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Effects of cold-formed steel framed gypsum partition walls on the seismic response of a medical facility

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EFFECTS OF COLD-FORMED STEEL FRAMED GYPSUM
PARTITION WALLS ON THE SEISMIC RESPONSE OF A
MEDICAL FACILITY

Ryan Davies¹, Rodrigo Retamales², Gilberto Mosqueda³, Andre Filiatrault⁴, and
Don Allen⁵

ABSTRACT

The first experimental phase of the NEES Nonstructural Grand Challenge
Project: “Simulation of the Seismic Performance of Nonstructural Systems”
investigated the in-plane hysteretic behaviors of thirty-six full-scale cold-formed
steel framed gypsum partition walls. Results of quasi-static reverse cyclic and
dynamic testing on sixteen wall configurations including walls with commercial
and institutional construction details and innovative connection techniques are
first briefly reviewed. Thereafter, six tri-linear hysteretic models of partition
walls with pinching behavior and strength and stiffness degradation are
developed based on the experimental data for use in a finite element analysis
platform. The partition wall models, represented by shear spring elements at
each floor level, are incorporated into a numerical model of a four story steel
moment frame medical facility. Although nonstructural components are required
to carry self imposed loads and minimal external loads and are not required to be
considered in the structural analysis and design of buildings, the addition of the
partition walls are shown to increase the stiffness and strength of the building,
reducing the natural period by more than 11%. Furthermore, partition walls are

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shown to introduce over 42% more damping into the building due to the continual energy dissipation through their pinched hysteretic behaviors. The effect of the nonstructural partition walls on the inter-story displacements and absolute accelerations is also examined.

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, focusing on cold-formed steel framed gypsum partition walls, was conducted at the University at Buffalo (UB), using the Nonstructural Components Simulator (UB-NCS) shown in Figure 1a (Mosqueda et al. 2007). Fifty full scale wall specimens with heavy and light gauge cold-form steel studs and gypsum wallboard were tested. Thirty-six walls were subjected to in-plane quasi-static and dynamic loading (load applied parallel to the wall), while the other fourteen specimens were dynamically loaded out-of-plane (load applied perpendicular to the wall). Further details regarding the testing protocol considered can be found in Retamales et al. (2008, 2011). Figure 1b shows an example of the test setup with two wall specimens in typical configuration for in-plane testing on the UB-NCS. The results of this testing were used to understand the seismic response of buildings with nonstructural partition walls. Additional information regarding the seismic fragility of cold-formed steel framed partition walls is provided by Retamales et al. (2012).

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 included both typical and atypical construction methods and are categorized into six groups, defined in Table 1, based on similar detailing and displacement behavior. These groups are:

- Group 1a - Commercial Slip Track,
- Group 1b - Commercial Full Connection,
- Group 2a - Institutional Slip Track,
- Group 2b - Institutional Full Connection,
- Group 3 - Partial Height, and
- Group 4 - Improved Details
Slip track and full connection configurations vary in the connection of the cold-formed studs and gypsum boards to the top and bottom tracks. The primary differences between the commercial and institutional configurations is the wall thickness of the 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 for stabilizing the walls, typical wall heights are 11 feet 5 inches (3.48m). All specimens were 12 ft (3600m) long with most specimens including 4 ft (1.22m) return walls at the ends. Improved details are atypical wall designs developed and tested to delay the onset of typical failures to higher drift ratios or remove them completely.

**Cold-Formed Steel Framed Partition Wall Performance**

Displacement controlled quasi-static and dynamic protocols were used to load the walls. Figure 2 provides typical force-displacement plots for one wall specimen of each of the six groups considered in the study. From Figure 2, Groups 3 and 4 had the lowest energy dissipation, whereas institutional full connection partition walls (Group 2b) exhibited the highest strength. Often times, the measured data showed an increase in stiffness beyond a 2% drift ratio, this was caused by racking of the gypsum boards. This phenomenon was not considered in the modeling and can be prevented in practice by leaving a ½” gap at the top portion of the gypsum wallboards.
Table 1. Summary of in plane cold-formed steel framed partition wall configurations

<table>
<thead>
<tr>
<th>Group</th>
<th>Config</th>
<th>Specimen Description</th>
<th>Loading Rate</th>
<th>Steel Frame and Sheathing Connectivity</th>
<th>0.060/0.125</th>
<th>Steel Stud Thickness (mil)</th>
<th>Stud to Bottom Track</th>
<th>Stud to Top Track</th>
<th>Gypsum to Bottom Track</th>
<th>Gypsum to Top Track</th>
<th>Return Walls</th>
<th>Attached Mass</th>
<th>Ceiling Connected</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>1</td>
<td>1, 2, &amp; 3</td>
<td>Basic (slip track)</td>
<td>Static</td>
<td>18</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>1B</td>
<td>2</td>
<td>4</td>
<td>Gypsum connected to top track</td>
<td>Static</td>
<td>18</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>5, 6, &amp; 10</td>
<td>Leer channel</td>
<td>Static</td>
<td>18</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>1A</td>
<td>4</td>
<td>7, 8, &amp; 9</td>
<td>Full connection</td>
<td>Static</td>
<td>18</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>11, 12, &amp; 13</td>
<td>Bookshelf</td>
<td>Static</td>
<td>18</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>14, 15, &amp; 16</td>
<td>Equivalent ceiling</td>
<td>Dynamic</td>
<td>18</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>17, 18, &amp; 19</td>
<td>Partial height braced wall</td>
<td>Static</td>
<td>18</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>2A</td>
<td>8</td>
<td>20, 21, &amp; 22</td>
<td>Institutional const. slip track</td>
<td>Static</td>
<td>30</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>2B</td>
<td>9</td>
<td>23, 24, &amp; 26</td>
<td>Institutional const. full connection (2&quot;)</td>
<td>Static</td>
<td>30</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>25, 27, &amp; 28</td>
<td>Institutional const. full connection (1&quot;)</td>
<td>Static</td>
<td>30</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>1A</td>
<td>11</td>
<td>29 &amp; 30</td>
<td>Leer channel</td>
<td>Dynamic</td>
<td>18</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>31 &amp; 32</td>
<td>C-shaped walls</td>
<td>Static</td>
<td>18</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>33</td>
<td>Solution to T corner damage</td>
<td>Static</td>
<td>18</td>
<td>Yes/No</td>
<td>No</td>
<td>Yes/No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>34</td>
<td>Solution to T corner damage</td>
<td>Static</td>
<td>18</td>
<td>Yes/No</td>
<td>No</td>
<td>Yes/No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>35</td>
<td>Solution to L corner damage</td>
<td>Static</td>
<td>18</td>
<td>Yes/No</td>
<td>No</td>
<td>Yes/No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>36</td>
<td>Solution to L corner damage/slip track</td>
<td>Static</td>
<td>18</td>
<td>Yes/No</td>
<td>No</td>
<td>Yes/No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

Figure 2. Partition Wall Hysteretic Responses: (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 edges. Initial damage observations included rocking of screws attaching the gypsum to the top and bottom tracks, unzipping of walls at intersections, and crushing of gypsum at 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 the cold-formed tracks around concrete fasteners, fasteners pulling through tracks, bending in top track flanges of transverse walls, and hinges forming in cold-formed studs. Further details on the damage observations can be found in Davies et al. (2011).

**Parameterizing Partition Wall Hysteretic Behavior**

The measured shear force-displacement curves of cold-formed steel framed partition walls exhibited three important characteristics. Two of these were stiffness and strength degradation with increased displacements, and third, ‘pinching’ behavior under reversed loading. The shear behavior of the partition walls closely resembles the behavior of wood framed shear walls. Previous research by Stewart (1987) provided a hysteretic model for wood shear walls with tri-linear stiffness, stiffness degradation, and pinching effects (Figure 3). The Wayne Stewart hysteretic model utilizes nine parameters to simulate behavior as shown in Figure 3. Four parameters are related to stiffness ($k_0$ – initial, $r k_0$ – post yield, $P_{tr} k_0$ – post capping, and $P_{UNL}$ - unloading), three to strength ($F_y$ – yield, $F_u$ – capping, and $F_i$ – intercept), and one to both pinching ($\alpha$) and stiffness degradation ($\beta$). These parameters were determined for the partition walls through least square regression fitting techniques on the force-displacement curves for each of the 36 in-plane walls. The resulting hysteretic parameters for the six groups of walls considered in this study are provided in Table 2.

![Figure 3. Wayne Stewart hysteretic model (from Carr 2005).](image)
Table 2. Wayne Stewart hysteretic model parameters per linear foot for cold-formed nonstructural partition walls.

<table>
<thead>
<tr>
<th>Group</th>
<th>k0 (kips/in (kN/mm))</th>
<th>r</th>
<th>PTri (kips (kN))</th>
<th>PUNL (kips (kN))</th>
<th>Fy (kips (kN))</th>
<th>Fu (kips (kN))</th>
<th>Fi (kips (kN))</th>
<th>β</th>
<th>α</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>0.22 (0.04)</td>
<td>0.48</td>
<td>-0.21</td>
<td>0.93</td>
<td>0.07 (0.31)</td>
<td>0.11 (0.49)</td>
<td>0.01 (0.05)</td>
<td>1.09</td>
<td>0.73</td>
</tr>
<tr>
<td>1b</td>
<td>0.6 (0.11)</td>
<td>0.33</td>
<td>-0.26</td>
<td>0.79</td>
<td>0.2 (0.88)</td>
<td>0.27 (1.19)</td>
<td>0.01 (0.07)</td>
<td>1.07</td>
<td>0.51</td>
</tr>
<tr>
<td>2a</td>
<td>0.46 (0.08)</td>
<td>0.29</td>
<td>-0.19</td>
<td>1.04</td>
<td>0.16 (0.72)</td>
<td>0.25 (1.11)</td>
<td>0.02 (0.1)</td>
<td>1.08</td>
<td>0.60</td>
</tr>
<tr>
<td>2b</td>
<td>1.26 (0.22)</td>
<td>0.28</td>
<td>-0.19</td>
<td>0.91</td>
<td>0.46 (2.05)</td>
<td>0.62 (2.76)</td>
<td>0.03 (0.15)</td>
<td>1.04</td>
<td>0.50</td>
</tr>
<tr>
<td>3</td>
<td>0.11 (0.02)</td>
<td>0.38</td>
<td>-0.39</td>
<td>1.00</td>
<td>0.05 (0.24)</td>
<td>0.09 (0.38)</td>
<td>0.01 (0.02)</td>
<td>1.05</td>
<td>0.63</td>
</tr>
<tr>
<td>4</td>
<td>0.11 (0.02)</td>
<td>0.32</td>
<td>-0.27</td>
<td>1.58</td>
<td>0.03 (0.22)</td>
<td>0.07 (0.31)</td>
<td>0.01 (0.05)</td>
<td>1.05</td>
<td>0.88</td>
</tr>
</tbody>
</table>

Figure 4. Specimen 31 (a) hysteresis curves and (b) dissipated energies and specimen 27 (c) hysteresis curves and (d) dissipated energies.

The parameters for each group 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 the identical full scale test displacement protocol. The model’s hysteretic response was evaluated and the error in estimated dissipated energy was minimized through a parametric analysis of the pinching (α) and stiffness degradation (β) factors up to a drift ratio of 2% (neglecting increase of forces from racking). Figure 5 shows a comparison of the measured and predicted hysteretic response for two wall specimens along with the evolution of their respective dissipated energy per cycle.
Modeling of Partition Walls in a Medical Facility

The cold-formed studs with gypsum wall boards in most commercial applications are considered nonstructural systems. The cold-formed steel framed partition walls are assumed to have little to no effect on the lateral force resistance. However, when the total length of partition walls in a given story is considered, the cumulative stiffness can make significant contributions to the structures’ seismic force resisting system. To evaluate this effect, a building model of an existing four story steel moment resisting medical facility (Wanitkorkul and Filiatrault 2008) was modified to include the behavior of the six groups of cold-formed partition walls. The seismic response of the modified building model was then analyzed with the general purpose computer software RUAUMOKO (Carr 2005).

The medical facility (floor plan shown in Figure 5) uses four four-story steel moment frames to resist lateral wind and seismic forces in the building's north-south direction. Because of symmetry, the two-dimensional building model in RUAUMOKO consists of two moment frames, one interior frame and one end frame linked by rigid elements at each floor to simulate rigid floor and roof diaphragms. Torsional effect was neglected in the analyses. The partition walls were included in the building model using a nonlinear shear spring element located at each floor level with the assigned behavior of the Wayne Stewart hysteretic model described above.

The Wayne Stewart stiffness and force parameters for Groups in Table 2 were linearly scaled based on half the total length of partition walls at each floor level (i.e., 1st floor – 366 ft, 2nd floor – 336 ft, 3rd floor – 407 ft, and 4th floor – 314 ft).
The total length of partition walls were estimated based on existing architectural drawings of the medical facility. Actual building inter-story height and test specimen height were approximately equal, therefore, parameters were not scaled for wall height differential. A total of seven building models were used in the following analysis procedures. The base model is the original unmodified building model (partition walls not included) and the other six include the cold-formed steel framed partition wall behaviors for each of the defined groups.

**Dynamic Analysis**

The addition of the cold-formed steel framed partition walls to the medical facility building model influences the dynamic response. Because buildings are designed to remain elastic (little to no residual displacements) under typical loadings and are expected to lose stiffness and strength when the structure undergoes inelastic deformations, the influence of the partition walls on two elastic dynamic properties are considered: (1) the elastic period of vibration, and (2) the equivalent viscous damping. Also presented are the dynamic responses of inter-story drift and absolute floor acceleration for the building model with partition walls. Lastly, a short summary is provided for a collapse analysis of the building with and without partition walls following the methodology provided in the recently developed “FEMA P695 (ATC-63) Quantification of Building Seismic Performance Factors” (FEMA 2009).

**Dynamic Properties**

The elastic period of vibration is determined through eigenvalue analysis. This procedure utilizes the buildings stiffness, seismic masses, and assumed equivalent viscous damping to characterize the buildings modes of vibration (cyclic behavior). Elastic analysis on the unmodified medical facility building model demonstrated that 96% of the seismic mass participates to the first two modes of vibration, therefore the elastic period of vibration results for the first two modes are provided in Table 3.

Due to the added stiffness to the structure from the partition walls a reduction is observed in the elastic periods of the structure. The first period reduces from 0.76 seconds, the first period of vibration for the medical facility without partition walls, in the range 0.01 to 0.08 seconds or respective reductions of 1.2% to 11.4% for the building with each of the partition wall behaviors included. Because of the much lower period of vibration for the second mode and the similar scale of percentage reduction for the partition wall models, results for the second mode are not specifically discussed and are provided for comparison.
Table 3. Period comparison of the first and second mode of vibration

<table>
<thead>
<tr>
<th>Group</th>
<th>Description</th>
<th>Mass Participation (%)</th>
<th>1st Mode Period</th>
<th>% Reduction</th>
<th>Mass Participation (%)</th>
<th>2nd Mode Period</th>
<th>% Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original Building</td>
<td>85</td>
<td>0.762</td>
<td>-</td>
<td>11</td>
<td>0.257</td>
<td>-</td>
</tr>
<tr>
<td>1a</td>
<td>Commercial Slip Track</td>
<td>85</td>
<td>0.739</td>
<td>3.0</td>
<td>11</td>
<td>0.25</td>
<td>2.7</td>
</tr>
<tr>
<td>1b</td>
<td>Commercial Full Connection</td>
<td>85</td>
<td>0.722</td>
<td>5.2</td>
<td>11</td>
<td>0.245</td>
<td>4.7</td>
</tr>
<tr>
<td>2a</td>
<td>Institutional Slip Track</td>
<td>85</td>
<td>0.719</td>
<td>5.6</td>
<td>11</td>
<td>0.244</td>
<td>5.1</td>
</tr>
<tr>
<td>2b</td>
<td>Institutional Full Connection</td>
<td>86</td>
<td>0.675</td>
<td>11.4</td>
<td>10</td>
<td>0.23</td>
<td>10.5</td>
</tr>
<tr>
<td>3</td>
<td>Partial Height</td>
<td>85</td>
<td>0.752</td>
<td>1.3</td>
<td>11</td>
<td>0.254</td>
<td>1.2</td>
</tr>
<tr>
<td>4</td>
<td>Improved Detail</td>
<td>85</td>
<td>0.753</td>
<td>1.2</td>
<td>11</td>
<td>0.254</td>
<td>1.2</td>
</tr>
</tbody>
</table>

The period results presented in Table 3 demonstrate that the partition wall groups with the partial height and improved detail construction methods have the smallest impact on building stiffness with period reductions of 1.2 and 1.3%. Consequently, results for these walls indicated a much lower stiffness and capacity (relative to typical slip track construction detailing) due to the failure modes of the two wall systems, diagonal bracing buckling in the partial height partition wall group and intersecting corner damage in the improved detail wall group. The partition walls with commercial and institutional slip track and commercial full connection construction details have a similar effect on the first period of vibration, with a reduction of the period in the range of 3.0 to 5.6% respectively. Failure modes for these wall groups included gypsum connection failure, stud bending, and track to slab connection failure. The institutional full connection partition walls (Group 2b) had the greatest effect of all the partition wall systems on the first mode of vibration, the additional stiffness from these partition walls reduced the period by approximately 11.4%. This reduction in period is significant for a steel moment frame; typically, steel moment frames are more flexible structures than other commercial lateral seismic resisting systems and therefore are more sensitive to the additional stiffness of the partition walls.

Inherent in building systems, but not immediately quantified, is the energy dissipation of both structural and nonstructural components and systems (e.g., friction at joints, yielding in structural system components, etc.). Typically, computer modeling of building structures to be subjected to dynamic loading, accounts for energy dissipation uncertainties by including viscous damping in the range of 2 to 5%.
The damping ratio in the fundamental mode of each building model was determined by subjecting the building model to an impulse acceleration at the base of the structure and allowing the structure to oscillate freely. The logarithmic decrement ($\delta$) of the displacement response history at the roof of the building (Figure 6) provides the level of damping in the structure through the following equation:

$$\delta = \frac{1}{n} \ln \frac{x_n}{x_0}$$

where $x_n$ is the peak displacement $n$ cycles after the application of the impulse, and $x_0$ is the starting amplitude of oscillation. The damping ratio ($\zeta$) can be determined by:

$$\zeta = \frac{1}{\sqrt{1 + \left(\frac{2\pi}{\delta}\right)^2}}$$

A damping ratio of 2% was assigned to the numerical model, however from a logarithmic decrement analysis on the unmodified model a damping ratio of 2.26% was measured. Similar to the elastic period analysis, the change in the damping ratio is a factor of the wall stiffness, strength, and pinching behavior. For example, the level of damping increases from 2.26% for the unmodified building to 2.38% and 2.53% for the models with low dissipating energy partition walls (i.e., partial height and improved details). The change in damping ratio is more significant for the improved detail partition walls than for the partial height. These results lead to the conclusion that the improved detail partition walls, because of construction details, have more energy dissipating
components when compared to the partial height walls where most of the energy is dissipated in the diagonal braces. Both slip track groups and the commercial full connection group experience damping in the range of 2.75% to 2.94% with the institutional slip track having the highest energy dissipation of the three. Similar to the elastic period analysis, the system with the greatest effect on the damping ratio is the institutional full connection partition wall group, with an equivalent viscous damping ratio of 3.22%.

**Dynamic Response**

The building models with the cold-formed steel framed partition wall groups were subjected to the North-South component of the El Centro ground motion with a peak ground acceleration (PGA) of 0.35g, the time history was obtained from the SAC Joint Venture Project (SAC 1997). This ground motion was chosen so that structural frame of the building model would remain elastic with a maximum inter-story drift of less than 1%. The reduction of the maximum inter-story drift (Figure 8a) for each model inversely follows the trend for increased stiffness due to partition walls. Also observed in Figure 8b, the maximum absolute floor accelerations decrease, this result is not consistent for stiffer structures, typically, floor accelerations increase with increased stiffness. The reduction to the maximum absolute floor acceleration, although relatively small, can be attributed to the additional energy dissipation provided by the partition walls. Additional results for the models subjected to higher intensity ground motions can be found in Davies et. al 2010. The results demonstrated that depending on the partition wall model an increase of absolute floor accelerations and inter-story drifts can occur, however, a reduction of plastic hinges was observed. Possible causes for the increases include but are not limited to – the ground motion response spectra, partition wall inelastic behavior, neglecting of partition wall second order effects, etc.

![Graphs](image_url)  
(a) (b)

**Figure 8.** Dynamic response for the North-South component of the El Centro ground motion (a) maximum inter-story drift ratios, and (b) maximum absolute floor acceleration
FEMA P695 (ATC-63) Collapse Analysis

The FEMA P695 methodology subjects building models to a modified Incremental Dynamic Analysis (IDA) for 44 ground motions. The median spectral acceleration ($\dot{S}_{CT}$) of the ground motions that cause building collapse in 50% or more scaled earthquakes is modified by factors determined from a pushover analysis and uncertainty factors. The final result is compared to the MCE spectral acceleration given in ASCE 7 (ASCE 2006). An 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.

![Graph](https://via.placeholder.com/150)

Figure 9. Results from FEMA P695 analysis (a) Incremental dynamic analysis curves for commercial slip track and (b) cumulative distribution

Results obtained from the FEMA P695 analysis for two of the cold-formed steel framed partition wall models (i.e., Groups 1a and 2b) were compared to the unmodified building model. Structural failure occurs at plastic hinges at beam ends for rotations of 0.01, 0.02, and 0.03 radians and in the partition walls. Figure 9a is a typical IDA plot of the maximum inter-story drift versus spectral accelerations. The plot includes the IDA curve for each of the forty-four FEMA P695 ground motions. The curve for the building model with strength degradation occurring at 0.02 radians is shown in Figure 9b. As shown in Figure 9b, including the nonstructural partition walls causes an increase in the median collapse spectral acceleration. Therefore the addition of partition walls shifts structural failure to the right or more intense ground accelerations. Results were similar for the other models with strength degradation at 0.01 and 0.03 radians.
Conclusions

Results from testing of cold-formed steel framed nonstructural partition walls performed as part of the NEES Nonstructural Grand Challenge project were parameterized for simulation by the Wayne Stewart hysteretic model, capturing stiffness and strength degradations and pinching effects. Addition of the partition wall model to a four story medical facility with steel moment frames demonstrated an increase in stiffness, providing over 11% period reduction, and over 1% additional damping for the stiffest and strongest partition wall system. From dynamic analysis, the additional stiffness and damping resulted in reduced inter-story drifts and maximum absolute floor acceleration. According to an analysis following the FEMA P695 methodology the collapse spectral acceleration increased for models including cold-formed steel framed partition walls. These results suggest that including the cumulative effect of this nonstructural system in a steel moment resistant building system improves building seismic performance.

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Appendix - References


Appendix - Notation

- $F_i$ – intercept strength
- $F_y$ – yield strength
- $F_u$ – capping strength
- $k_0$ – initial stiffness
- $PT_{Rk0}$ – post capping stiffness
- $P_{UNL}$ – unloading stiffness
- $n$ – number of cycles post impulse
- $rk_0$ – post yield stiffness
- $\dot{S}_{CT}$ – median spectral acceleration

- $x_a$ – cycle displacement amplitude
- $x_0$ – impulse displacement amplitude
- $\alpha$ – reloading or pinch
- $\beta$ – stiffness degradation
- $\delta$ – logarithmic decrement
- $\zeta$ – damping ratio