A Numerical Model for Capturing the In-Plane Seismic Response of Interior Metal Stud Partition Walls: Preliminary Coupled Analysis

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SUMMARY:
A commonly used nonstructural system in building construction is an interior partition wall. Using experimental data from the National Science Foundation and Network for Earthquake Engineering Simulation (NEES) Nonstructural project, an experimentally verified partition wall numerical model is developed using Open System for Earthquake Engineering Simulation (OpenSees) for capturing the in-plane seismic response of full-height partition walls.

The partition wall is developed as a lumped model, discretized as a zero-length element using a pinched material in a parallel configuration. To demonstrate the effect of partition walls, a coupled analysis was implemented in an eight story reinforced concrete building. The effects of the coupled system are demonstrated through eigenvalue analysis, nonlinear pushover curves, and nonlinear time history analysis. Nonlinear time history analysis considered realistic earthquake motions and demonstrated the effects of the coupled system through floor level acceleration and interstory drift.

Keywords: nonstructural components, partition walls, numerical modeling, time history analysis

1. INTRODUCTION

Partition walls are an example of a nonstructural component and system (NCS) within a building which are not designed nor anticipated to contribute to the primary load bearing system of the building. Nonetheless, they are subjected to the dynamic environment of the building and undergo seismic loading, an amplified and filtered ground motion transmitted by the building (BSSC 2000; Villaverde 2009). A partition wall is connected to multiple attachment locations within the building, inducing differential displacement demands which vary throughout the building. When NCSs are stiff and heavy enough, they may modify the response of the building structure. In this case study, the partition wall model and the building structure are considered as a combined system to effectively demonstrate the effect of a partition wall on a coupled building system response.

1.1. Modeling Overview Background

The following section briefly introduces past efforts on relevant lumped numerical modeling efforts to studying gypsum partition walls and its effect on buildings. The focus is directed towards idealized hysteretic behavior with simplistic rules while reliably representing the experimental behavior. Ibarra et al. (2004) postulated that hysteretic models on various materials are capable of simulating the main characteristics of an experimental specimen. A pinching model was identified as an ideal model to capture the hysteretic behavior of a plywood shear wall. Folz and Filiatrault (2004) developed a numerical model to predict the dynamic characteristics, quasi-static pushover and seismic response of woodframe buildings. Their approach targeted a shear spring element to reduce computational demands by creating a cyclic analysis of shear wall models (CASHEW), based on the Wayne-Stewart hysteresis model (Stewart 1987). Kanvinde and Deierlein (2006) proposed analytical models to determine the strength and stiffness of wood-framed gypsum panels accounting for the effects of wall geometry, door or window openings, connector type and spacing, and boundary conditions. Their focus was limited to partition walls constructed of gypsum board on wood framing, while recommending broader extension to partition walls framed with light-gauge steel studs.

Restrepo and Lang (2011) characterized the gypsum board partition response in a linear piecewise function, where the lateral force value of the wall was normalized by the wall length. Davies (2009) developed representative hysteretic models of in-plane partition walls using a shear spring and the Wayne-Stewart model. Hysteretic behavior followed a tri-linear relationship where the ratcheting effect was not considered. Davies examined the effect of including partition walls in a four story steel hospital building under three ground motions, finding a period shift up to 11% in the fundamental mode, an increase in equivalent damping, significant changes in the floor level acceleration at the top floors, and improvement in collapse performance under the FEMA P695 (ATC-63) project (ATC, 2009a).

In this work, a strength degrading pinched hysteretic model was developed to more closely capture the behavior of the partition walls measured in a recent experimental program (Davies, 2009). The calibrated partition wall model provides pinching characteristics as a function of displacement, capturing the post-peak hardening experienced in the experimental setup, and uses a set of four springs in a parallel configuration to closely capture the cumulative hysteretic energy. The effect of the partition wall inclusion in this case study of an eight story building was assessed using a set of 22 ground motions and examining the response in terms of interstory drift and floor level accelerations.

2. PARTITION WALL NUMERICAL MODEL

Using experimental data generated from the NEES-Nonstructural Project (Davies, 2009), a lumped numerical model was developed for capturing the in-plane seismic response of full-height gypsum board on cold-formed steel framed partition walls. The calibration of this model involved minimizing the error between measured and numerically predicted hysteretic energy and force. Additional details regarding the model calibration may be found in Wood and Hutchinson (2012). The behavior of the partition wall was realized using a discrete model localized within a simple nonlinear zero-length spring capable of capturing the global force-displacement response. The lumped model characteristics were calibrated by analyzing a large suite of experimental data on institutional and commercial categorized metal stud walls.

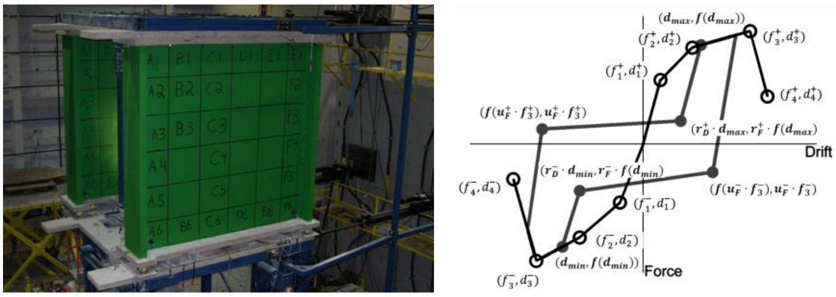
2.1. Experimental Overview

Fifty wall specimens were tested at the State University at New York, University at Buffalo (UB) with details directed by a group of industry practitioners familiar with common design configurations. The partition walls were approximately 11.5 feet tall by 12 feet long with return walls (perpendicular to the loading direction) of either 2 or 4 feet (Davies, 2009). The wall specimens were placed in the upper level of the Nonstructural Component Simulator (UB-NCS), shown with one of the partition wall experiments in Figure 1a. The UB-NCS is a full scale two story frame loading system capable of reproducing motions in terms of acceleration and displacement between adjacent floor levels (Mosqueda et al., 2009).

2.2. Model Formulation and Platform

The platform selected to model the partition walls is OpenSees, developed by the Pacific Earthquake Engineering Research (PEER) Center (Mazzoni et al., 2009). OpenSees is an open-source numerical platform based on finite element modeling that provides the capabilities to perform advanced nonlinear time history analysis of buildings, bridges and other structural systems. However, it does not have tools available for modeling nonstructural components and systems. To capture the nonlinear hysteretic behavior of the partition wall, a lumped material is assigned to a zero-length one degree-of-freedom element. The lumped material behavior is created using the *pinching4* material (Figure 1b).

Pinching4 is a uniaxial material model that allows for a “pinched” load-deformation response with an optional degradation contribution. To best represent the experimental specimens, this *pinching4* material is used in a parallel configuration providing better control of the unload and reload parameters as a function of the displacement range. Specific parameter definitions as adopted in this model are presented in Wood and Hutchinson (2009).To illustrate the model performance, an example specimen is shown for an institutional style construction as (refer to Davies, 2009 for specific details). Two key steps are required for the model development: 1) experimental force-displacement backbone and 2) the unloading and reloading parameters calibrated against the cumulative hysteretic area. Figure 2 illustrates the model performance for capturing the global behavior of the partition wall. Additional details on the partition wall calibration can be found in Wood and Hutchinson (2012).



(a) (b)

Figure 1. (a) Typical in-plane partition wall setup and b) Graphical description of the pinching4 material model.

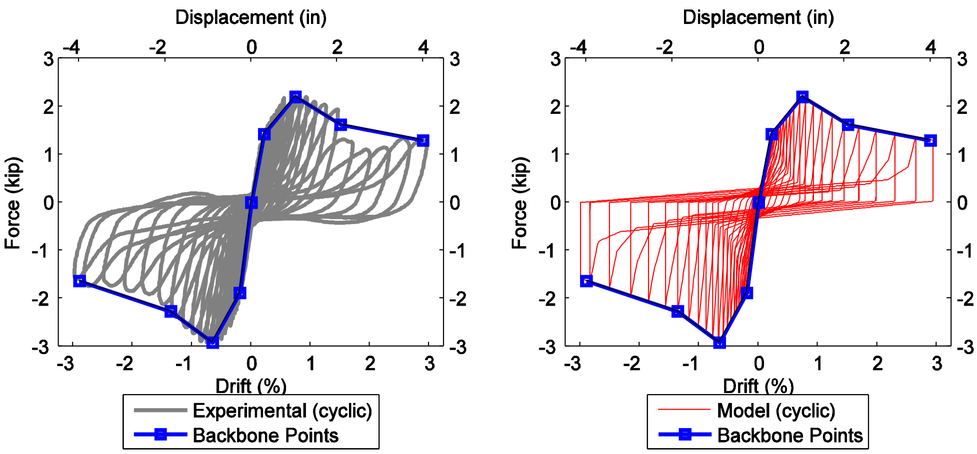


Figure 2. Experimental and numerical model comparison for specimen 20.

2.3. Developed Models

Ideally, each experimental specimen should have a detailed numerical model. However, it is more practical to develop representative models of specimens to capture their mean response and assess their variability. Two classes of models were developed, a subgroup model based on their mechanical configuration which drives their physical behavior and a normalized model to characterize the experimental variability of the wall specimens in terms of the force response through a mean, mean plus one standard deviation and mean minus one standard deviation models. In addition to exploring the experimental variability, the main advantage of the normalized model is that, the sum of the thicknesses of the stud webs in the lateral direction is a controlling parameter on the partition wall response; typically dictated by building occupancy and wall length. For this case study, the normalized model was selected. The mean response is shown in Figure 3.

3. PARTITION WALL IMPLEMENTATION

The lumped partition wall model was placed into a larger numerical building model. The first issue to address was the connectivity to building model. The second issue involved extending the developed partition wall model to account for walls of different lengths.

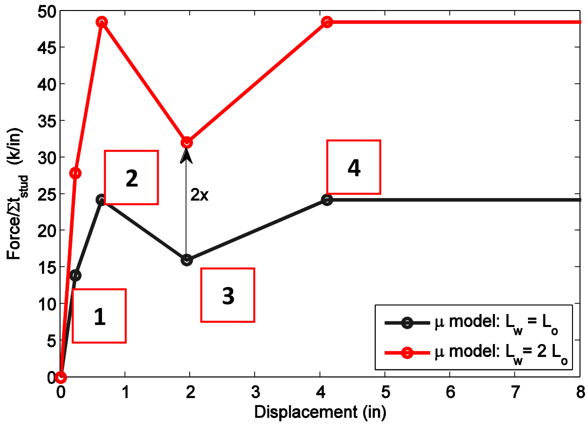


Figure 3. Example of the average normalized partition wall model. Scaling example, described in section 3.2.

3.1. Placement in Building Model

The connection configuration is shown in Figure 4, where the partition wall is connected to the structural model, spanning the beam midpoints between adjacent floor levels using slaved degrees-of-freedom (equalDOF command) to simulate rigid members. The boundary conditions for the intersections at the beam midpoints for the fully connected partition wall models are modeled by restraining the two lateral displacement and one rotational degrees of freedom at both the top and bottom nodes for a two dimensional model. This simplistic model allows for the partition wall to be lumped at the story mid-height and bay width, neglecting any torsional effect if placed in a three dimensional model.

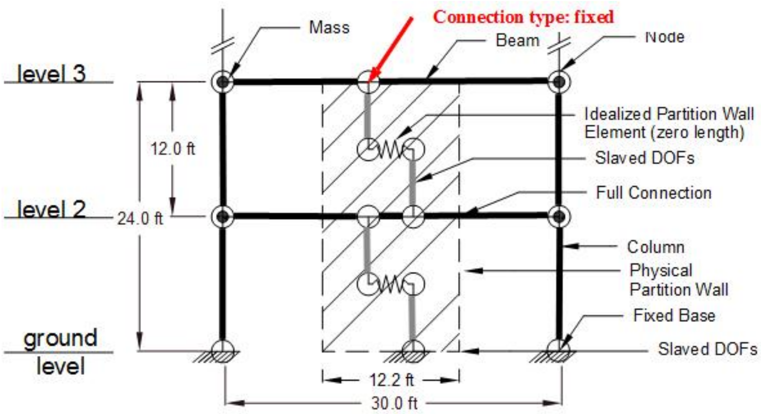


Figure 4. Partition wall implementation between two adjacent story levels.

3.2. Scaling Rules

After the walls are placed between the building floor levels, the method to represent walls of various lengths was assessed. To account for walls of different lengths, the four backbone points of the partition wall were configured to estimate the effect. The initial stiffness and maximum force, controlled by the first two points are adjusted by the total number of studs and stud thickness for a given partition wall.

The post-peak behavior (point 3) of the partition wall system was not well behaved for most of the tested partition wall systems. Degradation of the wall load carrying capacity does occur for displacement values in excess of the maximum force, and since no other justification exists, it is assumed to be linearly scaling. The post-yield hardening characterized by 4th backbone point is largely controlled by the damage characteristics. The post-yield hardening is envisioned to physically occur if the gap between the ceiling and drywall panel or return wall and drywall panel closes. This post-yield hardening does not always occur, but this physical behavior was realistic. Consequently this behavior was not neglected in the model. This post-yield hardening had not been considered in previous studies (Davies, 2009 and Restrepo et al., 2011).

4. PARTITION WALL-BUILDING SYSTEM

To demonstrate the partition wall implementation and study its impact on buildings, an eight story reinforced concrete building is selected. This case study building comes from a larger simulation study where partition walls were placed in a series of nine buildings. These nine buildings considered either steel or reinforced concrete style construction, have either an occupancy use of general office or hospital; and range from 2-20 stories in height (Wood and Hutchinson, 2012). The details on the eight story building follow.

4.1. Eight Story Building Model

The eight story building had a footprint of 150 feet by 120 feet with five bays in each direction. The building dimensions were chosen to have a longitudinal bay width of 30 feet, transverse bay width of 24 feet and story height of 12 feet. The building was assumed to have adequate foundation support and assumed fixed at its base. Design and analysis was conducted for the longitudinal direction. A short design summary is presented in Table 1, with complete details provided in Wood et al. (2009).

Table 1. Building design summary.

Member	Floor Levels	b (in)	h (in)	f'_c (ksi)	Longitudinal Reinforcing	ρ_l (%)	Confinement
8st-beam1	1-4	30	30	5	12 - #9s	1.34	#5 @ 5.5"
8st-beam2	5-8	26	30	5	10 - #9s	1.28	#5 @ 6.0"
8st-column	all	32	32	6	20 - #10s	2.67	#5 @ 4.0"

The building model was discretized using the *BeamWithHinges* element, developed by Scott and Fenves (2006). This element was selected because it performs well for members anticipated to undergo reasonably localized nonlinear deformation as well as softening or degradation of the material. This element is developed as a force-based, lumped plasticity, zero-volume line element with two different sections: a fiber section at each end, which represents the plastic hinge over a discrete length l_p, estimated using Paulay and Priestley’s (1992) model, and an interior linear elastic section. Within the fiber sections, the confinement effects were accounted using the model of Mander et al. (1988a, 1988b).

4.2 Wall Lengths

One method to determine representative wall lengths is based on partition indices. French and Xu (2010) determined partition indices by analyzing three model building blueprints and compared their findings to that proposed in ATC-58 (ATC, 2009b). The partition index is a takeoff quantity defined as the total lineal feet of partition walls per floor divided by the floor area ($L/L^2 = 1/L$). To explore the full range of partition wall lengths, commonly observed, herein the upper and lower bound values are utilized (0.07-0.13 1/feet). Knowing the details of each of the building plans, the corresponding partition wall lengths are estimated assuming the walls are proportional to the building geometry and the tributary area of an interior frame. Using these partition indices results, two partition wall lengths, L_{min} and L_{max}, are calculated. For the eight story building, the total in-plane wall lengths are 56 and 104 feet.

5. CHARACTERISTICS OF THE PARTITION WALL-BUILDING SYSTEM

To assess the effect of coupling the partition wall with the building, two lengths of the partition walls were considered and placed equally at every floor level. To explore the variability which existed in the experimental testing, the normalized model was considered where the mean and the mean plus/minus standard deviation responses are evaluated. The effects of coupling the partition wall with the building model were assessed using three methods: eigenvalue analysis, nonlinear pushover curves, and nonlinear time history analysis.

5.1. Eigenvalue Analysis

In the eigenvalue analysis, modal frequencies (periods) and mass participation factor estimates for the first four modes were obtained. In Table 2, the periods and mass participation factor estimates are shown for bare structure (no wall) and the short and long walls placements considering each of the normalized models: mean, mean minus one standard deviation, and mean plus one standard deviation. To simplify the comparison, normalized period (T^*) and normalized mass participation factor (MP^*) are calculated and used to demonstrate the dynamic shift when considering the addition of partition walls to the bare frame system (no wall):

$$T_i^* = \frac{T_i^n}{T_i^{bare}} \tag{5.1}$$

$$MP_i^* = \frac{MP_i^n}{MP_i^{bare}} \tag{5.2}$$

where the period of the structure with the wall (T_i^n) is divided by the period of structure without a wall (T_i^{bare}) in the i^{th} mode. In addition, the mass participation factor (MP_i^n) of the structure with the wall is divided by the mass participation factor of structure without a wall (MP_i^{bare}) in the i^{th} mode.

Table 2. Modal periods and mass participation factor sensitivity.

			Mean		Minus Standard Deviation		Plus Standard Deviation	
	Mode	No Wall	56 feet	104 feet	56 feet	104 feet	56 feet	104 feet
Period (s)	1	0.784	0.748	0.724	0.755	0.735	0.742	0.714
	2	0.241	0.233	0.226	0.234	0.229	0.231	0.224
	3	0.126	0.122	0.120	0.123	0.121	0.122	0.119
	4	0.079	0.077	0.076	0.078	0.077	0.077	0.076
Mass Participation (%)	1	0.784	0.787	0.789	0.787	0.788	0.788	0.790
	2	0.106	0.105	0.105	0.106	0.105	0.105	0.105
	3	0.043	0.042	0.041	0.042	0.042	0.042	0.041
	4	0.027	0.026	0.026	0.026	0.026	0.026	0.026

The illustration of these normalized parameters is shown in Figure 5. Note that the y-axis range for Figure 5 is 0.85 to 1.0 and 0.95 to 1.05 for T^* and MP^*, respectively. When one considers the use of the mean minus a standard deviation, the period shift on the building is reduced, as the stiffness of the wall is reduced. This statement holds true as well when considering the mean plus a standard deviation, as the period shift is increased. However the degree to which this dynamic shift occurs is most influenced by length of the wall. The greatest period shift of 8% is found under the long wall and the mean plus one standard deviation representative model. Changes on mass participation factor are minimal, within ±5%.

5.2. Nonlinear Pushover Analysis

Nonlinear static pushover analyses were conducted to assess their global capacities. The shape of the lateral force distribution used for the pushover was a normalized curve accounting for 100% of the fundamental mode and 20% of the second mode, accounting nominally for higher mode effects. The nonlinear static pushover analysis provided an estimation of the force-deformation characteristics of the buildings in the linear and nonlinear range. Figure 6 illustrates the normalized pushover curves to illustrate the significance of the inclusion of the partition walls for the minimum and maximum wall lengths, considering the mean response. The pushover curves are normalized such that the bare building frame is set to 1 at the maximum roof drift. With inclusion of the maximum length partition wall, at a roof drift of 3% an additional 25% of force is required to push the building to the same roof drift as the corresponding bare frame building. The addition of the partition wall into the building model results in a nonlinear force-displacement behavior that appears to hold some strength increase post-yield, with an approximate "strain hardening" of 12% considering the maximum wall length."

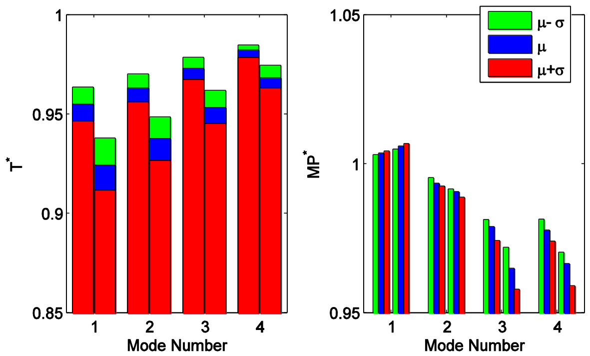


Figure 5. Normalized plots demonstrating period and mass participation factors sensitivities.
Note for the period and mass participation factor illustration, right and left bars refer to the short and long wall lengths.

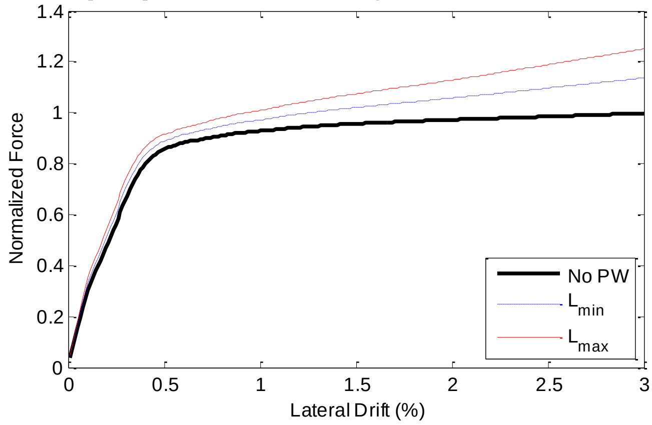


Figure 6. Normalized pushover response demonstrating effect of included partition walls.

5.3. Nonlinear Time History Analysis

To perform nonlinear time history analysis, a selection of ground motions was required. The ground motions proposed within ATC-63/FEMA p695 project are adopted (ATC, 2009a). ATC-63 is a project which quantified the seismic performance factors of various types of buildings (concrete, steel, masonry infill) and focused on collapse evaluation. The set of motions is considered to be reasonably robust for the purposes of this study. Moreover it has been vetted through the engineering community for use in simulation studies. Using this above criteria, a far-field record set is proposed. The far field motions, defined as distances greater than 6.2 miles (10 km), contain 22 motions. Some of the characteristics of these motions include minimum peak ground acceleration of 0.2 g, minimum peak ground velocity of 0.14 ft/sec (15 cm/sec) and valid frequency content for at least four seconds. The selected ground motions serve as input to the base of the building models.

In order to populate sufficient data for comparison purposes, the records proposed by ATC-63 are applied in an incremental dynamic analysis (IDA) (Vamvatsikos and Cornell, 2002). Incremental dynamic analysis applies multiple scale factors to each ground motion in order to develop multiple intensity levels. This procedure allows for a direct assessment of an intensity measure (i.e.: PGA, $Sa(T_1)$) to a damage measure of interest, such as interstory drift. The use of IDA allows the structural behavior of a building model to be examined at the various intensity levels, while reducing the dependency on a single record for each intensity level. However since the scaling of the motions is performed multiple times, this procedure can become computationally intensive. For coupled incremental dynamic analyses, the procedure is outlined herein: scale each record in increments of 0.2 g in terms of peak ground acceleration (PGA) where failure or stoppage of the incremental dynamic analysis occurs when first occurrence of 1) 2% interstory building drift, 2) localized failure when the model does not converge and interstory drifts suddenly enlarge greatly, or 3) sufficiently high PGA analysis not associated with realistic records.

Using the ATC-63 ground motions and incremental dynamic analysis, the nonlinear time history analyses were carried out for the following cases: mean response considering the maximum and minimum wall lengths, mean plus one standard deviation response considering the minimum wall length, and mean minus one standard deviation response considering the minimum wall length. The maximum wall length cases were not conducted for the standard deviation responses, however the effect of considering the mean ± standard deviation are demonstrated for the minimum wall length with a similar trend anticipated for the maximum wall length. In addition, while PGA is not an ideal engineering demand parameter, it allowed for quick scaling and running of the ground motions. Converting PGA to spectral acceleration and spectral displacement values at the fundamental mode was carried out, considering 5% damped of critical.

5.3.1. Effects on Interstory Drift

To assess the effect on the maximum interstory drift, it is first necessary to compute the average response of the simulation results. The maximum interstory drift is calculated as the maximum of the difference in adjacent floor level displacement time histories. Since the IDA was carried out with scaling respect to the peak ground acceleration, a conversion to spectral displacement at the fundamental mode (5% damped of critical) allows for only the moving average to represent the average response. Figure 7 illustrates the calculation of the moving average for floors 1, 3 and 5 for the 8 story building without a partition wall. Floors 1, 3 and 5 are selected due to the higher interstory drift demands.

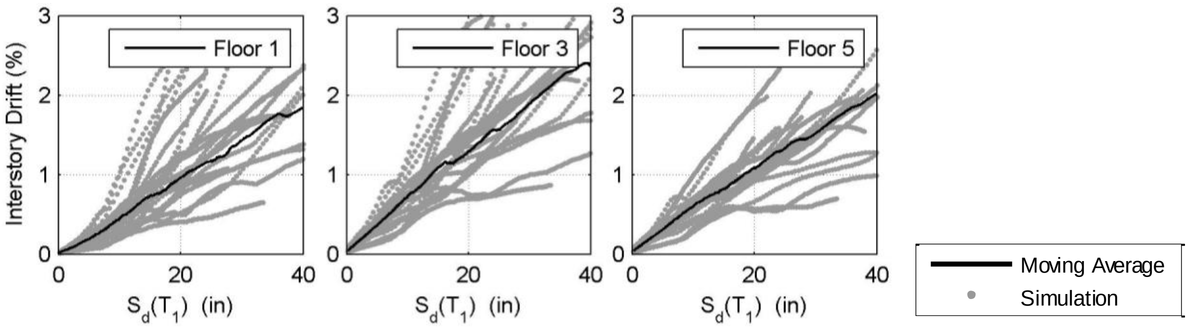


Figure 7. Average interstory drift response against spectral displacement at the fundamental period (T_1).

In a similar approach to the moving average calculation illustrated previously, the moving average responses were calculated for the coupled wall cases. In converting peak ground acceleration to the spectral displacement, the fundamental mode was taken as the fundamental mode without a partition wall; to illustrate the effect if an analyst neglects the partition wall entirely. To simplify the effect of the coupled system, the coupled average responses were normalized by that of the building without a partition wall. These results are illustrated in Figure 8, for the same floor levels as previously shown. Initially it is illustrated that the partition wall increases the interstory drift value by as much as 2.5 times that of the uncoupled (no partition wall case). As the intensity scaling of the motions increases, the effect of the partition wall on the maximum interstory drift generally decreases where the maximum interstory drift are overestimated by nearly twice the value. For larger values of spectral displacement (> 40 inch), an increase on the effect on the interstory drift is noted due to the partition wall post-yield hardening behavior.

5.3.2. Effects on Floor Level Acceleration

Similar to the interstory drift assessment, to assess the effect on the maximum floor level acceleration, it is first necessary to compute the average response of the simulation results. Likewise since the IDA was carried out with scaling respect to the peak ground acceleration, a conversion to spectral acceleration at the fundamental mode (5% damped of critical) allows for only the moving average to represent the average response. Figure 9 illustrates the calculation of the moving average for floors 4, 6 and 8 for the 8 story building without a partition wall. Floors 4, 6 and 8 are selected due to the higher floor level acceleration demands.

In a similar approach to interstory drift, the effect on the floor level acceleration is shown in Figure 10. Initially it is illustrated that the partition wall increases the floor level acceleration value by as much as two times that of the uncoupled (no partition wall case). However after the wall stiffness degrades, the effect on the increase in the floor level is greatly reduced to range around 20% additional when compared to the uncoupled case. For larger values of spectral acceleration (> 5 g), an increase on the effect on the floor level acceleration is noted due to the partition wall post-yield hardening behavior.

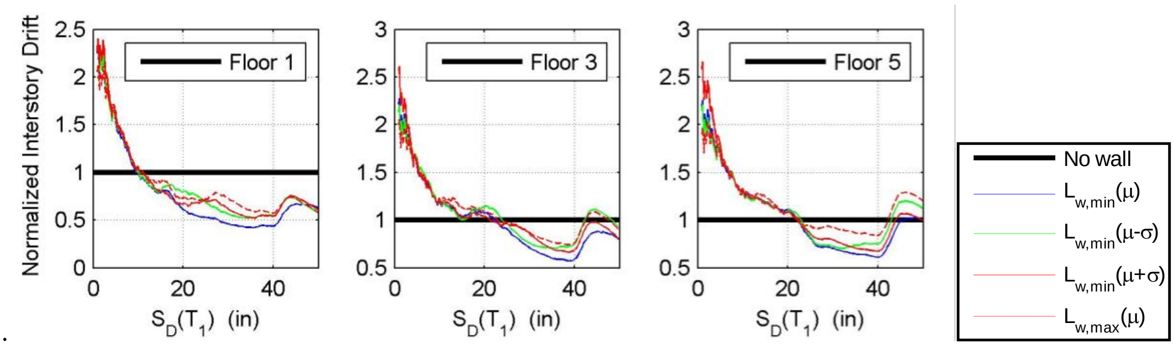


Figure 8. Normalized comparison of average interstory drift versus spectral displacement response at T_1.

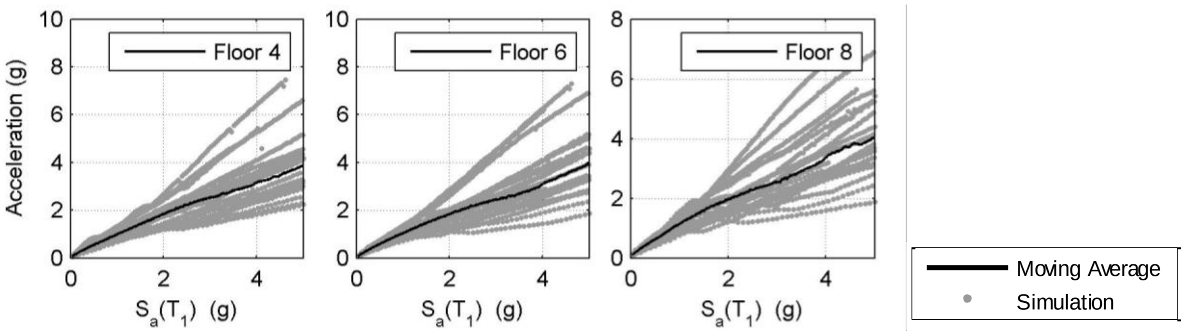


Figure 9. Average floor acceleration response against spectral acceleration at the fundamental period (T_1).

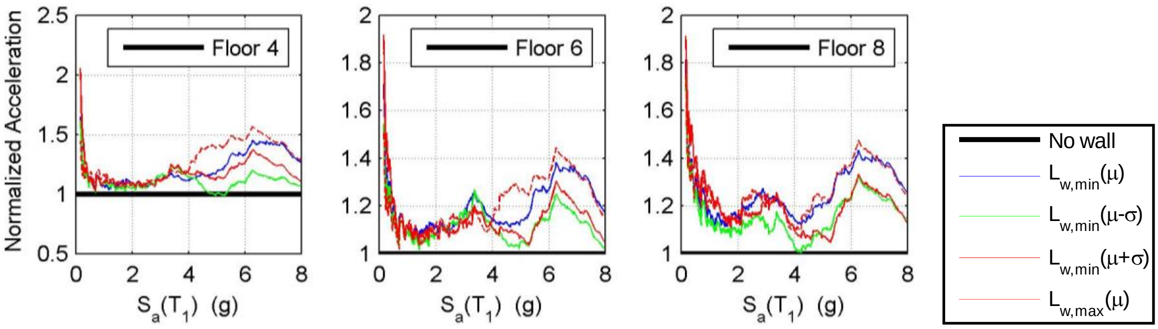


Figure 10. Normalized comparison of average floor acceleration response versus spectral acceleration at T_1.

6. CONCLUDING REMARKS

Using an experimentally verified partition wall model, a case study was carried out for an eight story reinforced concrete special moment resisting frame building. When including the partition wall is placed within the building a coupled analysis can be conducted and one observes a decrease in elastic period of about 5-10% and a strength increase (realized as a 'hardening') in the nonlinear pushover response, post-yield. Inclusion of the partition wall was determined to significantly impact maximum interstory drift when the model was subjected to earthquake time history analyses, sometimes on the order of 250% more than the building model without consideration of a partition wall. Floor level acceleration values were also impacted, up to approximately twice as much, but with most values within 20-30% of the building model not considering partition walls.

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