16th World Conference on Earthquake Engineering, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 2251

Registration Code: S-V1463084241

Development of Compact Damper Framing Systems for Seismic Protection of Structures

M. Symans[(1)], S. Yang[(2)], G. Mosqueda[(3)], J. Karns[(4)] and D. Lee[(5)]

[(1)] *Associate Professor, Dept. of Civil and Environmental Engineering, Rensselaer Polytechnic Institute, Troy, NY, symans@rpi.edu*
[(2)] *Former graduate student, Dept. of Civil and Environmental Engineering, Rensselaer Polytechnic Institute, Troy, NY, yang.steve.411@gmail.com*
[(3)] *Associate Professor, Dept. of Structural Engineering, UC San Diego, gmosqueda@ucsd.edu*
[(4)] *Director of Engineering Research, MiTek, Ventura, CA, jkarns@mii.com*
[(5)] *West Coast Technical Director, Taylor Devices, N. Tonawanda, NY, davidlee9@aol.com*

Abstract

The effectiveness of damping devices for seismic protection of structures can be improved by installing the dampers in displacement amplification frames. This paper describes recently developed damper amplification frames that are compact while providing large amplification and thus large capacity to dissipate energy. One area of application of such frames is wood-framed buildings with soft ground stories. In the United States, such structures have been subject to major damage, and sometimes collapse, in large seismic events. The failure of such structures is typically dominated by damage in the ground story, which is significantly weaker than the upper stories due to the presence of large openings for storefront windows or vehicle access. Furthermore, such large openings are typically located asymmetrically relative to the center of mass, resulting in combined lateral and torsional motion of the structure. One approach to protecting these structures is to add a damping system to the flexible ground story. To preserve the large openings that are desirable for building owners, compact damper framing systems can be employed. Such frames are narrow relative to their height and provide high displacement amplification due to the geometry of the frame components. In this paper, two compact damper framing systems are examined relative to a third damper amplification framing system that is currently in use. Analytical studies are presented to examine the displacement amplification provided by each frame. The effectiveness of the frames is then evaluated for application to soft-story wood-framed buildings via numerical simulations of a four-story building with dampers installed in the ground story. Finally, experimental test results are presented for cyclic and seismic testing of the frames. The results of this comprehensive study demonstrate that the compact damper framing systems can be highly effective in providing seismic protection of buildings.

Keywords: Damping, energy dissipation, seismic protection

1. Introduction

Soft story structures arise when two adjacent stories have a significant difference in lateral stiffness. This is typically a result of changes in building material, differences in floor height, or variations in floor plan. A relatively common type of construction that features a soft ground story is low-rise (three to five-story) woodframe structures. Such structures typically contain multi-family units (apartments) in the upper stories while the ground story is used for resident parking or commercial space. Large openings in street-side exterior walls provide garage access or large storefront windows. Unfortunately, structures with such openings, combined with minimal interior walls, have often performed poorly under seismic loading, with significant damage being concentrated in the soft ground story while the upper stories remain relatively undamaged.

Several seismic retrofits for such structures were examined as a part of the recently completed NEES-Soft Project [1]. The goals of this project were to develop and evaluate, via numerical simulations and experimental testing, seismic retrofits that would preserve the large ground story openings. To be consistent with the philosophy described in FEMA P-807 [2, 3], for some of the analyses and tests, only the ground story was modified, leading to an expected performance level of "onset of strength loss" with a probability of exceedance of 20% under an MCE (Maximum Considered Earthquake) event. For the weak wall lines of the ground story, the retrofits should be positioned behind or in parallel with the short wall segments between openings to maintain access to the ground story (e.g., behind the narrow wall segments between garage doors or behind the wall framing segments between windows). In the NEES-Soft Project, one soft ground story retrofit that was evaluated employed damping devices installed within displacement amplification frames. Since the space for dampers is limited to the area behind narrow walls, dampers installed in a standard frame (e.g., along a diagonal brace) would be subject to axial displacements that are a small portion of the lateral drift of the ground story, thus reducing their effectiveness.

An energy dissipation retrofit approach was evaluated in a series of experiments including hybrid testing of a stacked shear wall test specimen at the University of Alabama [4], pseudo-dynamic hybrid testing of a three-story specimen at the University at Buffalo [3, 5], and full-scale shake table testing of a four-story structure at the University of California San Diego [6]. The full-scale test structure had a soft ground story that was retrofitted with toggle-braced dampers. The results demonstrated that dampers installed in such frames are effective in controlling both the translational and torsional response of the building; however, the damper frames used in testing were too wide for practical use. The goal of the present study is to evaluate the potential effectiveness of compact displacement amplification frames that would minimize encroachment on the wall openings located along the weak wall lines of the ground story.

This paper presents the effectiveness of two new compact damper displacement amplification frames for application to soft-story buildings. The concepts for the frames were first presented in a paper by Schott et al. [7]. The effectiveness of the frames in controlling the response of a multi-story building is evaluated relative to the aforementioned toggle-braced frame, and with consideration given to various frame aspect ratios. The relationship between the lateral drift of the damper frame and the axial displacement (stroke) of the damper (i.e., the damper displacement amplification factor) is discussed for each frame. The effectiveness of the frames is then evaluated via numerical simulations of a seismically-excited multi-story building that was physically tested as part of the NEES-Soft Project. Finally, experimental test results are presented for cyclic and seismic testing of the frames. The results of this comprehensive study indicate that the compact damper framing systems can be highly effective in providing seismic protection of soft-story buildings.

2. Description of Compact Damper Amplification Frames

The three damper displacement amplification frames discussed in this paper are shown in Fig. 1. In all three frames, the dampers are fluid dampers with the main body of the damper being a cylinder containing the piston head, piston rod and hydraulic fluid. The pinned connections allow the frames to deform as a global shear mechanism while extending and compressing the dampers. All of the pin-ended members are light steel framing elements and the two ends of the damper are pin-connected to the framing elements.

The swing arm frame utilizes a lever arm to amplify the motion of the damper. Lateral drift of the frame results in rotation of the bar (lever arm) located at the bottom of the frame. The rotation of the bar is converted to translational motion along the axis of the damper. Note that this frame has also been designated as a "four-bar linkage" since removal of the two framing members along the top and along the right side results in a four-bar linkage. The collinear tube frame (also known as a butterfly frame) uses two telescoping tubes placed along the diagonal of a frame to drive the displacement amplification mechanism. Each end of a lever-type mechanism is fixed to a separate tube. Lateral drift of the frame results in the telescoping tubes sliding relative to each other and, in turn, causes a bar (lever arm) to rotate. The rotation of the bar is converted to translational motion along the axis of the damper. The toggle-braced frame utilizes a toggle arrangement consisting of two non-collinear bars. Lateral drift of the frame results in rotation of the bars which in turn produces translational motion along the axis of the damper.

To evaluate the effectiveness of these frames when configured to have a narrow shape (tall relative to its width), each frame was examined for aspect ratios (width-to-height) of 2:8, 3:8, and 4:8. Note that the frames shown in Fig. 1 are not drawn to scale and that careful consideration of the deformed geometry of the displacement amplification mechanism must be given to minimize the possibility of the frame becoming locked in position (e.g., the diagonal elements becoming collinear in the toggle case) and to avoid excessive deformation (e.g., swing arm reaching the limits of its rotation) under the expected levels of frame lateral drift.

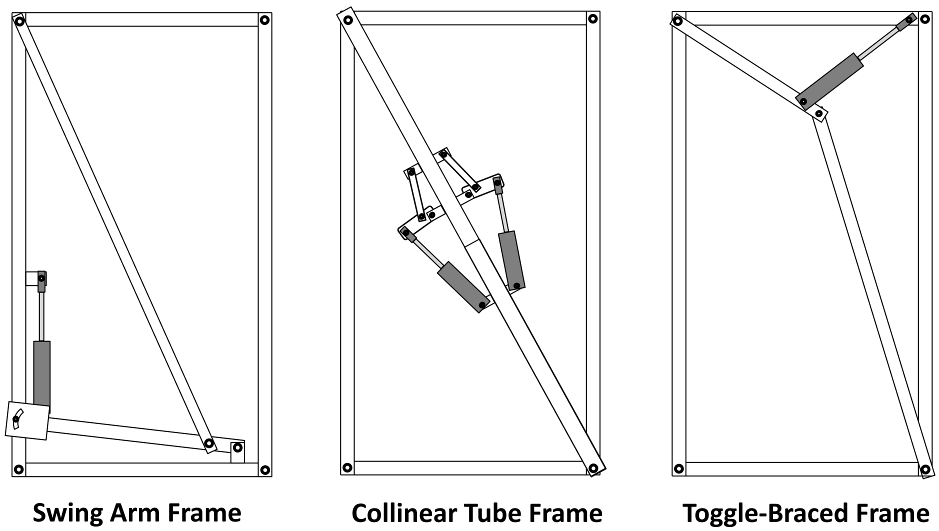

Figure 1 Compact Displacement Amplification Frames

3. Damper Displacement Amplification

The damper displacement amplification factor, η, defines the change in damper length relative to the lateral drift of the frame:

$$\eta = \left| \frac{u_d}{u} \right| = \left| \frac{f(u)}{u} \right| \tag{1}$$

where u_d is the deformation of the damper and u is the lateral drift of the frame. Note that the damper deformation is a function of the lateral drift and thus the displacement amplification factor varies as the lateral drift of the frame changes. The displacement amplification factor is an indirect measure of the effectiveness of a particular frame in terms of providing energy dissipation capacity. A more direct measure is the ratio of effective damping coefficients for the case of the damper installed in a displacement amplification frame relative to installation within a traditional framing system that is not designed to provide displacement amplification. Expressions for the amplification factor can be obtained by considering the kinematics of the deformed frame when subjected to an imposed lateral drift, u. A simplified approach includes the assumption that that all framing elements are rigid and that all pinned connections are frictionless. A brief description of the process for obtaining the amplification factor is provided below while details are available in Yang [8].

As shown in Fig. 2, the swing arm frame can be simplified to a four-bar linkage where joints A and D are pinned connections that only permit rotation relative to the base of the frame while joints B, C, E, and F are able to rotate and translate relative to the base of the frame. Joints F' and D' are fixed connections and all elements, except the damper (element EF), are assumed to have constant lengths (i.e., rigid elements). For a given lateral drift, u, the angle element AB makes with respect to the horizontal can be determined. Next, the rotation of elements BC and CD can be determined. Since element ECD is a rigid bar, element F'F is fixed to member AB, all element lengths are constant, and the positions of members BC and CD are known for some lateral drift, u, the deformation of the damper can be determined as a function of u. The dependency of the displacement amplification factor on the lateral drift of the frame is shown in Fig. 3a for a moderate aspect ratio (3:8). Note that the amplification factor exceeds 1.5 for a wide range of drift values (±5%).

The collinear tube frame (see Fig. 1) can be analyzed in a similar manner. As the lateral drift of the frame increases, the smaller diagonal tube (lower tube) slides inside the larger diagonal tube (upper tube), allowing the diagonal to change in length. The relative motion of the tubes results in rotation of the bars (lever arms) that are positioned between the upper tube and the damper piston rod. Thus, the dampers are stroked with a displacement that can be defined as a function of u. The dependency of the displacement amplification factor on the lateral drift of the frame is shown in Fig. 3b for a moderate aspect ratio (3:8). Note that the amplification factor exceeds 1.25 for a wide drift range (±5%).

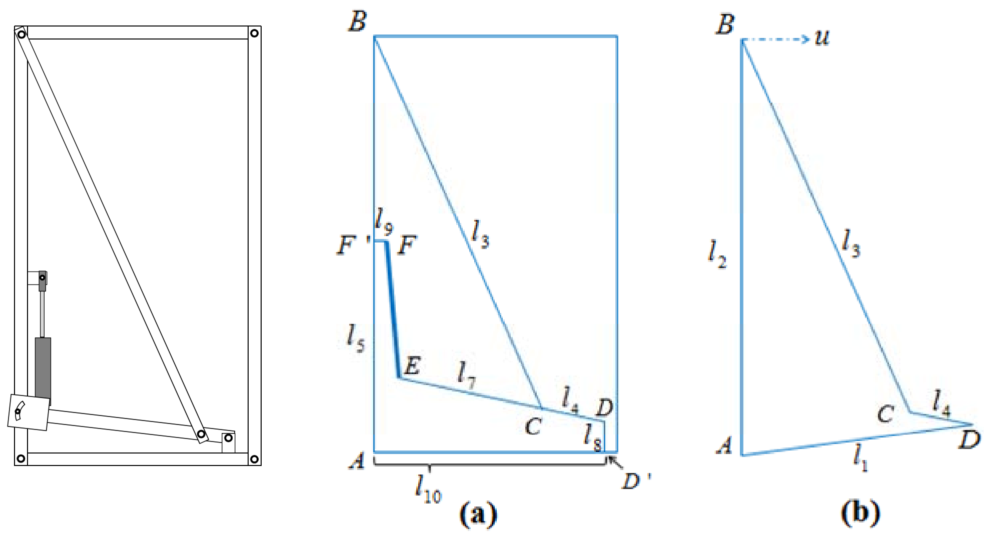

Figure 2 Swing Arm Frame: Undeformed geometry and a) component labels and b) four-bar linkage model.

As noted previously for the toggle frame, the lateral drift of the frame, u, results in rotation of the two bars that are skewed relative to the diagonal. The rotation in turn induces translational motion along the axis of the damper. Thus, the deformed length of the damper can be determined as a function of u. The dependency of the displacement amplification factor on the lateral drift of the frame is shown in Fig. 4 for a moderate aspect ratio (3:8). Note that, over a drift range of ±5%, the displacement amplification factor is both smaller and larger than unity. Thus, for this drift range, the frame provides high amplification in one direction (as much as about 2.8) and deamplification can occur in the other direction. As can be seen, there is lower limit on the frame drift (at about -1.2% drift, the frame elements along the diagonal become collinear and thus the frame "locks-up").

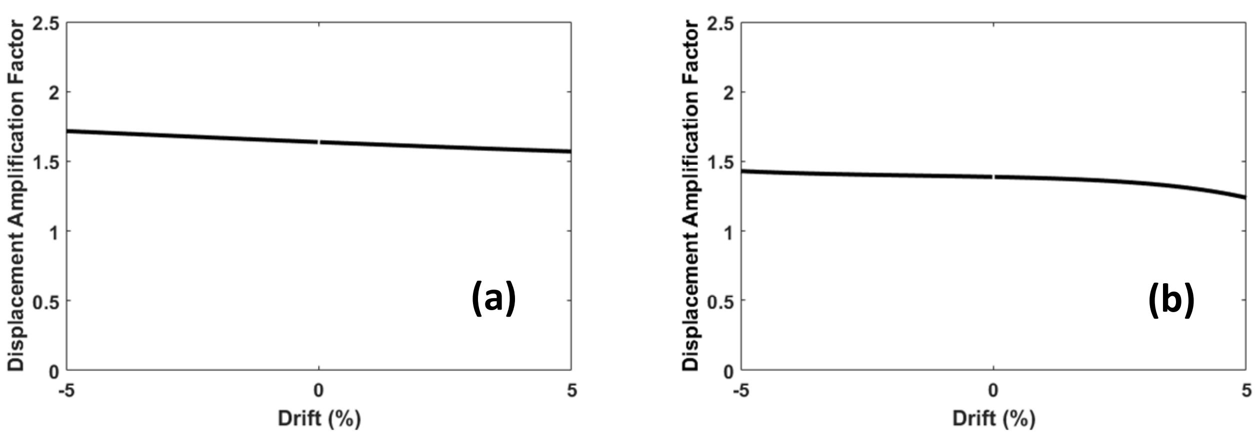

Figure 3 Drift-dependence of amplification factor for a) swing arm frame having 3:8 aspect ratio and b) collinear tube frame having 3:8 aspect ratio.

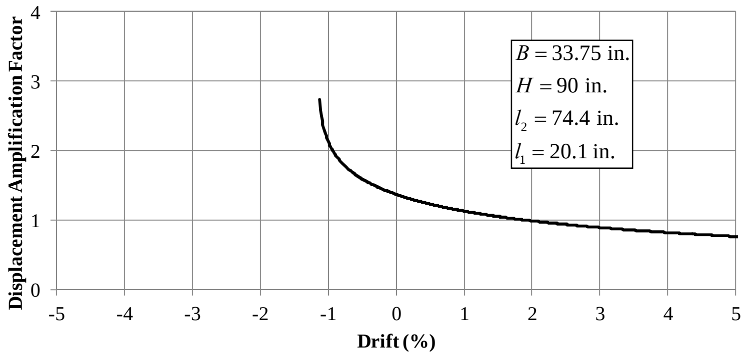

Figure 4 Drift-dependence of amplification factor for toggle frame having 3:8 aspect ratio.

4. Wood-Framed Building Model for Numerical Simulations

The building model used in the numerical simulations represents a 4-story wood-frame structure with a soft ground story. This is a common type of structure that has performed poorly during seismic events. The soft ground story typically arises due to the mixed use of the different stories. In such a structure, residential apartments typically occupy the upper stories while the ground story is used for either garage parking or commercial space. The residential portion contains many interior walls to create rooms and partition spaces; these walls result in a relatively stiff and strong structure above the ground story. Conversely, ground-level retail space and vehicle storage space typically results in large amounts of open space with relatively few interior walls and large openings on the street side for storefront windows or for garage doors. This combination of openings and lack of interior walls results in a ground story that is much more flexible and weak than the stories above.

The building model was based on a full-scale building that was constructed and tested on a shake table as part of the NEES-Soft project [1]. Figure 5 shows an aerial view of the test specimen and Figure 6 shows the floor plan for the ground story. The floor plan is a 38 ft x 24 ft rectangle with a small portion of the diaphragm removed along the north face of the structure to create a light well and with small extensions for bay windows in the upper stories along the south and east wall lines. All story heights are 106.75 inches. The floors are connected to each other by wood-framed walls that provide lateral resistance via horizontal wood siding (throughout the exterior of the building) and gypsum wallboard (throughout the interior of the building). In addition, as part of a performance-based seismic retrofit, supplemental wood shear walls were located along selected wall lines within the upper stories. The shear wall sheathing to framing connectors had different edge fastener spacing for each story to account for the increase in shear demand in the lower stories (fourth, third, and second story shear walls were nailed at 6, 3 and 2 in. on center, respectively, with field spacing of 6 in.).

The soft story effect results from only a portion of the upper story walls extending from the roof to the ground (a large number of internal walls exist to create rooms in the upper stories while very few internal walls exist in the ground story). Furthermore, as can be seen in Fig. 5, there is discontinuity in the exterior walls along the south and east wall lines between the ground and second stories.

One phase of the NEES-Soft Project involved retrofitting the test specimen with damper frames that were installed along the perimeter wall lines in the ground story. The location of the damper frames is shown in Figure 6 and was intended to provide simultaneous control of translational and rotational motion of the structure. Note that, for the experimental testing, the damper frames along the south wall line were located in the openings of the wall. This was necessary since, due to time constraints, the damper frames that were available for testing were too wide to fit within the narrow spaces defined by the wall piers that are located between the openings. One of the goals of the numerical analysis conducted as part of this study was to evaluate the effectiveness of compact damper frames that could fit in such spaces. To maintain consistency with the experimental tests, the same distribution of dampers was used (i.e., damper frames in the ground story were distributed as shown in Figure 6).

Figure 5 Full-scale four-story wood-framed test specimen on shaking table at NEES-UCSD.

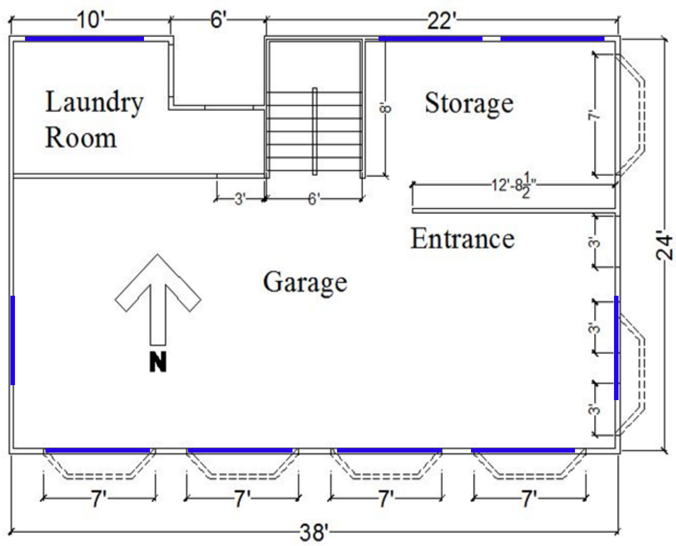

Figure 6 Floor plan of ground story showing location of damper frames (blue)

Note that most of the dampers were placed along the South wall line since this wall line is much weaker than the other wall lines and thus was expected to experience significant amounts of deformation from both translational and torsional response of the structure. Also note that most of the damper frames were not located directly underneath existing shear walls in the upper stories. Consequently, the diaphragm above the ground story was retrofitted by adding wood sheathing to the underside of the diaphragm to increase its in-plane stiffness, thereby allowing it to transfer forces from the shear walls to the damper frames.

A numerical model of the test specimen was created using version 2.1 of the software SAWS ("Seismic Analysis of Woodframe Structures") [9]. The model employed a simplified floor plan where the bay windows in the upper stories were removed and the floor diaphragms were extended to fill the stairwell space. The weight of each floor was 27.9 kips (except at the roof level where the weight was 20 kips) and the total height of the building, distributed uniformly among the stories, was 36 ft. All walls in the building, including the supplemental shear walls in the upper stories, and damper frames in the ground story were positioned in the numerical model in the same locations as they were in the test specimen. To maintain consistency between the experimental tests and numerical simulations, the earthquake records used in the present study were applied in the East-West direction only (X-direction). Earthquake records used in the numerical simulations were DBE- and MCE-scaled versions of the 0° component of the 1989 Loma Prieta - Gilroy record (G03000) and the 360° component of the 1992 Cape Mendocino - Rio record (RIO360).

5. Effective Damping Coefficient of Compact Damper Framing Systems

The effectiveness of the compact damper framing systems is dependent on their ability to dissipate energy. The ability of a given frame to dissipate energy can be characterized by the effective damping coefficient of the frame which is equal to the magnitude of the required lateral force to produce a unit lateral velocity. Recognizing that, in the region of small drifts (say, less than about 1 to 2%), the displacement amplification factor has relatively small variation, considering equilibrium of forces for a unit imposed lateral velocity, and assuming the damper behaves as a linear viscous dashpot, the effective damping coefficient may be written as [8]:

$$C_{effective} = \beta \eta^2 C_o \tag{2}$$

where β is the number of dampers in the frame, η is the displacement amplification factor at zero drift, and C_o is the damping coefficient of each damper in the frame. Note that, with the small drift approximation made, the above result is the same effective damping coefficient defined by Sigaher and Constantinou [10].

As mentioned previously, to evaluate the effectiveness of narrow damper frames relative to wide damper frames, three aspect ratios (base-to-height ratios) were examined for each frame (4:8, 3:8, and 2:8). A frame height of 96 in. (8 ft.) was used, resulting in frame widths of 48 in. 36 in., and 24 in. Note that the toggle frame used in the NEES-UCSD test specimen had dimensions of 37.75 in. x 89.14 in., which corresponds to an aspect ratio of approximately 3.39:8. This aspect ratio was examined in addition to the other three toggle frame aspect ratios to allow for comparison with the experimental test results.

To evaluate the effectiveness of the different damper frames relative to each other, it is assumed that the same linear viscous damper is used in each frame and that the damper is the same as that which was used in the NEES-UCSD testing (damping coefficient of 0.26 kip-sec/in). The damping coefficient amplification (ratio of effective damping coefficient to damping coefficient of a single damper) is shown in Fig. 7. As can be seen in Fig. 7, considerable damping coefficient amplification is provided for the wider frames, reaching a value of more than six in the 4:8 Collinear Tube case. On the other hand, the 2:8 Toggle-Braced case has a damping coefficient amplification that is much lower than unity (although it is larger than the case where the damper is installed along a diagonal brace within a frame having the same aspect ratio). All other cases have a damping coefficient amplification that exceeds unity with an upper bound of about four, indicating that even narrow displacement amplification frames can provide some degree of amplification.

6. Numerical Simulation Results

The results of the numerical analysis indicated that the non-retrofitted building would reach a life-safety performance level (about 2% peak drift) under the DBE-level ground motions and would likely collapse under the MCE-level motions. For the case where the building is seismically retrofitted using viscous dampers installed in any of three aforementioned displacement amplification damper frames, and considering a range of frame aspect ratios (width-to-height ratios of 2:8, 3:8 and 4:8), the peak drifts under DBE-level motions are typically less than about 1% (immediate occupancy performance level) and, for MCE-level motions, are typically less than about 2% (life-safety performance level) (see Fig. 8). Thus, the damping retrofit was effective in protecting the ground story and thus preventing collapse of the structure under strong ground shaking. However, the effectiveness of the damper frames was strongly dependent upon the frame configuration and the aspect ratio. The frame configurations for a given aspect ratio can be ranked in terms of effectiveness in reducing ground story drift, with the collinear tube frame being most effective while the toggle frame was the least effective (this is consistent with the effective damping coefficients shown in Fig. 7). Although high levels of damping are beneficial for reducing the ground story drift, amplifying the damping coefficient too much results in transfer of damage from the ground story to the upper stories. This is evident in Fig. 8 where frames that produce the smallest ground story drift generally produce the largest upper story drifts. As a result, certain combinations of frame type and aspect ratio were found to be particularly effective.

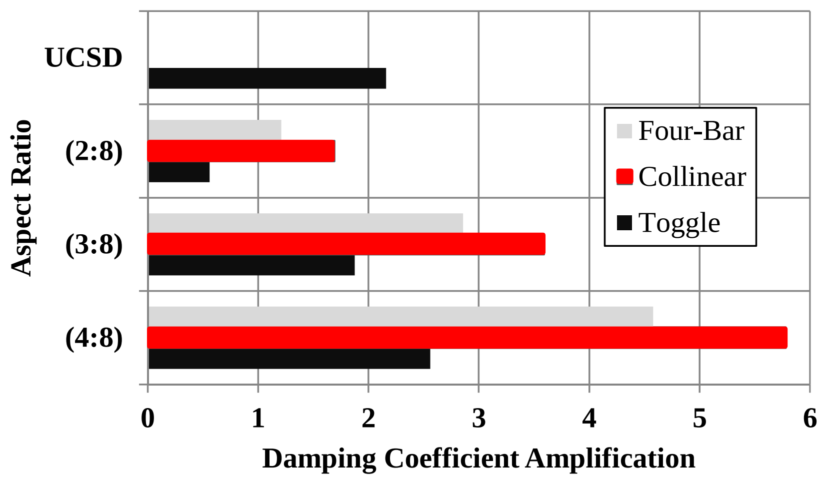

Figure 7 Theoretical effective damping coefficients (used in numerical simulations).

The narrowest frames evaluated in the study by Yang [8] had an aspect ratio of 2:8 and, as expected, had the lowest amplification factors. The collinear tube frame is recommended for such narrow frames since the large amplification of this frame compensates for the reduced effectiveness due to its narrow geometry. For that particular aspect ratio, the collinear tube frame was shown to be most successful in limiting ground story drift (limited to about 1.5% for MCE level motion) while minimizing the transfer of damage to the upper stories (maximum drift of about 0.75% for MCE level motion). If there is sufficient space to accommodate wider frames (say, 4:8 aspect ratios), the toggle frame is recommended. As expected, the largest amplification factors occurred for the widest frames (4:8 aspect ratio). As noted above, high amplification factors are beneficial for reducing ground story drift but can restrain the ground story to the extent that large drift demands, and thus damage, are transferred to the upper stories. As an example, among all of the frames considered by Yang (2015), the 4:8 collinear tube frame resulted in the smallest ground story drift but also the largest upper story drifts. For the 4:8 toggle frame, the ground story drifts were somewhat larger than for the 4:8 collinear tube frame but the upper story drifts were smaller. Thus, the 4:8 toggle frame would be preferred (under the assumption that the nominal damping coefficient of the dampers is the same). Finally, in buildings where a 3:8 frame can be accommodated, it may be advantageous to use swing arm (four-bar linkage) frames. For this aspect ratio, Yang [8] showed that the collinear tube frame resulted in the largest upper story drifts, while the toggle resulted in the largest ground story drifts. The four bar linkage frame occupied a middle ground with both smaller drifts in the ground story than the toggle frame and smaller upper story drifts than the collinear tube frame.

7. Experimental Test Results

Experimental testing of the three compact damper framing configurations has been completed at the University of California, San Diego (UCSD) to evaluate their ability to dissipate energy under cyclic loading conditions, including seismic loading [11]. A schematic of the testing configuration is shown in Fig. 9 and photographs of two of the tested frames are shown in Fig. 10. As shown in Fig. 9, the bottom of each frame is mounted to a shake table and the top is anchored to a rigid reaction wall. A load cell is installed in-line with the attachment to the reaction wall to measure the horizontal load applied to the frame. Lateral support was provided along the top of the frame to limit out-of-plane movement and to prevent lateral-torsional motion of the frame. As shown in Fig. 9, some of the tests were conducted with the damper frame in parallel with a commercially available steel shear wall to represent structural stiffness of a wall line within a prototype structure. Sensors for monitoring the response of the damper frames included displacement transducers, accelerometers and strain gauges.

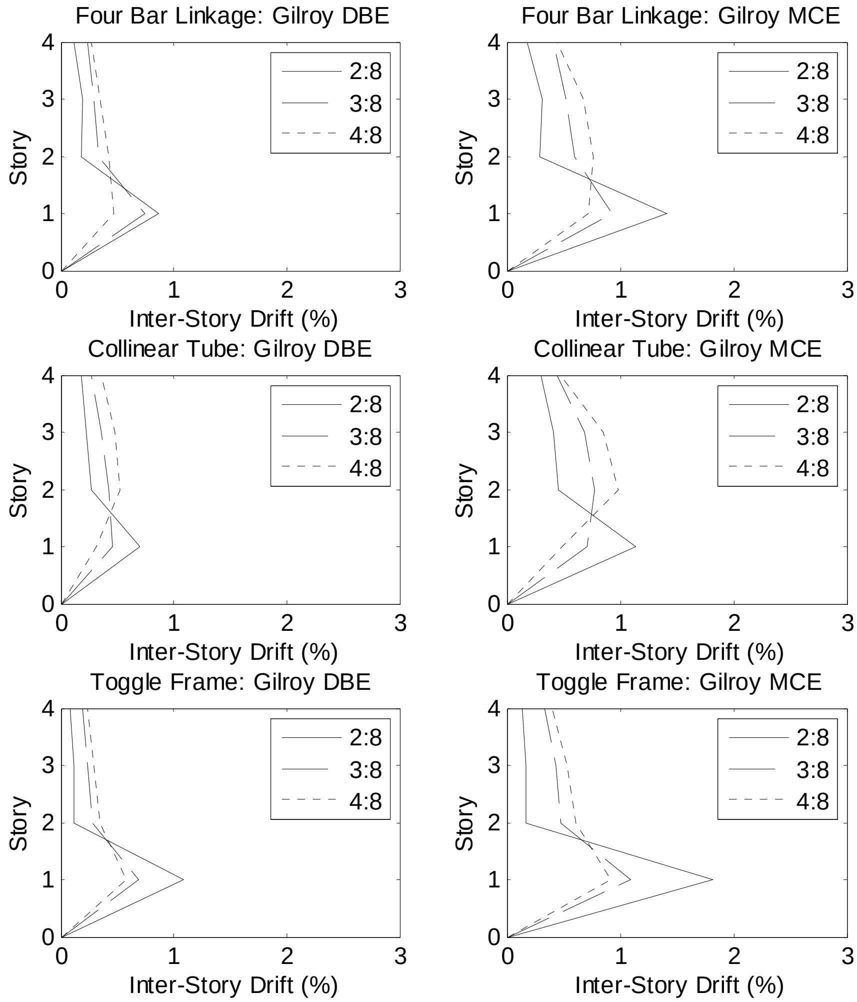

Figure 8 Peak inter-story drift profiles for structure with damper displacement amplification frames having various aspect ratios and subjected to 1989 Loma Prieta Earthquake (0 degree component of Gilroy record scaled to DBE (left) and MCE (right) levels).

Each of the frames was dynamically tested using both harmonic (sinusoidal) motion and selected ground motion displacement histories. The objective of the sinusoidal testing was to subject each frame, and the dampers within, to (and beyond) the maximum displacement and velocity amplitude that would be expected for wood structures subjected to earthquake loading. As such, the frames were tested to the point that the force or drift capacity of the frame was reached or, in some cases, the damper stroke or velocity capacity was reached. Since force in linear viscous dampers is proportional to their velocity, testing was performed at high velocities to reach limit states associated with forces.

For the tests with earthquake loading, two earthquake ground motions were used (Rio record from the 1992 Cape Mendocino Earthquake and Sylmar Hospital record from the 1994 Northridge Earthquake). The earthquake records were scaled to be consistent with a generic location in the San Francisco area subjected to an MCE-level event and were further modified to produce damper frame drifts that are consistent with the seismic response of a light-framed wood residential structure. For each frame, the motions were further scaled to consider the expected drift and force capacity of the frames. Since the test setup did not allow for full-scale structural testing with associated mass of the structure loaded on the frames, a hybrid analysis was conducted to develop the displacement time histories used in the test protocol. The nonlinear analysis included the damper frame, associated building stiffness (Hardy Frame HFX Panels) and the building mass. The drift response time-histories were recorded from the analysis and used as the loading input for the earthquake tests.

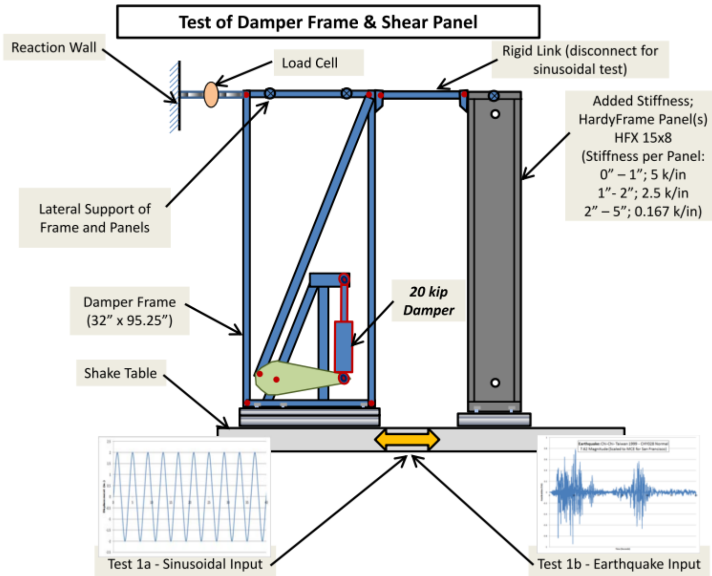

Figure 9 Testing configuration for damper displacement amplification frames (Swing Arm Frame shown here)

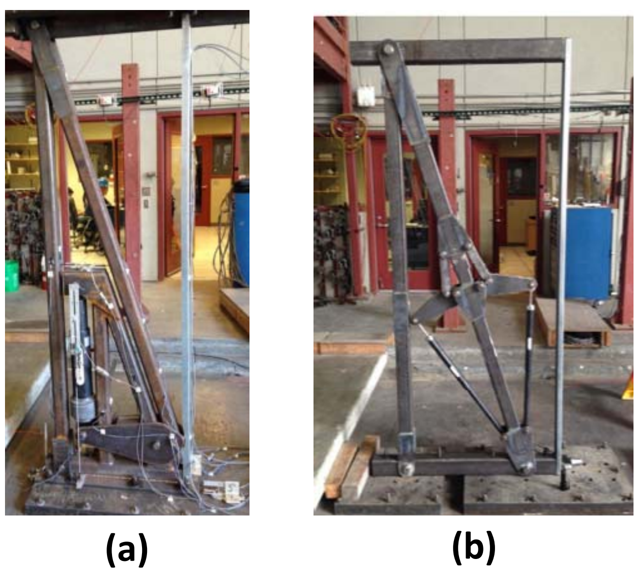

Figure 10 Two experimentally tested compact frames: a) Swing arm frame and b) Collinear tube frame

Test results are presented herein for the Collinear Tube Frame (Butterfly Frame) shown in Fig. 10b. The damper displacement amplification factor is 1.57, corresponding to a damping coefficient amplification of 4.93 (based on Eq. 2). The members and connections of the damper frame specimens were designed to remain elastic at the rated capacity of the dampers. Each damper was nominally linear (velocity exponent of unity) with a damping coefficient of 0.26 kip-sec/in and a rated capacity of 3.5 kips (based on buckling of the piston rod). The frame itself was designed to remain elastic up to approximately 15 kips of lateral force, which is about 1.5 times the rated lateral force capacity of the frame associated with the damper reaching its rated capacity (i.e., the damper force capacity multiplied by the displacement amplification factor). The velocity at which the damper reaches its rated capacity is 13.5 in/sec, which equates to a frame velocity of about 8.6 in/sec.

Although there were some observed losses in efficiency due to slip at connections, loose fit-up of framing elements, etc., the loss was minor as evidenced by the calculated values of displacement amplification, maximum velocity and maximum force being consistent with the experimentally recorded values (the Swing Arm Frame exhibited more significant slipping due to looser construction tolerances at the pinned connections; current studies are examining the effect of slip behavior on the effective damping coefficient for the tested frames). The Collinear Tube Frame was tested repeatedly to 11 kips of lateral force and up to 2 in. of lateral displacement (with the dampers reaching the end of their stroke at 1.9 in. of lateral displacement). Throughout the testing of the frame, no member yielding or other damage was evident. The recorded velocities of the dampers exceeded 16 in/sec over multiple cycles in the later tests (this equates to 4.3 kips of force in each damper which is above the rated force capacity of the dampers).

The hysteretic response of the frame for 20 cycles of harmonic loading (amplitude = 1 in.; frequency = 1 Hz) is shown in Fig. 11a. The slope of the hysteresis loop is primarily due to the steel shear wall acting in parallel with the damper framing system while the area within the hysteresis loop is primarily due to energy dissipation from the viscous damper. The overall stability of the hysteresis loops is evident. The hysteretic response for the frame subjected to seismic loading (Northridge ground motion) is shown in Fig. 11b. Again, the overall positive slope of the loops is associated with stiffness from the shear wall and the area within the loops is associated with energy dissipation due to viscous damping.

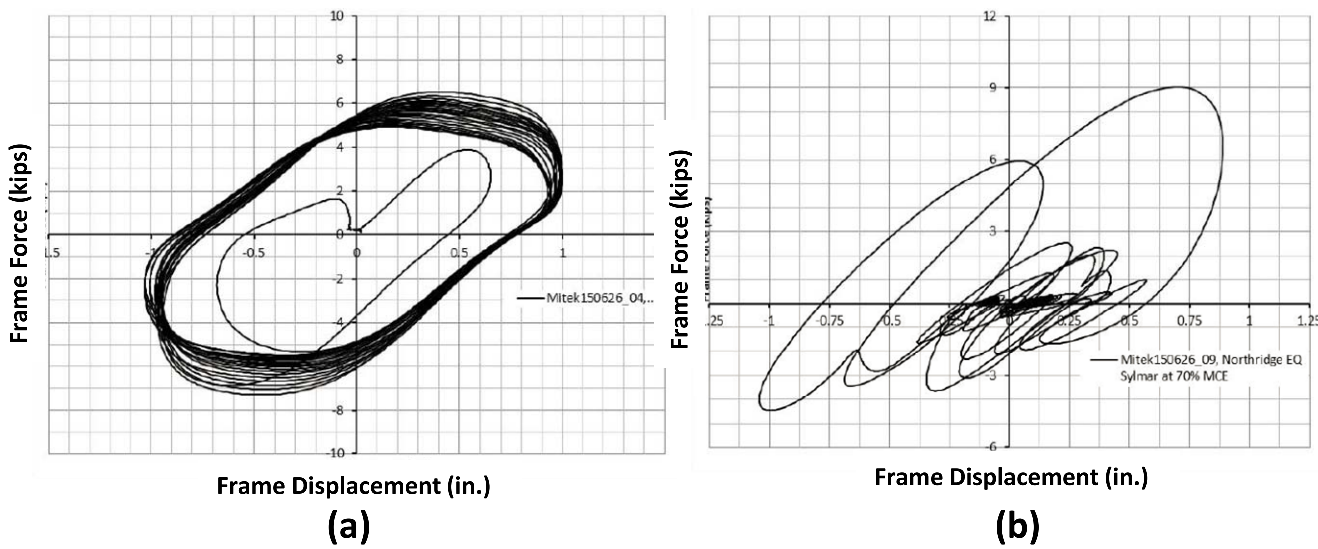

Figure 11 Hysteretic response of Swing Arm Frame in parallel with steel shear wall:
a) Harmonic loading and b) Seismic loading

8. Conclusions

This paper presented results of numerical and experimental investigations of three different compact damper framing systems that are suitable for application to structures with soft stories characterized by large openings in the soft-story perimeter wall lines. For a given damper size, such frames can provide damper displacement amplification and thereby increase seismic resistance of the structure. Alternatively, for a given level of seismic resistance, the displacement amplification reduces the required size of the dampers. The numerical simulation results showed that space available for a frame (i.e., the aspect ratio) should be considered when selecting the frame displacement amplification mechanism. The experimental test results showed that compact damper framing systems can provide repeatable hysteretic response, thereby providing stiffness and energy dissipation over repeated cycles of motion. The reliable energy dissipation provided by the damper framing system can be used to relieve the inelastic energy dissipation demand on a structure during an earthquake and thus reduce damage and, more importantly, control drift of the soft story to the extent that instability of the structure is prevented.

9. Acknowledgements

The authors would like to acknowledge Dr. Chia-Ming Uang, Professor of Structural Engineering at USCD, for providing oversight for the experimental program and Mr. Alireza Sarebanha, a graduate student at UCSD, for conducting the experiments and processing data. The support of the UCSD Powell Lab staff and students that supported the experimental program, especially Darren McKay, is also gratefully acknowledged.

10. References

[1] Bahmani, P., van de Lindt, J., Gershfeld, M., Mochizuki, G. L., Pryor, S. E. and Rammer, D. (2014). "Experimental Seismic Behavior of a Full-Scale Four-Story Soft-Story Wood-Frame Building with Retrofits. I: Building Design, Retrofit Methodology, and Numerical Validation." *J. of Structural Engineering*, Vol. 142, No. 4 (Special Issue on Seismic Resistant Timber Structures), ASCE (doi: 10.1061/(ASCE)ST.1943-541x.001207).

[2] FEMA (2012). Seismic Evaluation and Retrofit of Multi-Unit Wood-Frame Buildings with Weak First Stories. *FEMA P-807*, Federal Emergency Management Agency, Washington D.C.

[3] Tian, J., Symans, M.D., Pang, W., Ziaei, E. and van de Lindt, J. (2015). "Application of Energy Dissipation Devices for Seismic Protection of Soft-Story Woodframe Buildings in Accordance with FEMA Guidelines," *J. of Structural Engineering*, Vol. 142, No. 4 (Special Issue on Seismic Resistant Timber Structures), ASCE (doi: 10.1061/(ASCE)ST.1943-541X.0001269).

[4] Shao, X., van de Lindt, J., Bahmani, P., Ziaei, E., Symans, M., Tian, J. and Dao, T. (2014). "Real-Time Hybrid Simulation of a Multi-Story Wood Shear Wall with First-Story Experimental Substructure Incorporating a Rate-Dependent Seismic Energy Dissipation Device." *Smart Structures and Systems*, 14(6), 1031–1054.

[5] Jennings, E., van de Lindt, J., Ziaei, E., Mochizuki, G., Pang, W. and Shao, X. (2014). "Retrofit of a Soft-Story Woodframe Building Using SMA Devices with Full-Scale Hybrid Test Verification." *Engineering Structures*,80,469–485.

[6] van de Lindt, J., Bahmani, P., Mochizuki, G., Pryor, S.E., Gershfeld, M., Tian, J., Symans, M.D. and Rammer, D. (2014). "Experimental Seismic Behavior of a Full-Scale Four-Story Soft-Story Woodframe Building with Retrofits. II: Shake Table Test Results," *J. of Structural Engineering*, Vol. 142, No. 4 (Special Issue on Seismic Resistant Timber Structures), ASCE (doi: 10.1061/(ASCE)ST.1943-541X.0001206).

[7] Schott, F., Lee, D. and Symans, M. (2014). "Sustainability in Soft Weak Open Front Buildings." *Proc. of Tenth U.S. National Conf. on Earthquake Engineering*, EERI, Anchorage, AK, doi: 10.4231/D3BN9X38K.

[8] Yang, S.M. (2015). "Evaluation of Seismic Energy Dissipation Systems for Application to Narrow Wall Piers in Soft-Story Wood-Frame Structures," M.S. Thesis, Dept. of Civil and Env. Eng., Rensselaer Polytechnic Institute, Troy, NY.

[9] Christovasilis, I.P. and Filiatrault, A. (2009). "SAWS-Version 2.1: A Computer Program for Seismic Analysis of Woodframe Structures," User Manual, Buffalo, NY.

[10] Sigaher, A. and Constantinou, M. (2003). "Scissor-Jack-Damper Energy Dissipation System." *Earthquake Spectra*, 19(1), 133–158.

[11] Sarebanha, A., Mosqueda, G. and Uang, C.-M. (2015). "Experimental Evaluation of Damper Frames with Displacement Amplification Mechanisms," *Report No. TR-15/02*, Structural Systems Research Project, Dept. of Structural Engineering, University of California, San Diego, La Jolla, CA.