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EFFECTS OF NONSTRUCTURAL PARTITION WALLS ON THE SEISMIC PERFORMANCE OF A MEDICAL FACILITY

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ABSTRACT

Contribution of nonstructural partition walls is often assumed negligible in the lateral response of common seismic force resisting systems, however, this assumption becomes un-conservative as the sum effect of individual wall systems are considered. The first phase of the NEES Nonstructural Grand Challenge Project tested full scale light gauge steel studded gypsum partition walls using the University at Buffalo Nonstructural Component Simulator (UB-NCS). Parameters for a tri-linear hysteretic model, aimed at reproducing the in-plane mechanical behavior of partition walls, are determined from the experimentally obtained force-displacement curves. The calibrated partition wall models are combined with the structural model of an existing four story steel moment resisting framed medical facility to demonstrate the effect on dynamic properties. Incremental dynamic analyses, performed according to the ATC-63 methodology, show that including the contribution of steel studded gypsum partition walls to the lateral force resisting system increases the building collapse safety margin.

Introduction

The NEES Nonstructural Grand Challenge Project: "Simulation of the Seismic Performance of Nonstructural Systems" aims to improve the seismic performance of buildings through analyzing, testing, and modeling of common nonstructural systems (ceilings, piping systems, and partition walls). The first phase of this project, emphasizing on nonstructural partition walls, was conducted at the University at Buffalo, using the Nonstructural Components Simulator (UB-NCS) shown in Figure 1a (Mosqueda *et al*. 2007). Fifty full scale light gauge steel studded gypsum partition wall specimens were tested. Thirty-six of them were tested in-plane, while the other fourteen were tested out-of-plane. Figure 1b shows an example of a wall

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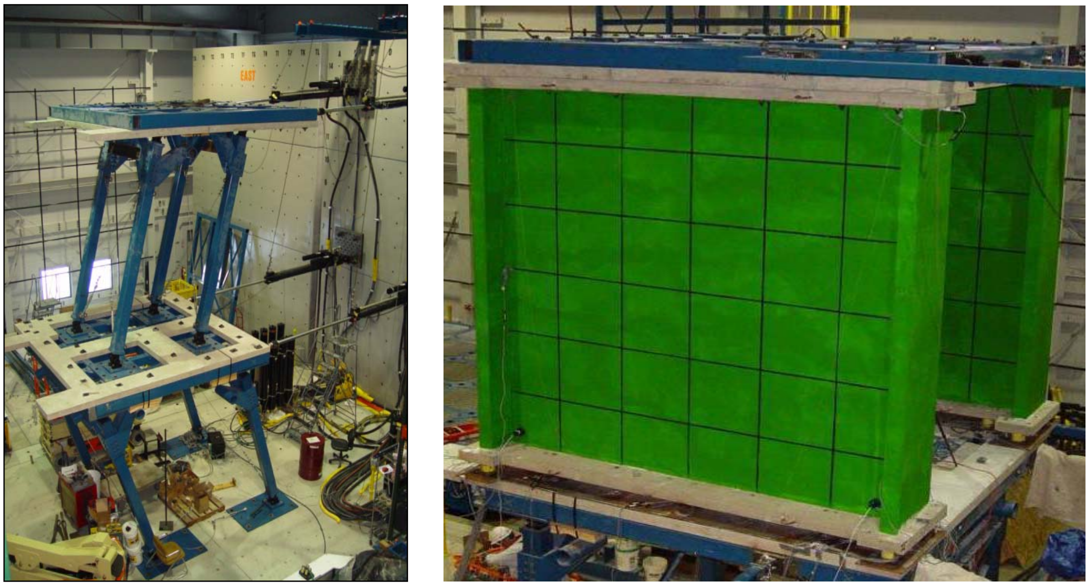
specimen in typical configuration for in-plane testing. Walls were subjected to quasi-static and dynamic protocols to assess their seismic fragility (Retamales *et al*. 2008).



(a) (b)

Figure 1. Photos of the UB-NCS: (a) Bare test frame; and (b) Full-scale partition wall specimen for in-plane testing

Sixteen different wall configurations for in-plane testing, as shown in Table 1, were developed by the experimental team at UB in coordination with the Practice Committee and Advisory Board of the NEES Nonstructural Grand Challenge Project. The partition walls are categorized into the six groups shown in Table 1, based on similar detailing and observed mechanical response. The group categories are: Commercial Slip Track (Group 1a); Commercial Full Connection (Group 1b); Institutional Slip Track (Group 2a); Institutional Full Connection (Group 2b); Partial Height (Group 3); Improved Details (Group 4).

Slip track and full connection configurations vary in the connection of studs and gypsum boards to the top and bottom tracks. The primary differences between the commercial and institutional configurations is the thickness of steel framing material, respectively 18 and 30 mils (0.48mm and 0.79mm), and the typical details of wall intersections. Partial height walls are 8 ft (2.44m) tall with diagonal braces stabilizing the walls. Improved details are special designs developed and tested to offset damage states to higher drift ratios or remove them completely.

Partition Wall Performance

Displacement controlled quasi-static and dynamic protocols were used to load the partition walls. Figure 2 shows typical force-displacement plots of one wall specimen representative of each of the six groups. From Figure 2, Groups 3 and 4 had the lowest energy dissipation, whereas institutional full connection partition walls exhibited the highest resistance to drift. Often times, the measured data showed an increase in stiffness at the 2% drift ratio, caused by racking of the gypsum boards.

Table 1. Summary of tested partition wall configurations.

Group	Config	Specimen ID	Specimen Description	Loading Direction/Rate	Steel Stud Type	Stud to Bottom Track	Steel Frame and Sheathing Connectivity					
							Stud to Top Track	Gypsum to Bottom Track	Gypsum to Top Track	Return Walls	Attached Mass	Ceiling Connected
1a	1	1, 2 & 3	Basic (slip track)	In plane/static	350S125-18	No	No	Yes	No	Yes	No	No
1b	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
1a	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
3	7	17, 18 & 19	Partial height braced wall	In plane/static	350S125-18	Yes	Yes	Yes	Yes	Yes	No	No
2a	8	20, 21 & 22	Institutional const./slip track	In plane/static	350S125-30	Yes	No	Yes	No	Yes	No	No
2b	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
1a	11	29 & 30	No Return	In plane/dynamic	350S125-18	No	No	Yes	No	No	Yes	No
	12	32 & 32	C-Shaped Walls	In plane/static	350S125-18	Yes	No	Yes	No	Yes	No	No
4	13	33	Solution to T corner damage/corner gaps	In plane/static	350S125-18	Yes/No	No	Yes/No	No	Yes	No	No
	14	34	Solution to T corner damage/double slip track	In plane/static	350S125-18	Yes/No	No	Yes/No	No	Yes	No	No
	15	35	Solution to L corner damage/corner gaps	In plane/static	350S125-18	Yes/No	No	Yes/No	No	Yes	No	No
	16	36	Solution to T corner damage/slip track	In plane/static	350S125-18	Yes/No	No	Yes/No	No	Yes	No	No

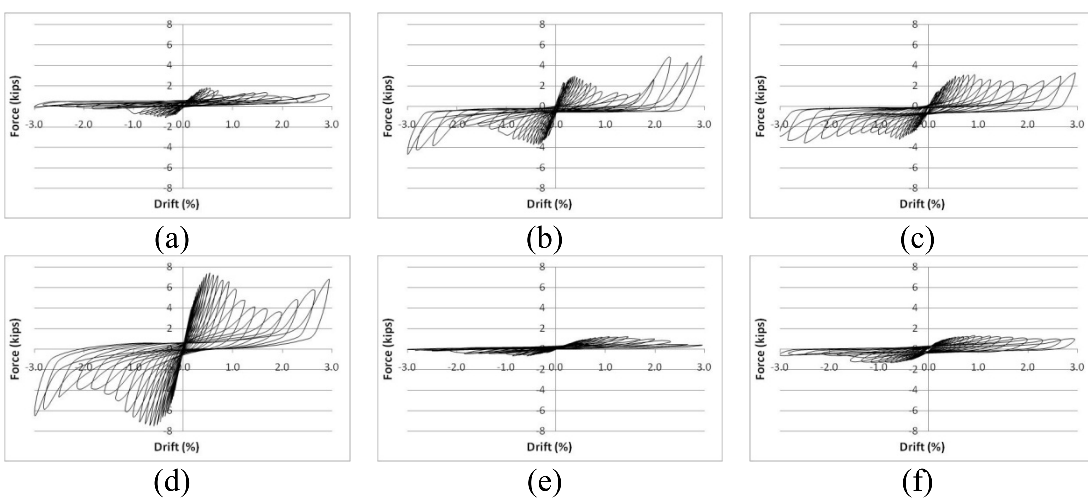


Figure 2. Hysteretic Response: (a) Group 1a – Specimen 3; (b) Group 1b – Specimen 4; (c) Group 2a – Specimen 21; (d) Group 2b – Specimen 27; (e) Group 3 – Specimen 19; and (f) Group 4 – Specimen 34. (1 kip = 4.45 kN)

Damage observed in the partition walls was mainly concentrated at wall intersections. Initial damage observations included rocking of screws attaching the gypsum to the top and bottom tracks, openings at wall intersections, and crushing of gypsum at wall corners. Higher levels of damage to the partition walls included bending and cracking of gypsum at wall intersections and bending in boundary studs. The most severe damage observed included tearing in steel tracks around concrete fasteners, fasteners pulling through tracks, bending in top track flanges of transverse walls, and hinges forming in studs. Further details on the damage observations can be found in Retamales *et al*. (2010).

Parameterizing Partition Wall Hysteretic Behavior

The recorded data exhibit three important characteristics. First, stiffness and strength degradation with increased displacement, and third, 'pinching' behavior as loads are reversed. The behavior of these wall specimens closely resembles the behavior of wood shear walls. Wayne Stewart (WS) developed a hysteretic model (Figure 3) with tri-linear behavior and pinching effects to simulate wood shear wall behavior (Stewart 1987). The nine hysteretic model parameters shown in Figure 3 were determined through least square regression fitting techniques on the force-displacement curves for each of the 36 test specimen.

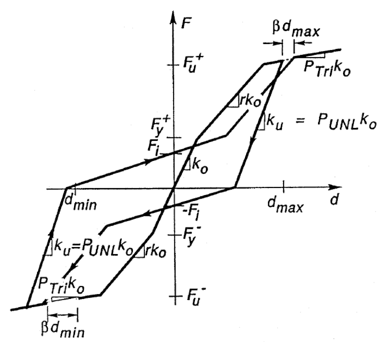


Figure 3. Wayne Stewart hysteretic model (Taken from Carr 2005).

The stiffness and force parameters per linear foot of an 11'-5" (3.48 m) story height are given in Table 2 for each of the groups. In an effort to simplify assignment of the parameters, the initial stiffness (k_0) and strength parameters, yield (F_y) and intercept (F_i) forces, are related to the readily available maximum (capping) force (F_u) for all wall specimen. Figure 4 plots the histograms for these ratios. Figure 4a shows the histogram of capping force by group. The unloading factor (P_{UNL}) had a mean value of 0.97. However, the WS model limits this factor to ≥1.0, therefore, this factor is set equal to the minimum 1.0. Table 2 also gives the 'simplified' parameters to use in simulating the response of the partition walls under Group 0 (all specimens).

Table 2. Wayne Stewart hysteretic model parameters per linear foot.

Group	k_0 (kips/in (kN/mm))	r	P_{tri}	P_{UNL}	F_y (kips (kN))	F_u (kips (kN))	F_i (kips (kN))	β	α	F_y/F_u	F_i/F_y	k_0/F_y
0	-	0.37	-0.24	0.97	-	-	-	1.07	0.64	0.70	0.09	2.05
1a	0.22 (0.04)	0.48	-0.21	0.93	0.07 (0.31)	0.11 (0.49)	0.01 (0.05)	1.09	0.73	-	-	-
1b	0.6 (0.11)	0.33	-0.26	0.79	0.2 (0.88)	0.27 (1.19)	0.01 (0.07)	1.07	0.51	-	-	-
2a	0.46 (0.08)	0.29	-0.19	1.04	0.16 (0.72)	0.25 (1.11)	0.02 (0.1)	1.08	0.60	-	-	-
2b	1.26 (0.22)	0.28	-0.19	0.91	0.46 (2.05)	0.62 (2.76)	0.03 (0.15)	1.04	0.50	-	-	-
3	0.11 (0.02)	0.38	-0.39	1.00	0.05 (0.24)	0.09 (0.38)	0.01 (0.02)	1.05	0.63	-	-	-
4	0.11 (0.02)	0.32	-0.27	1.38	0.05 (0.22)	0.07 (0.31)	0.01 (0.05)	1.05	0.88	-	-	-

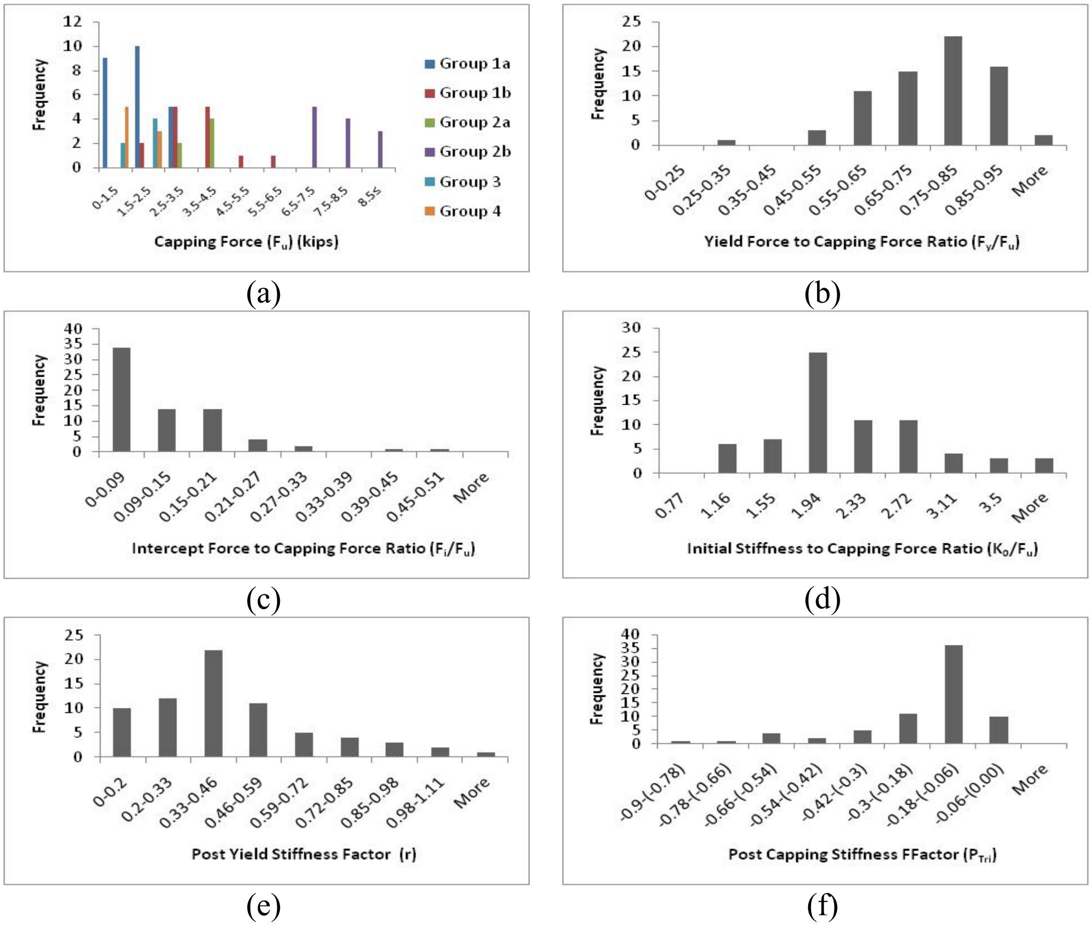


Figure 4. Histograms for: (a) Capping force by group; ratio of (b) yield force, (c) intercept force, and (d) initial stiffness to capping force; stiffness factors (e) post yield and (f) post capping. (1 kip = 4.45 kN)

The mean parameters obtained for each wall group (i.e., Group 1a, 1b, 2a, 2b, 3, and 4) and the mean parameters correlating to capping force (Group 0), were assigned to a shear spring element exhibiting the Wayne Stewart hysteretic behavior. The shear spring was modeled within a single degree of freedom elastic frame and subjected to a displacement protocol similar to the quasi-static protocol used in the full scale tests. Hysteretic response was evaluated and the error in estimated dissipated energy were minimized through a parametric analysis of the pinching (α) and softening (β) factors up to a drift ratio of 2% (neglects increase of forces from racking). The respective values of 0.64 and 1.07 were chosen for these factors. Figure 5 shows a comparison of the measured and predicted hysteretic response for two wall specimens along with their respective dissipated energy per cyclic peak for the individual group parameters and for the model using Group 0 (simplified) parameters. For each of the models, the individual group parameters better represent the partition wall systems. The models using simplified parameters do have a higher error in dissipated energy, however, because these parameters are solely dependent on F_u perhaps the increase in error is justifiable.

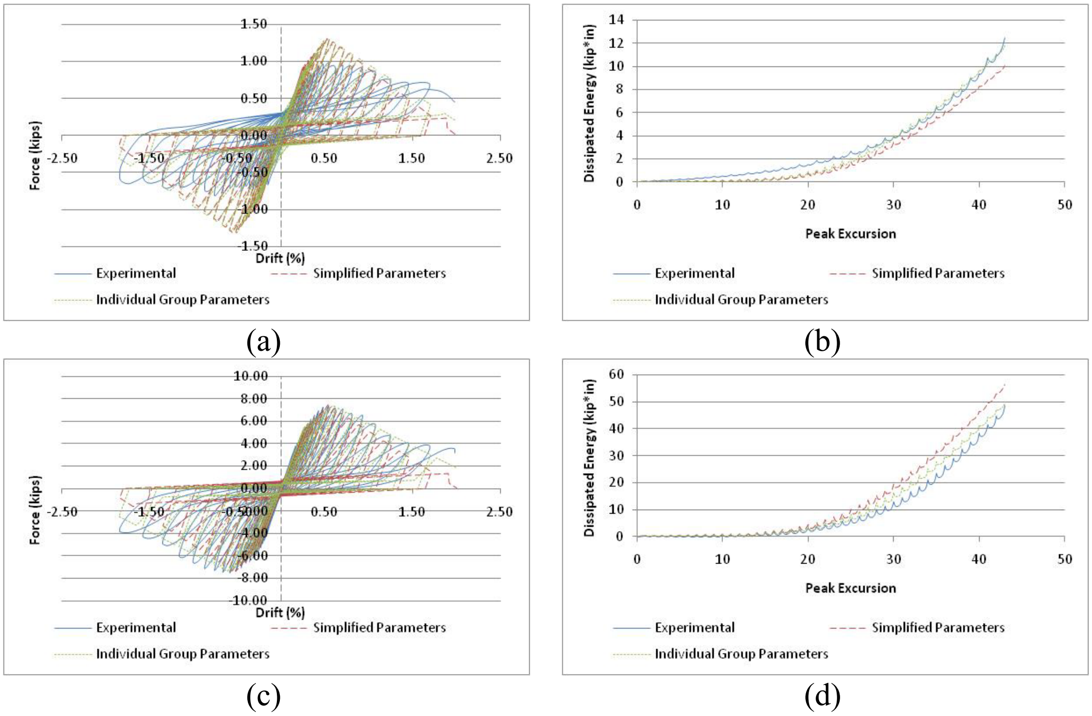


Figure 5. Specimen 31 (a) hysteresis curves and (b) dissipated energies; and specimen 27 (c) hysteresis curves and (d) dissipated energies.

Effects of Walls on Dynamic Response

The steel studded gypsum partition walls in most commercial applications are considered nonstructural systems. Individual nonstructural partition walls have little to no effect on the lateral force resistance. However, totaling length of partition walls in a given story, the cumulative stiffness's and forces can be sufficient to contribute to the structures' seismic force resisting system. To evaluate this effect, a RUAUMOKO building model of an existing four story steel moment resisting medical facility (Wanitkorkul and Filiatrault 2008), was modified to include partition walls. The RUAUMOKO building models using shear springs simulating group 1a and 2b partition wall behaviors are added at each level. Stiffness and force parameters for the WS model in Table 2 are linearly scaled based on the total length of partition walls at each floor level, model interstory height and test specimen height are assumed equal. The total length of partition walls were estimated based on architectural drawings of the building under investigation.

Dynamic Properties

Addition of the partition walls to the building model, depending on the wall system considered, can influence the building dynamic behavior. Because of the added stiffness to the structure, and given that partition wall mass has already been considered in the building design, a reduction is observed in the fundamental period of the structure. Reductions of 3% to 12%, from 0.76 sec to 0.74 sec and 0.67 sec, are observed in the fundamental vibration period of the structure when commercial slip track and institutional full connection partition walls are considered, respectively. The models including the improved details and partial height walls had a period reduction of only 1%. Also considered in the dynamic analysis of the structures is the amount of added damping due to the increase in stiffness. To determine the damping ratio each building model was subjected to high impulse accelerations, maintaining elasticity in all structural members, the top floor displacement was measured during free vibration. Using the logarithmic decrement the damping ratio for the building models were found to increase from 2.26% to 2.29% in the models with low dissipating energy partition walls (i.e., partial height and improved details) to 2.43% in the model with the highest energy dissipation (i.e., institutional full connection).

Dynamic Responses

The building models were subjected to three arbitrary historical earthquakes: the North-South component of the 1940 El Centro earthquake as well as the LA14 and LA16 records from the SAC Joint Venture Project (SAC 1997). The envelope interstory drift and absolute floor accelerations were measured for both the Design Earthquake (DE), 10% probability of exceedance in 50 years, and the Maximum Considered Earthquake (MCE), 2% probability of exceedance in 50 years. Figure 7 shows these responses for each of the buildings under the LA14 and LA16 MCE ground motions. The impact of the partition walls on the maximum absolute floor acceleration is shown in Figure 7b, where the acceleration increases by 23% in the top story from 1.02g to 1.25g for the institutional full connection partition walls. Under the LA16 MCE this same building model has an increase of peak absolute floor acceleration of only 8%, whereas the maximum interstory drift decreases 28% from a 0.6% drift ratio to 0.43%. Figure 8 shows a plot of the total kinetic and strain (including hysteretic) energy time histories for three building models (original building, commercial slip track (ST), and institutional full connection (FC)) under the LA14 MCE record. In the original building no hysteretic energy is observed, however an increase in energy levels in the other building models occurs as yielding occurs in the nonstructural partition walls.

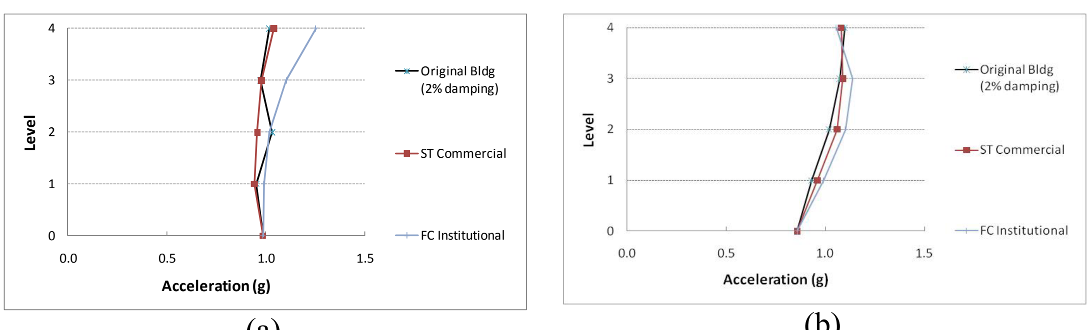


Figure 7. Peak absolute floor accelerations for: (a) LA14 MCE; and (b) LA16 MCE.

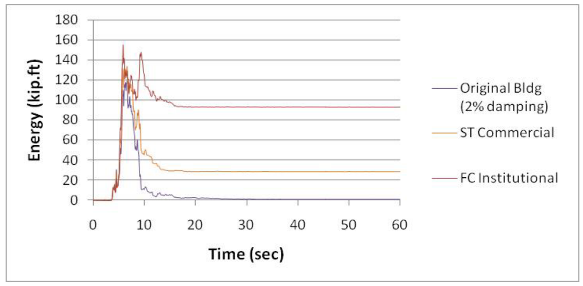
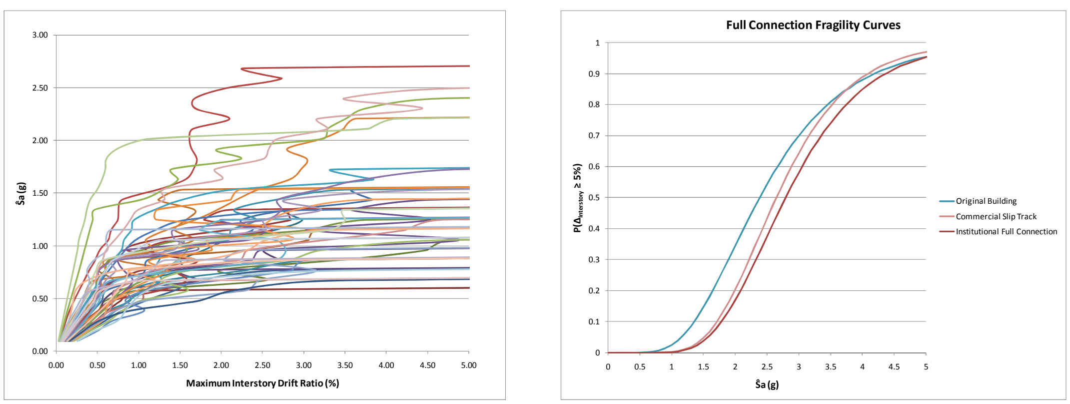


Figure 8. Strain and kinetic energy for LA14 MCE.

ATC-63 Analysis

The FEMA P695 (ATC-63) methodology found in the "Quantification of Building Seismic Performance Factors" document (FEMA 2009), subjects building models to a modified Incremental Dynamic Analysis (IDA) for 44 pre-determined ground motions. The median spectral acceleration $\hat{S}_{CT}$ of the ground motions that cause building collapse in 50% or more scaled earthquakes is compared to the MCE spectral acceleration given in ASCE 7 (ASCE 2006). The median collapse spectral acceleration, overstrength and period based ductility factors obtained from a pushover analysis, and assigned levels of uncertainty for design requirements, test data, and model quality are used to compare acceptable levels of collapse probability. The individual building model (index archetype) must have a collapse probability less than 20% to meet the requirements of the ATC-63 methodology for an acceptable lateral load-resisting system.



(a) (b)

Figure 9. (a) Incremental dynamic analysis curves for commercial slip track and (b) cumulative distribution plot for buildings with steel strength degradation at 0.02 rad.

The three base nonlinear building models (original building, commercial slip track, and institutional full connection) were analyzed according to the ATC-63 methodology. Three building models from the base models are developed considering an onset of strength degradation at hinge rotations of 0.01, 0.02, and 0.03 radians in steel columns and beams. Figure 9 is a plot of maximum interstory drift versus spectral accelerations. Each line in the figure corresponds to one of the 44 ATC-63 ground motions and traces the increase of maximum drift as the ground motion is increased in intensity (e.g., IDA curve). The curve for the commercial slip track partition wall with strength degradation occurring at 0.02 radians is shown. As shown in the cumulative distribution plot in Figure 10 for each of the building types using 0.02 radians as the strength degradation parameter, including the nonstructural partition walls causes an increase in the median collapse spectral acceleration.

ATC-63 uses the Adjusted Collapse Margin Ratio (*ACMR*) to estimate the collapse performance. The ACMR is the ratio of median collapse spectral acceleration to the ASCE 7 MCE spectral acceleration, multiplied by the Spectral Shape Factor (SSF), which accounts for the level of uncertainty in ground motions and system ductility. The ACMR for each of the building models needs to exceed the maximum *ACMR20%* values given in the ATC-63 methodology. According to this methodology, the addition of the partition walls into the lateral force resisting system reduces the collapse probability of the studied four story steel moment frame. Each of the building models exceed the *ACMR20%* values except for the original building model which had an *ACMR* of 1.60 compared to an *ACMR20%* of 1.66, therefore the collapse probability of this structure is higher than the requirements proposed in the ATC-63 methodology.

Table 2. ATC-63 methodology results

Plastic Rotation (rad)	ACMR/ACMR20%			Collapse Performance (Pass/Fail)		
	Original Building	Slip Track	Full Connection	Original Building	Slip Track	Full Connection
0.01	1.60/1.66	2.09/1.66	2.36/1.73	Fail	Pass	Pass
0.02	1.78/1.66	2.24/1.73	2.67/1.73	Pass	Pass	Pass
0.03	1.91/1.73	2.47/1.73	3.00/1.73	Pass	Pass	Pass

Conclusions

Results from testing of nonstructural light-gauge steel studded gypsum partition walls as part of the NEES Nonstructural Grand Challenge Project were parameterized into the Wayne Stewart hysteretic model. Parameters according to similar wall configurations are recommended. Factors associating stiffness and strength parameters to capping forces were given to simplify the modeling of partition walls. Wall systems were simulated using a nonlinear shear spring element at each level of an existing steel moment frame four story medical facility building model. Dynamic characteristics for the models including the partition walls show a decrease of over 11% in the natural period from the original structure (without considering partition wall stiffness), which corresponds also to an 8% increase in damping. Analysis shows that an increase is observed in the maximum absolute floor acceleration under two different MCE ground motions. According to the ATC-63 methodology, including the nonstructural steel studded gypsum partition walls in the analysis of a lateral force resisting system decreases the collapse margin of safety by 60%. The results from this study show that neglecting nonstructural partition walls in the seismic analysis of steel buildings underestimates the increased amplitude of absolute floor accelerations and increases the collapse probability, suggesting the need of including these walls in the lateral analysis to better predict the performance of building systems in seismic events.

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