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ANALYTICAL MODEL FOR SEISMIC ASSESSMENT OF NONSTRUCTURAL PARTITION WALLS WITH RETURNS

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Abstract

This paper presents an experimentally verified methodology to analytically model the in-plane and out-of-plane seismic behavior of steel-framed gypsum nonstructural partition walls with returns. In this methodology, the steel-framing members are simulated by nonlinear beam elements. The in-plane and out-of-plane nonlinear behaviors of the connections are represented by nonlinear load-deformation springs, which have been calibrated using the component-level experimental data. The gypsum boards are simulated using linear four-node shell elements. The proposed methodology is employed to generate analytical models of three configurations of experiments at the University of Buffalo as well as the analytical model of a C-shaped wall system, tested at the University of Nevada, Reno. Comparison of analytical and experimental results shows that the analytical model accurately captures the force-displacement response, the out-of-plane dynamic characteristics, and the out-of-plane responses of nonstructural partition walls. In addition, the model can predict the possible damage mechanisms in partition walls. The procedure proposed in this paper can be adopted in future studies by researchers and also engineers to assess force-displacement responses and damage mechanisms of wall configurations for which experimental results are not available.

Keywords: Nonstructural Systems; Partition Walls; Analytical Modeling; Cold-Formed Steel; Seismic Response

1. Introduction

Cold-formed light-gauged steel framing (CFS) is regularly employed in the construction of walls for both commercial and industrial buildings in many parts of the world. In United States, approximately 60% of steel framing is used in nonstructural partition walls [1]. These walls support the architectural layout of a building and facilitate its functionality for occupants [2]. As observed in past earthquakes, the partition walls are susceptible to various types of damage mechanisms, including bending of studs; failure of gypsum board-to-stud/track connections; cracking of gypsum boards around openings; damage in stud-to-track connections; failure of track-to-concrete connections; crushing of wall corners; failure of brace connections; damage in corner connections; and complete collapse [3, 4, 5]. Unfortunately, this damage has frequently been triggered at story drift levels well below the yield point of structures [3]. Damaged partition walls can leave buildings inoperable, causing huge economic losses and extensive downtime, even in low-intensity earthquake events [6].

The seismic performance of nonstructural partition walls has been evaluated in previous experimental studies [1, 7, 8, 9]. The researchers studied the damage mechanisms and hysteresis behaviors of partition walls with different configurations. According to these studies, the majority of the damage mechanisms occurred at the connections between various elements of the partition walls (e.g. gypsum board-to-stud/track and track-to-concrete connections). It was also reported that the force and displacement characteristics and behavior of partition walls (i.e. stiffness, strength, degradation, and pinching) relied on the performance of these connections as well as the out-of-plane properties of return walls [10]. Therefore, in order to accurately capture the lateral behavior and damage mechanisms of partition walls through analytical modeling, it is essential to include the behavior of connections and return walls.

Although limited, the analytical modeling of nonstructural CFS gypsum partition walls have been studied by researchers. Restrepo and Lang [1] proposed a four-line piecewise backbone response envelop for these walls. Using the experimental data from the NEESR-GC project (NEESR-GC: Simulation of the Seismic

Performance of Nonstructural Systems) Davies et al. [11] and Wood and Hutchinson [2] calibrated equivalent analytical models (a single complex spring) for the in-plane behavior of CFS partition walls. The equivalent models are valuable for predicting the global behavior of a wall and evaluating its effect on the structural response. However, they only represent the partition walls with details and dimensions for which they were calibrated. Any change in partition dimensions (i.e., length and height) and/or construction details (e.g., stud or connection spacing) means that a new series of full-scale experiments should be performed in order to evaluate the performance and calibrate the equivalent models. Also, the equivalent models do not provide any information on the local behavior of individual wall components.

This paper presents the results of an effort at the University of Nevada, Reno (UNR) to develop a detailed yet computationally efficient analytical model of CFS gypsum partition walls that includes all wall components, considers the effect of return walls, and can capture the walls' out-of-plane response. The paper begins with a description of typical partition walls and the proposed analytical model, followed by a summary of required parameters for the modeling. Subsequently, the modeling procedure is adopted to generate the analytical model of three full-scale partition wall assemblies, tested at the University of Buffalo (UB). The analytical and experimental hysteresis force-displacement responses, dissipated energy, and damage mechanisms are compared. Finally, the modeling methodology is used to develop the analytical model of a C-shaped partition wall system, tested as part of a series of full-scale system-level experiments at UNR. The analytical dynamic characteristics and partition acceleration responses in the out-of-plane direction are compared to experimental results. This research provides a mechanically based method to estimate the lateral response of various CFS gypsum partition wall configurations for which experimental results are not available. The model can also help to monitor components' local behaviors and identify the sequence of damage mechanisms in these walls.

2. The Proposed Analytical Model

Typical construction of partition walls consists of C-shaped, cold-formed light-gauge steel studs nested in and screwed to C-shaped steel tracks at the top and bottom. The track is usually fastened to the structural slab with powder actuated fasteners (PAFs) and is used to align the vertical studs [1]. The gypsum board is attached to the studs and track with bugle-headed drywall screws placed at regular intervals. The goal of this study is to develop an elaborated and yet computationally efficient numerical model of CFS gypsum partition walls that includes the behavior of all these components. For this purpose, various combinations of the material and element models, available in the OpenSees library [12], have been deeply investigated. The following sections summarize the findings of this investigation and present general recommendations required to construct the analytical model of a partition wall in future studies, without repeating the trial-and-error process.

2.1. Gypsum boards and frame elements

The studs and tracks are modeled using nonlinear "Force-Based Beam-Column" elements with a fiber-section consisting of the Giuffre-Menegotto-Pinto steel material [12] (Fig. 1). The gypsum boards are simulated by "ShellMITC4" four-node elements with the "ElasticMembranePlate-Section." The shell and frame elements are meshed into a number of subelements in order to provide nodes at locations of gypsum-to-stud/track connections and increase the accuracy of modeling. The section and martial properties, including modulus of elasticity, yield strength, Poisson ratio, and hardening slope ratio, can be determined based on the manufacturer catalog or more accurately based on coupon test results. The mass of stud and track elements are concentrated at the nodal points, while the mass of gypsum boards are considered by assigning a unit mass to "ElasticMembranePlate-Section." The weights of the elements are defined as the nodal loads.

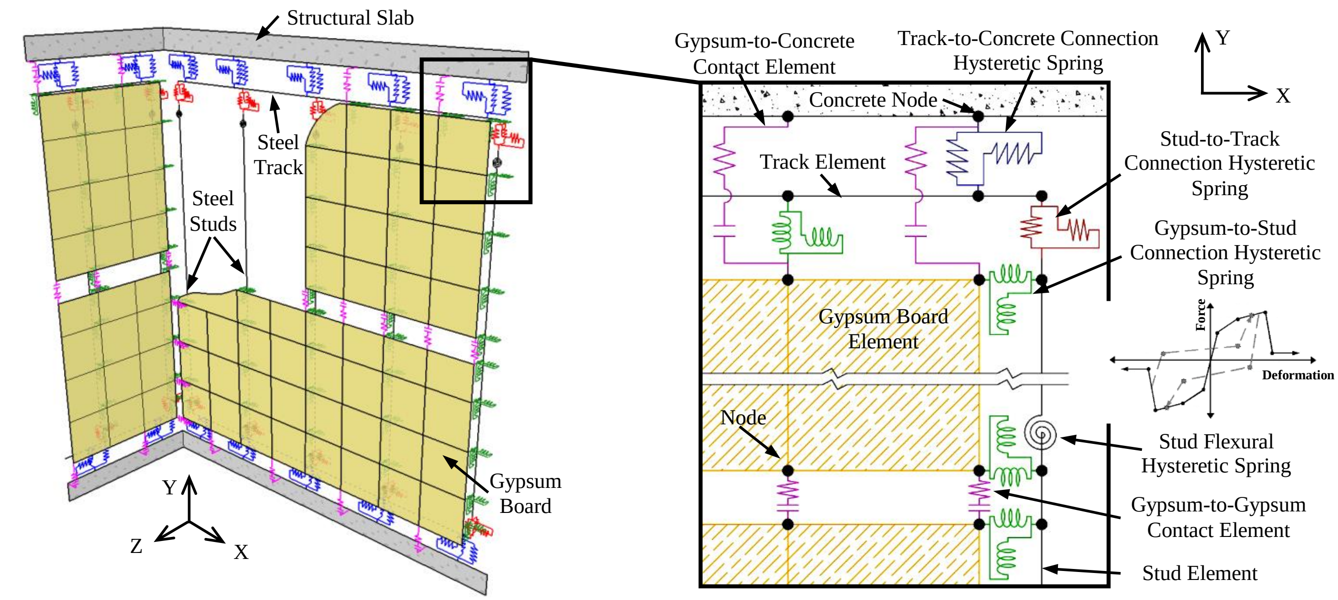

Fig. 1 - Schematic diagram of the analytical model of a CFS gypsum partition wall with return

2.2. Partition wall connections

The nonlinear behaviors of partition wall connections, namely the gypsum board-to-stud/track (only in the in-plane direction), stud-to-track, and track-to-concrete connections, are represented employing the "Pinching4" material along with "twoNodeLink" elements [12]. The "Pinching4" material requires the definition of 39 parameters as presented in Fig. 2(a). Sixteen parameters describe the backbone curve in positive (*ePdi* and *ePfi*) and negative directions (*eNdi* and *eNfi*). An additional eight parameters characterizes the "pinched" (*rDispP*, *rForceP*, *uForceN*, etc.) and unloading/reloading (*gKi*, *gDi*, and *gFi*) behavior of the model. These parameters were calibrated using the component-level experimental data, conducted as a part of the current project. Tables 1 and 2 provide sample material parameters for the connections. More information on component-level experiments and calibrated materials can be found in Rahmanishamsi et al. [13, 14, 15, 16].

The "Pinching4" material (Tables 1-2) was assigned to "twoNodeLink" elements in three independent perpendicular directions, two in-plane (X and Y directions in Fig. 1) and one out-of-plane (Z direction in Fig. 1). For stud-to-track connections, when the screw was not provided between studs and tracks, an "Elastic" material with minimal stiffness was used in lieu of the "Pinching4" material. Moreover, in the vertical direction (Y direction), an additional compression only "Elastic-Perfectly Plastic Gap" (EPPG) material was located in parallel with the primary material ("Pinching4" or "Elastic" material) to simulate the stud-track interactions [12]. The parameters of EPPG material include: 1) initial stiffness, k_g; 2) yield force, F_y; 3) initial gap, gap; 4) post-yield stiffness ratio, $b=k_h/k_g$; and 5) damage type (Fig. 2(b) and Table 3). To represent the compressive behavior of the concrete underneath the tracks, an "Elastic-No Tension (ENT)" material was added to track-to-concrete "twoNodeLink" elements in the vertical direction [12]. The initial stiffness of the ENT material was 16,000 kN/mm.

The tensile behavior of gypsum-to-stud connections (when the gypsum moves away from the stud) is captured by an EPPG material with a zero initial gap along with "twoNodeLink" elements. An initial stiffness of 288 N/mm and a yield force of 560 N are assigned to this material. These values are borrowed from a previous study by Schafer et al. [17]. A post-yield stiffness ratio of -0.5 was used for the EPPG material to simulate the brittle failure of connections. An additional ENT material with a very large initial stiffness is paralleled with the

EPPG material to simulate a rigid compressive behavior for gypsum-to-stud connections (when the gypsum moves towards the stud).

2.3. Stud flexural hysteretic response

During past experimental studies on CFS partition walls, when studs were screwed to the top tracks, local buckling of the studs has been widely reported. The buckled region formed a plastic hinge commonly at the top horizontal line of gypsum-to-stud screws, approximately 300-mm below the top track [7, 8]. To represent this behaviour in in the partition model, a “Pinching4” material along with a rotational “twoNodeLink” element is located between two consecutive nodes of each stud, approximately 300-mm below the top track. The parameters of the “Pinching4” material were calibrated using the component-level experiments.

2.4. Contacts

The contacts between the gypsum boards and the top and bottom concrete slabs were simulated using a combination of “zeroLengthContact3D” elements and “twoNodeLink” element with EPPG material while the contacts between the adjacent gypsum boards were represented by a single “zeroLengthContact3D” element (OpenSees 2015). The parameters of the contact element include: 1) penalty in the normal direction, Kn; 2) penalty in the tangential direction, Kt; 3) friction coefficient, μ; and 4) cohesion, c. The elements were always oriented perpendicular to the gypsum board edges. The contact elements captured the friction between two surfaces when the nodes move towards each other. The EPPG material accounted for the cumulative damage (crushing) in gypsum boards due to interaction with concrete. The properties of contact elements and EPPG material are provide in Table 4. The initial gap of EPPG material should be determined based on the available gap in the construction.

Table 1 - Sample force and displacement values for backbone points in various connections

Description	*ePfi* and *eNfi* (N) and *ePdi* and *eNdi* (mm)							
	ePf1 *ePd1*	*ePf2* *ePd2*	*ePf3* *ePd3*	*ePf4* *ePd4*	*eNf1* *eNd1*	*eNf2* *eNd2*	*eNf3* *eNd3*	*eNf4* *eNd4*
Gypsum-to-Stud Connection, In-Plane Direction								
THK=0.48/0.76 mm, e1 ≥ 38 mm	376	565	310	0.01	-376	-565	-310	-0.01
	1.0	8.9	17.8	39.4	-1.0	-8.9	-17.8	-39.4
Stud-to-Track Connections, In-Plane Direction								
THK=0.48 mm, e2 < 13 mm	254	1909	1867	0.01	-200	-1554	-1517	-623
	0.1	2.5	5.1	10.2	-0.1	-2.0	-6.4	-8.4
Track-to-Concrete Connections Subjected to Tension Force								
THK=0.48 mm	47	356	2284	0.01	-200	-356	-2284	-0.01
	0.1	2.5	9.5	11.7	-0.1	-2.5	-9.5	-11.7
Track-to-Concrete Connections Subjected to Shear Force								
THK=0.48 mm	2577	2111	1816	1151	-2577	-2111	-1816	-1151
	0.8	2.8	22.9	30.5	-0.8	-2.8	-22.9	-30.5
Stud Flexural Capacity								
THK=0.48 mm	2146	8229	2002	890	-2094	-11334	-2882	-756
	0.08	0.43	1.27	2.54	-0.08	-0.69	-1.37	-2.03
Stud-to-Track Connections, Out-of-Plane Direction								
THK=0.48 mm, 3 mm < g ≤ 13 mm, W/	40	943	1496	489	-40	-943	-1496	-489
Screw Attachment	0.2	8.1	25.4	35.6	-0.2	-8.1	-25.4	-35.6

THK: stud/track thickness
e1: edge distance, here the distance from the center of the screws to the edge of the gypsum board
e2: edge distance, here the distance from the center of the screws to the edge of the stud/track flanges
g: gap, here the gap between the end of the stud and the track web

Table 2 – Sample pinching parameters in various connections

Description	*rForceP* *rForceN*	*rDispP* *rDispN*	*uForceP* *uForceN*	*gK1* *gK2*	*gK3* *gK4*	*gD1* *gD2*	*gD3* *gD4*	*gKLimit* *gDLimit*	*gF* *gE*	*dam*
Gypsum-to-Stud Connection, In-Plane Direction										
THK=0.48/0.76 mm, e1 can vary	0.12	0.77	-0.01	0	0	0	0	0	0	cycle
Stud-to-Track Connections, In-Plane Direction										
THK=0.48/0.76 mm, e2 can vary	0.10	0.50	-0.01	0	0.2	0	0	0.4	0	cycle
Track-to-Concrete Connections Subjected to Tension Force										
THK=0.48 mm	0.33	0.65	0.01	0	0	0	0	0	0	cycle
Track-to-Concrete Connections Subjected to Shear Force										
THK=0.48 mm	0.12	0.75	0.01	0	0	0	0	0	0	cycle
Stud Flexural Capacity										
THK=0.48/0.76 mm	0.70 0.30	0.60 0.25	0.10 -0.40	0 0	0 0.2	0 0	0 0	0.2 0	0 1	cycle
Stud-to-Track Connections, Out-of-Plane Direction										
THK=0.48/0.76 mm, g can vary	0.10	0.60	-0.10	0	0	0	0	0	0	cycle

Table 3 - EPPG material parameters

Location	Stud/Track THK (mm)	k_g (N/mm)	F_y (N)	*b*	Gap	damage
Stud-to-Track Connection	0.48	650-1450	6000-9000	0.0	Can vary	"noDamage"
	0.76	1950-2500	6000-9000	0.0	Can vary	"noDamage"
Gypsum-to-Concrete Contact	n/a	3.0e3-3.0e4	900-1400	0.0	Can vary	"Damage"

Table 4 - "ZeroLengthContact3D" element parameters*

Location	*Kn* (N/mm)	*Kt* (N/mm)	*μ*	*c*
Gypsum-to-Concrete Contact	3.0e3-3.0e4	3.0e2-3.0e3	0.5-0.8	0.0
Gypsum-to- Gypsum Contact	3.0e3-3.0e4	3.0e3-3.0e4	0.5-0.8	0.0

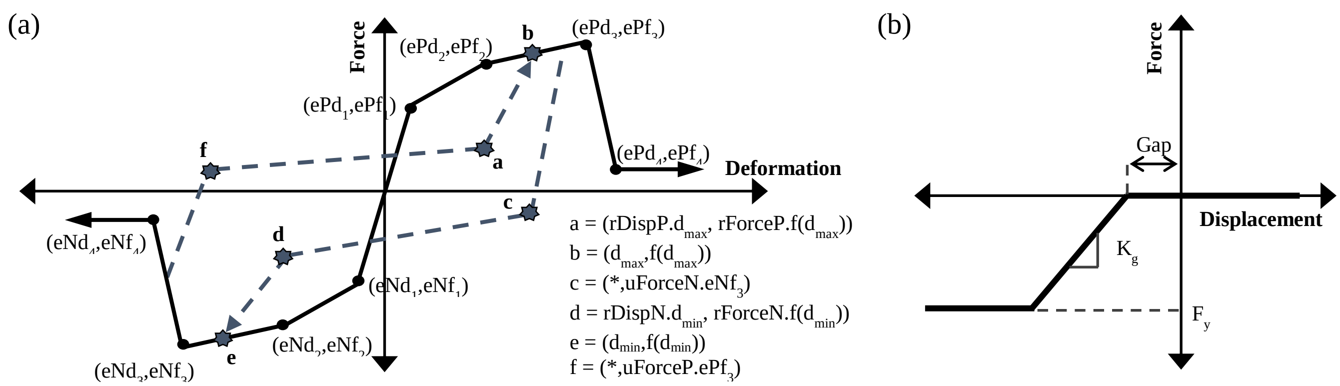

Fig. 2 - (a) Pinching 4 material properties, (b) EPPG material properties (OpenSees 2016)

3. Validation of the Proposed Modelling Methodology

Two different sets of experimental data were used in the validation process of the proposed modelling methodology. The data from the University of Buffalo (UB) experiments was utilized to mainly verify that the model is capable of predicating the force-displacement response and damage mechanisms of partition walls with returns. In addition, the data from the University of Nevada, Reno (UNR) experiments was employed to assess the proficiency of the model in estimating the out-of-plane response of partition walls.

3.1. Available data from full-scale experiments at UB

As a part of the "NEESR-GC" project, 50 partition wall specimens corresponding to 22 different configurations of CFS gypsum partition walls were tested at the University of Buffalo (UB) [7]. To validate the proposed analytical model, the configurations 1, 2, and 4 of these experiments were used in the current study. Configurations 1 and 4 included three nominally identical specimens while configuration 2 only consisted of one specimen. All specimens were approximately 3500 mm tall and 3710 mm long with return walls of 610 mm (Fig. 3). The specimens were constructed using 15.9-mm-thick gypsum boards attached to studs and bottom tracks by standard #6 Phillips self-drilling screws, spaced 305 mm on center. The studs were 0.48 mm thick (350S125-18), located typically 610 mm apart. The main difference between the three configurations (1, 2, and 4) was the construction detail employed for top and bottom connections. In configuration 4, all studs were screwed to top and bottom tracks; however, no screw connection was provided between field-studs and tracks in the other configurations. Moreover, the gypsum boards were connected to top tracks in configuration 2 and 4 while they were not in configuration 1. All specimens were subjected to a quasi-static loading protocol.

The methodology described in the previous section was followed to generate the analytical models of the UB specimens. The material properties of studs and tracks (Table 7) were determined based on the coupon test results [11]. A modulus of elasticity of 993 MPa, Poisson ratio of 0.3, and a weight density of 6931 N/m^3 were assigned to the gypsum board elements according to the manufacturer catalog. The wall connections were represented using the calibrated "Pinching4" materials (Tables 1-3). The edge distance for the perimeter gypsum-to-stud/track connections was considered to be 13 mm. For field connections, the material model with an edge distance larger than 38 mm was adopted. An initial gap of 6 mm and screw-to-stud/track edge distance of 13 mm were used for stud-to-track connections. The initial stiffness and yield force of the EPPG material was assumed to be 1000 N/mm and 7000 N, respectively. Representative contact elements were also included in the model with properties provided in Table 8. Note that these values were selected from common construction details since the actual values were not reported in the experiment.

Fig. 8 compares the analytical and experimental force-displacement hysteresis response and cumulative hysteresis energies for configuration 2. The experimental response has been accurately captured by the model. The comparison of the analytical and experimental force-displacement backbone curves for configurations 1 and 4 are presented in Fig. 9. The three specimens within each configuration were intended to be designed and constructed identically; however, their experimental responses were different in terms of maximum force, hysteresis energies, and observed damage mechanisms. Despite these discrepancies, the analytical model has successfully estimated the average experimental response.

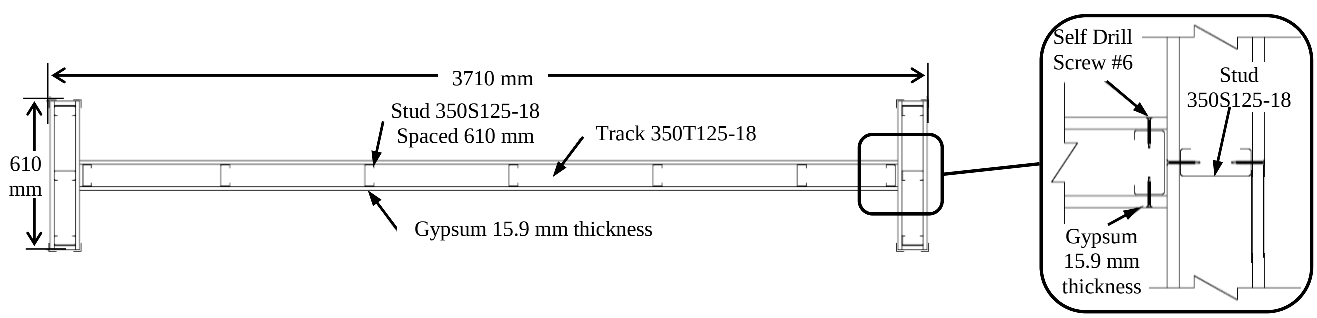

Fig. 3 - Plane view and corner details of configurations 1, 2, and 4, after [7]

Table 5 - Steel material properties

Experiment	Element	Modulus of Elasticity (GPa)	Yield Strength (MPa)	Hardening Slope Ratio (%)
UB	Stud & Track	219 & 153	330 & 359	0.1 &0.1
UNR	Stud & Track	200	227	0.1

Table 6 - Representative contact element parameters

Location	*Kn* (N/mm)	*Kt* (N/mm)	μ	*c*	F_y (N)	*Gap (mm)*
Gypsum-to-Concrete Contact	7.0e3	3.5e2	0.6	0.0	1100	0-13
Gypsum-to- Gypsum Contact	3.0e4	3.0e4	0.6	0.0	-	0.0

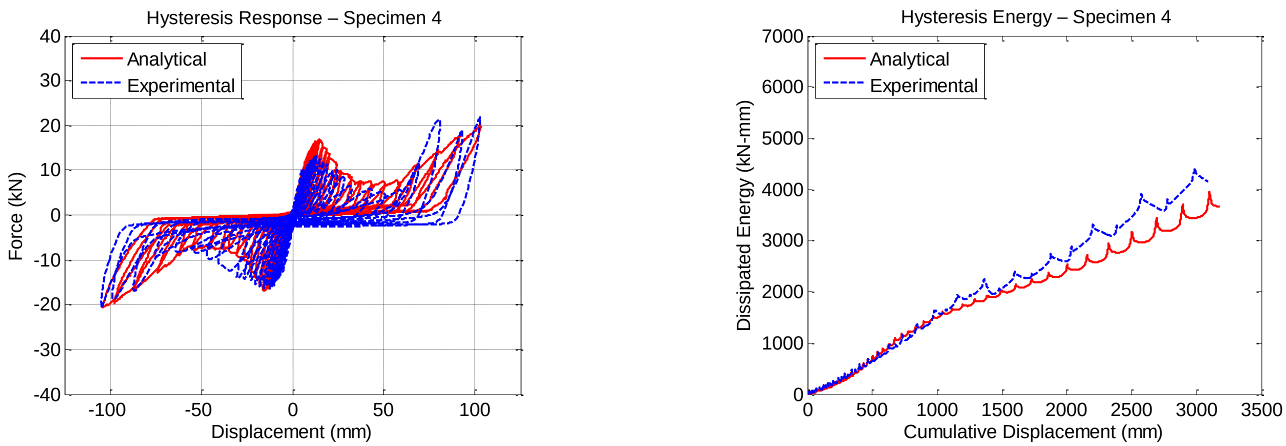

Fig. 4 - Comparison of the analytical model and experimental results for configuration 2

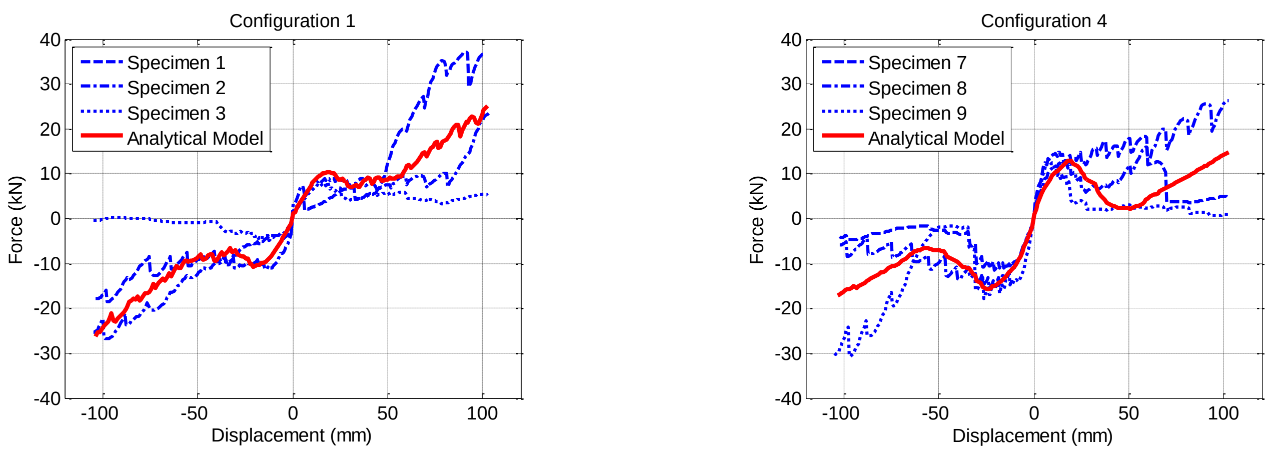

Fig. 5 - Comparison of the analytical model and experimental results for configurations 1 and 4

According to the analytical model, the possible damage mechanisms in configuration 1 include damage to screw connections of gypsum to bottom-track/boundary-studs [Fig. 6(a)], bending of boundary studs, damage to partition corners due to the separation of two perpendicular walls, damage to the top tracks of return walls, crushing of gypsum board corners, and damage to the top tracks-to-concrete connections in return walls. To determine whether a component sustained damage in the analytical model, the force-displacement response of components was monitored (Fig. 6). For configuration 2, the analytical model suggested a widespread failure of gypsum to top-track connections [Fig. 6(b)] in addition to the aforementioned damage mechanisms. Connecting the field studs to top tracks in configuration 4 resulted in damage to gypsum-to-field stud connections and the formation of plastic hinges in field studs [Fig. 6(d)]. It also increased the possibility of failure of PAF connections [Fig. 6(c)]. The predicted damage mechanisms by the analytical model were consistent with the observed damage mechanims in the experiments. Nontheless, the experimnetal observations also included breaking of gypsum boards in return walls, which cannot be captured by the anlytical model. This is due to the fact that the anlytical model assumes a linear behavior for gypsum boards.

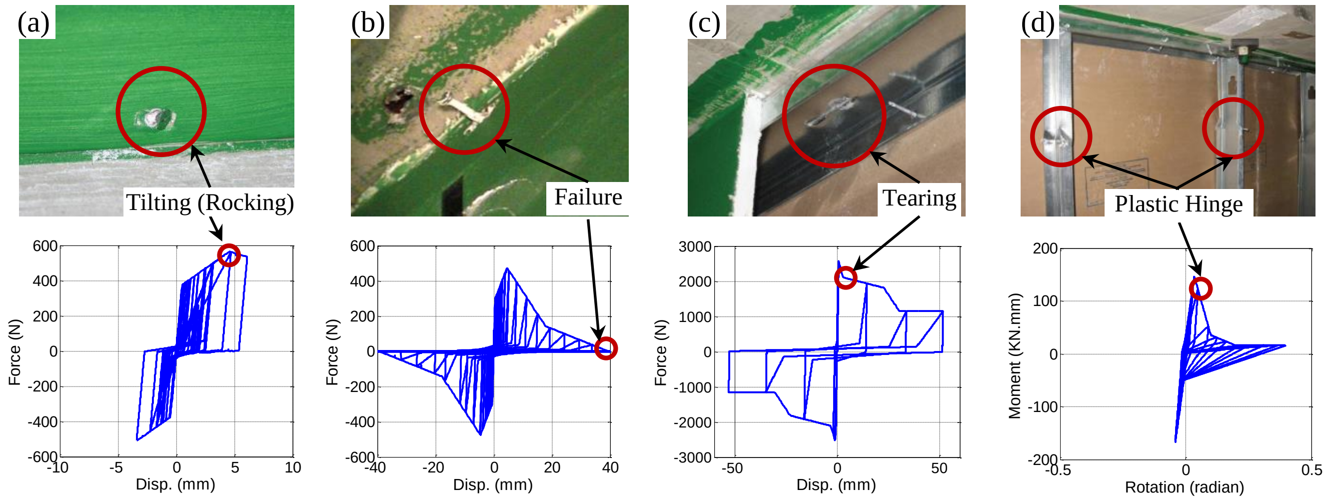

Fig. 6 - Examples of experimental and analytical damage mechanisms: (a) and (b) tilting and failure of screws connecting gypsum boards to tracks, (c) tearing of the top track, (d) plastic hinges forming in studs

3.2. Available data from full-scale experiments at UNR

A series of system-level, full-scale experiments was conducted at the UNR-NEES site. In these experiments, an integrated partition-ceiling-sprinkler piping system was installed on each floor of a two-story, steel-framed building. The experimental program consisted of two phases. In the first phase (five linear tests), the structure remained linearly elastic during all runs in order to achieve high floor acceleration. Yielding braces were implemented in the second phase (three nonlinear tests) to impose large drifts to nonstructural systems. A set of ramp-up table motions were artificially generated (using the spectrum-matching procedure) and applied to the building. In total, 59 motions were applied during linear and nonlinear test runs (in addition to white noise). Further information about the experimental setup and motions is provided in Soroushian et al. [18].

Over 100 light-gauged steel-framed partition walls with various configurations were tested during the UNR study [6]. The variables in the wall configurations included the following: 1) connectivity of the gypsum boards and studs to the top tracks, 2) presence of return walls, 3) presence of window/door openings, 4) details of wall intersections, 5) height of the partition walls, and 6) stud and track thickness. In the current study, a combination of three walls (namely P3-S, P4-S, and P5-S) that formed a C-shaped wall system was utilized to validate the analytical model in the out-of-plane direction [Fig. 7(a)]. In particular, the experimental results from the first linear and second nonlinear tests (test L1 and test NL2) were used. The aforementioned partition walls were constructed between the first and the second floor of the building using 92-mm (3.5-in.) steel studs/tracks and 16-mm-thick gypsum boards. Studs were located 610 mm apart and screwed to the bottom tracks. The gypsum boards were attached to the studs and bottom tracks by #6 self-drilling screws spaced 305 mm in the field and 203 mm at the boundaries. Tracks were fastened to concrete slabs utilizing PAFs typically spaced 610 mm center-to-center. Fig. 7(b) and Fig. 7(c) show the elevation view of partition walls P3-S and P4-S. The geometry of wall P5-S was similar to the wall P3-S. The partition walls included one window and two door openings. Studs and tracks were 0.48 mm thick in P3-S, and 0.76 mm thick in P4-S and P5-S. In test L1, the gypsum boards of P4-S were screwed to the top tracks while in test NL2 they were not. No screw connection was ever provided between gypsum boards and top tracks in other walls. Other details were similar in the two tests. During the experiments, the floor accelerations and displacements were recorded. In addition, an accelerometer was located approximately 914 mm below the second floor to report the out-of-plane acceleration of partition P4-S.

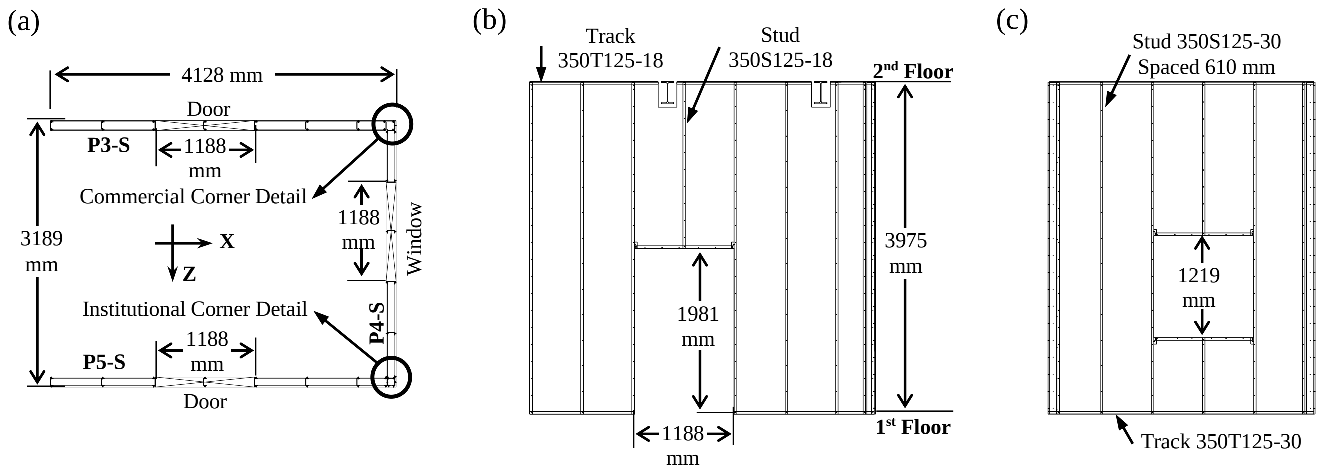

Fig. 7 - UNR partitions (a) plan, (b) elevation of partitions P3-S and (c) P4-S (Rahmanishamsi et al. 2014)

The analytical model of the UNR partition system was generated in OpenSees. The stud/track material properties (Table 7), were selected based on the manufacturer catalog. All other properties, including gypsum properties, element weights, gypsum-to-stud/track edge distances, stud-to-track gap and edge distances, EPPG material properties, and contact element parameters were assumed to be similar to those presented for the UB partition walls. The weight of the 0.76-mm-thick stud and track elements were considered to be 9.6 N/m and 9.3 N/m, respectively. Where the gypsum-to-track connection was provided, a rigid-behavior was assigned to the out-of-plane rotation (e.g. about Z-axis in Fig. 7a for P4-S) of stud-to-track connections, assuming that the gypsum boards prevented the rotation of studs. Alternatively, the stud was considered to be free to rotate relative to the track in the out-of-plane direction. The recorded floor displacement histories were applied to the top and bottom concrete nodes of the analytical model using the "Multi-Support Excitation Pattern" command in OpenSees (2015).

The 5% damped spectrums of analytical and experimental partition acceleration responses were calculated and compared for several motions. Fig. 8 provides some examples of the spectrums while Fig. 9 displays a sample comparison of the analytical and experimental acceleration response histories. In these figures, White Noise-1 and Run-i refer to the first white noise and the i^{th} motion that were applied to the building in each test. The maximum partition acceleration (acceleration at period equal to zero) in the analytical model is comparable to the experimental results. Moreover, even though there are some differences between the analytical and experimental results, the analytical model has successfully estimated the trend of the out-of-plane response of the partition walls. The difference is more highlighted in Run-4 of test L1, which might be due to the interaction of ceiling systems and partition walls. The interaction occurred in motions that imposed high acceleration to the ceiling system (e.g. test L1, Run-4, Fig. 8c). The high acceleration led to damage to the ceiling perimeter and then pounding of the ceiling system on the partition walls [19]. The pounding might affect the out-of-plane response of partition walls. Note that the analytical model does not account for the interaction since the ceiling system is not simulated.

The predicted damage mechanisms in the analytical model consisted of damage to partition corners due to the separation of two perpendicular walls, damage to the top tracks of return walls, damage to gypsum-to-tracks screw connections, crushing of gypsum boards, and slight damage to track-to-concrete PAF connections. These damage mechanisms were consistent with the experimental damage mechanisms. However, similar to the UB specimens, breaking of gypsum boards in the out-of-plane direction was observed during the motions with large drift, which could not be captured by the model.

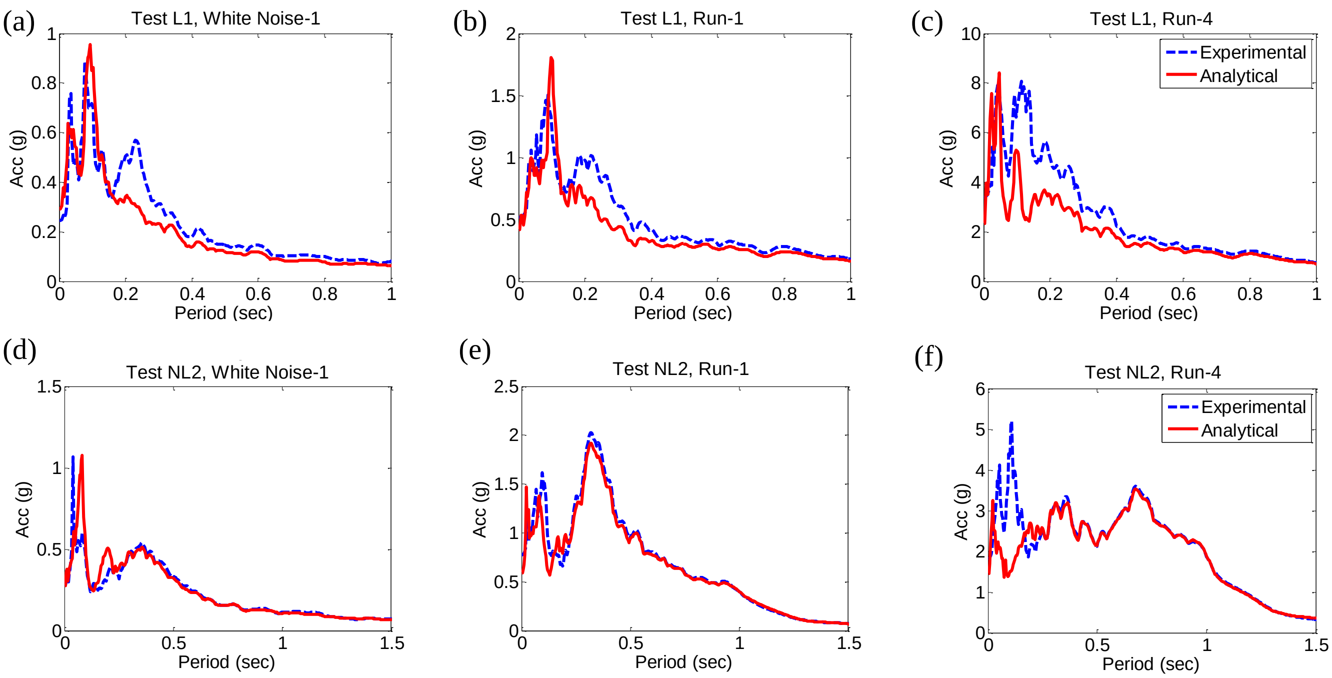

Fig. 8 - Experimental and analytical partition acceleration response spectrums for sample runs of Test L1 [(a), (b), and (c)] and Test NL2 [(d), (e), and (f)]

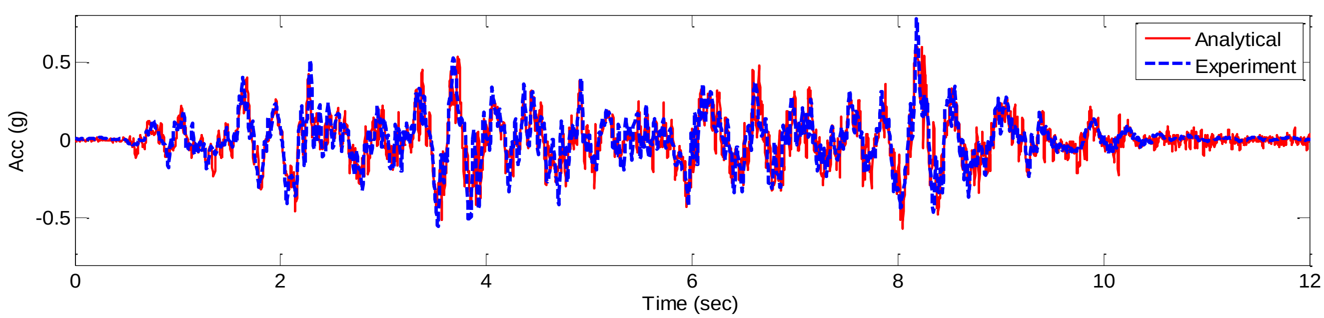

Fig. 9 - Experimental and analytical partition acceleration response history in Test NL2-Run 1

4. Summary and Conclusions

An elaborated and yet computationally efficient modeling methodology was proposed to capture the in-plane and out-of-plane behavior of cold-formed steel-framed gypsum partition walls accounting for the effect of return walls. In this modeling methodology, the steel framing members were simulated by nonlinear beam elements. Linear four-node shell elements were used to model the gypsum boards. The in-plane and out-of-plane nonlinear behaviors of the stud-to-track and track-to-slab connections, as well as the in-plane nonlinear behaviors of the gypsum-to-stud/track connections, were represented by hysteretic load-deformation springs. The behaviors of all springs were calibrated using the results of a series of the component-level experiments performed. An approximate method was utilized to model the out-of-plane behavior of gypsum-to-stud/track connections. The model also included the contacts between gypsum boards and concrete slabs as well as the contacts between the adjacent gypsum boards.

To validate the proposed modeling procedure, two different sets of experimental data were used. Initially, the analytical models of configurations 1, 2, and 4 of the University of Buffalo (UB) experiments were assembled. The analytical force-displacement responses, cumulative dissipated energy, and damage mechanisms were compared to the experimental results. The comparison showed that the analytical model accurately predicted the average response as well as the observed damage mechanisms. Subsequently, the proposed methodology was followed to generate the analytical model of a C-shaped wall system, tested at the University of Nevada, Reno (UNR). The out-of-plane dynamic characteristics, partition acceleration responses, and damage mechanisms from the analytical simulation were compared to the experimental results. Although there were some differences, the analytical model successfully captured the trend of the out-of-plane response of the partition wall and predicted the possible damage mechanisms.

The procedure proposed here can be implemented in future studies to investigate the in-plane and out-of-plane performance of existing partition walls with dimensions (i.e., length and height) and construction details (e.g., stud spacing, screw spacing, and corner detail) for which experimental results are not available. The investigation results may lead to improving/modifying the current design provisions of nonstructural walls. In addition, the proposed model can be utilized as a preliminary tool to examine and compare the performance of various innovative details for partition walls. The model can also estimate the out-of-plane acceleration response of partition walls, which can be used as the perimeter input motion in the seismic analysis of ceiling systems.

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