tools. During the quasi-static experiments it was observed that using slip tracks and incorporating ¼ to ½" gaps at the top end of the gypsum wallboards reduce the seismic damage of the longitudinal walls and concentrate the damage in the vertical joints between perpendicular walls. No significant difference in the seismic performance of specimens with institutional and commercial construction details was observed. Adding typical bookshelf masses to the partition walls may induce collapse due to cumulative damage effects. Severe damage was observed around the connectors of unbraced ceiling wall moldings to the gypsum boards and in the diagonal braces used in partial height partition walls. In general, significant differences were observed in the seismic performance and failure mechanisms of specimens constructed using identical construction techniques, materials and personnel. This observation is reflected in the high logarithmic standard deviations calculated during the analysis of the experimental fragility data. A series of construction details was proposed to reduce the seismic damage to partition walls. The effectiveness of these improved details was demonstrated through experimentation.

Acknowledgments

This material is based upon work supported by the National Science Foundation under Grant CMMI-0721399. Any opinions, findings, conclusions or recommendations expressed in this document are those of the investigators and do not necessarily reflect the views of the NSF. The input provided by the Practice Committee of the NEES Nonstructural Project, composed of W. Holmes (Chair), D. Allen, D. Alvarez, R. Fleming, and P. Malhotra; by the Advisory Board, composed of R. Bachman (Chair), S. Eder, R. Kirchner, E. Miranda, W. Petak, S. Rose and C. Tokas; and by the other members of the Experimental Group, M. Maragakis (Project PI), A. Itani, G. Pekcan, A. Reinhorn, and J. Weiser, has been crucial for the completion of this research. The collaboration of the UB-NEES site personnel is gratefully acknowledged. The authors are most grateful to Telling Industries for donating the steel studs used in these experiments.

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