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ENERGY DISSIPATOR STEEL CUSHIONS

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ABSTRACT

Energy dissipation is among the most effective concept available for protecting structures against the damages due to earthquakes. Many types of energy dissipative devices have been generated and implemented to different types of structures. The earthquake damage is mainly concentrated on these devices and they may be replaced after the severe earthquakes. A new low-cost energy dissipative device called *steel cushion* has been developed within the framework of an FP7 research project named SAFECLADDING. The steel cushions are being used first in the panel to panel, panel to frame and panel to foundation connections in the precast construction. During the first period of the project, a large experimental campaign has been performed in the Structural and Earthquake Engineering Laboratory of ITU. The material characteristics especially the deformation capacity of steel being used, location of the welded section on cushion are the main parameters investigated to maximize the efficiency of the device. The uniaxial tests were performed on the steel cushions with the thicknesses of 3, 5 and 8 mm. The great deformation capability and stable hysteretic curves are the common properties observed from the tested specimens. Load vs. displacement and cumulative energy dissipation vs. displacement relations are presented and discussed for the nine specimens tested.

INTRODUCTION

The structural energy dissipation capability provides the structure to withstand to the loads induced by the earthquakes. A large portion of the input energy from earthquake is dissipated by the steel dissipators throughout the structure. Thus the structural components remain elastic without having important damages. The metallic fuse devices can be classified into flexural types such as hourglass shape ADAS (Bergman and Goel 1987), triangular shape TADAS (Tsai et.al.1993); shear types such as YSPD (Chan et.al. 2009) and axial types such as the buckling restrained brace, Black (2004). Devices are mainly designed to be incorporated into lateral-load-resisting system in structural frames, but some are developed to be installed between beam and columns like Koetaka et.al. (2005).

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The development of energy dissipation devices for absorbing wind and earthquake effects, has been the main research area in earthquake engineering for past few decays. Numerous experimental and analytical studies have been performed in order to determine the earthquake behavior of passive energy dissipators. Initial elementary tests were performed on flat U strips type steel elements whose relative motion is directed parallel between adjacent surfaces, might be important energy absorption source through rolling and bending, Kelly et. al. (1972). This study highlighted the importance of the steel bent plates incorporated to the structure. The energy dissipater type steel members in jointed wall system of two or more precast concrete walls, post-tensioned to the foundation using unbounded tendons, and connected along the vertical joints with special energy dissipating shear connectors were studied in the content of *Precast Seismic Structural Systems (PRESSS)* program, Priestley et al. (1999). A series of experiments on the determination of behaviors for energy dissipating shear connectors were performed to find out the inelastic flexural deformation capacity of the U-shaped plates which are mobilized by the rolling action, Shultz et al. (1996). As the connector bends and unbends, the source of resistance and hysteretic energy dissipation is turn out to be improving seismic resistance of precast shear walls by increasing overall system toughness and energy dissipation. As a part of the PRESSS program, an experimental study on the determination of behavior of various shear connectors was conducted under reverse cyclic vertical displacement history, Magana and Shultz (1996). A self-centering concept was used in the development of the post-tensioned split rocking wall system. Energy dissipation can be introduced by grouting reinforcing bars into vertical ducts at the edges of the wall, so that they yield in tension and compression cycles during an earthquake, Nakaki and Stanton (1999). Several self-centering systems as part of the co-coordinated PRESSS research program phases on precast concrete systems were studied. Appropriate level of hysteretic damping was added to the wall system through the connection devices located at the vertical joint between the panels. U-shaped rolling stainless steel plates were designed for energy dissipation and used to couple the walls. A new low-damage structural system that uses self-centering design called Pre-WEC which consisted of precast wall with end columns was proposed by Henry et.al. (2008). The Pre-WEC system was designed to overcome the deficiencies of previous low-damage wall system by increasing the moment capacity in a cost effective manner, so that the Pre-WEC system is comparable to the traditional reinforced concrete construction in addition to providing superior seismic resistance. The O-connectors performed with stable response till cracking occurred in the critical regions of the connectors during the third 3% drift cycle. It was found that the O-Connectors produced nearly 17% viscous damping. Nineteen monotonic and cyclic experiments on the yielding shear panel device (YSPD) were performed to utilize the energy dissipation through plastic shear deformation of a thin steel plate welded inside a square hollow section (SHS), Chan et.al. (2008).

The hysteretic energy dissipation in the cladding connections is intended as an additional energy dissipation source. The steel cushions will be used in different locations such as between adjacent claddings, in beam to cladding connections and cladding to foundation connections. The proposed cushions have some advantages like that no sophisticated technology is required for manufacturing, straightforward integration with the precast members and easy replacement possibility after earthquakes.

A series of experimental works have been conducted in order to clarify the uni-axial cyclic behaviors of the cushions. The steel quality and location of the welding are the major parameters discussed here to take full advantage of the steel cushions. Dimensions of a typical cushion are illustrated in Figure 1.

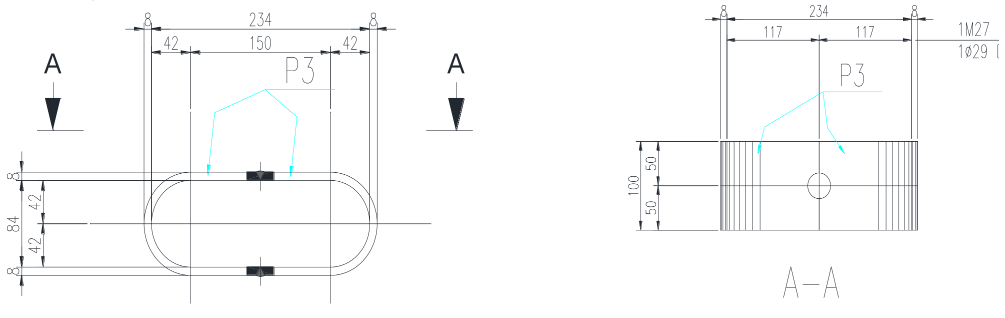


Figure 1. Geometry of the steel cushion for 8 mm thickness

TEST PROGRAM

A series of uni-axial quasi-static cyclic tests were carried out in order to investigate the hysteretic behavior and energy dissipation capacity of the steel cushions. A total number of 9 specimens were fabricated with three different thicknesses of 3, 5 and 8 mm. The diameters of the holes existing on the cushions are 20 mm for 3 and 5 mm thickness and 29 mm for 8 mm thickness, respectively. The cushions are bolted to the testing set-up shown in Figure 2. The main test parameters are thickness, steel quality and welding location on the cushion.

Cyclic axial tests were performed on three of six specimens made of mild steel for three dissimilar thicknesses. Cyclic shear tests were applied to the remaining three specimens of the first group. In the second group, three specimens made of stainless steel were used to evaluate the effect of welding location, Figure 3.

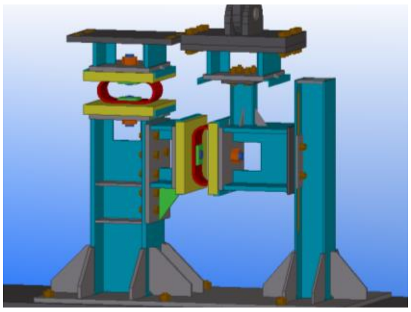
	
Schematic drawing of test set-up	General view of test set-up

Figure 2. General view of test set-up

Cyclic axial and shear tests were performed by using the same testing set-up. Left column of the set-up serves for the axial loading while the right part of it is used for shear testing. The short beam can move vertically in shear testing, Figure 2.

The performed tests might be gathered into two groups namely *mild steel tests* and *S340 quality stainless steel tests*. Cushion thickness is the parameter of the first group, while welding location is the parameter of the second group, Figure 3. The specimens in the second group have the thickness of 8 mm. Location of the welding and tag of specimens are illustrated in Figure 4.

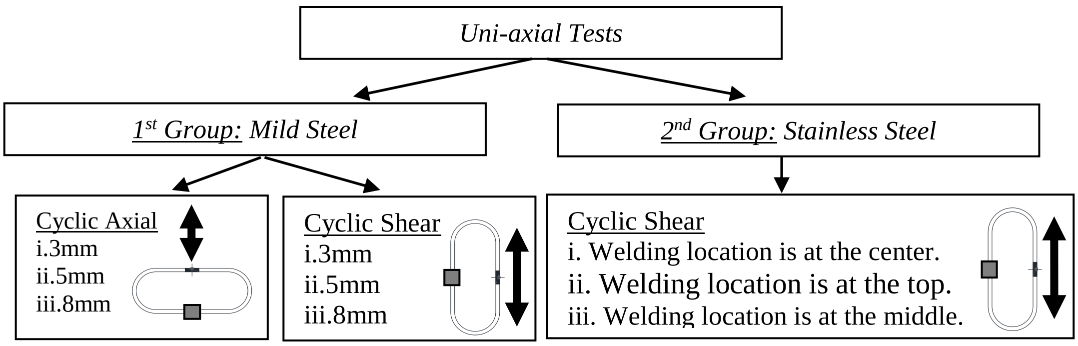


Figure 3. Summary of the test program

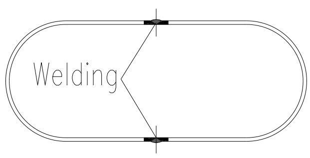
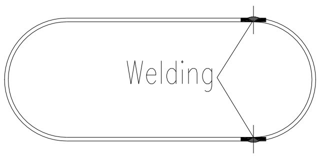
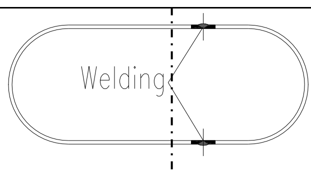
		
SST8WC-S1	*SST8WE-S2*	*SST8WM-S3*

Figure 4. Welding locations of the stainless steel cushions

The testing protocol which is based on the expected ultimate drifts is selected in accordance with the recommendations of FEMA 461. In considering the expected deformability of the cushion, the target displacements are derived by multiplying "a_i / a_{10}" ratios with the specimen height of 250 mm. Ten distinct displacement target are existing in the protocol and two full cycles are applied for each of them. The complete loading protocol is presented in Figure 5.

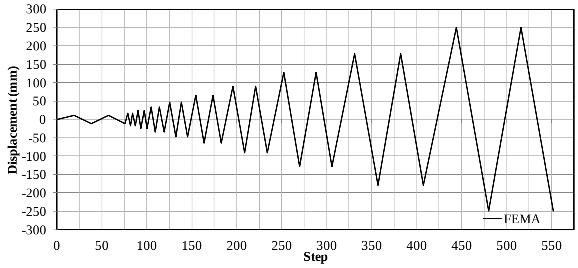
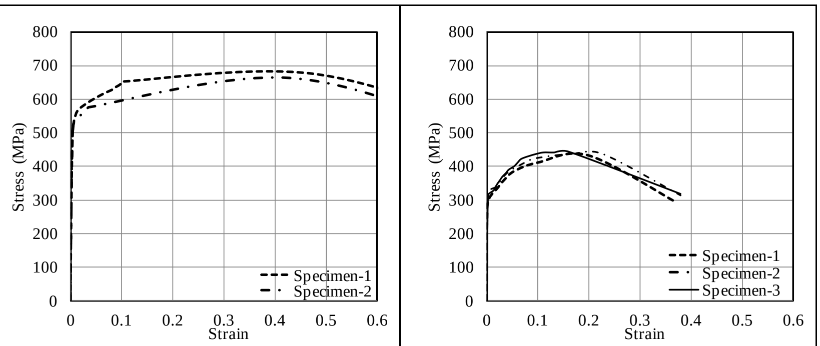


Figure 5. Drift based cyclic loading protocol applied to stainless steel cushions

The coupon tests were achieved for both types of steel. The ultimate strength of the stainless steel is determined as 680 MPa, where yield strength is about 550 MPa. Stainless steel behaved in ductile manner. The ultimate strength of the mild steel is determined as 450 MPa with the yield strength of 320 MPa. The comparative stress-strain curves are illustrated in Figure 6.



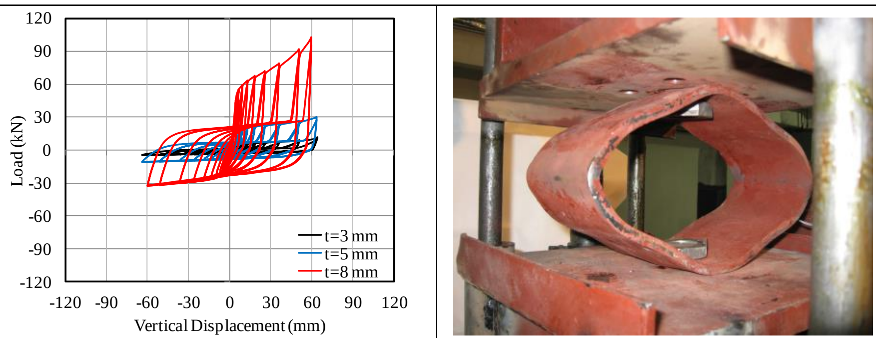
Stainless Steel	Mild Steel

Figure 6. Stress-strain relations obtained from the coupon tests

TEST RESULTS

Cyclic Axial Tests of Mild Steel Cushions

Force vs. displacement cycles obtained from the axial loading and the deformed shape of the cushion are presented in Figure 7. As expected, thickness is directly incorporated with the increments of stiffness and strength.



Force-Displacement Relations	Deformed Shape for Tension

Figure 7. Axial loading tests performed on mild steel specimen for three different thicknesses in axial loading

The achieved ultimate compression strengths are 10 kN, 30 kN and 100 kN for 3 mm, 5 mm and 8 mm thick specimens, respectively, Figure 7. All the specimens had dissimilar strengths in tension and compression sides.

The axial displacement vs. cumulative hysteretic energy diagrams which are deliberated as the enclosed area of the force vs. displacement curves are presented in Figure 8. For 50 mm axial displacement, 8 mm thick cushion dissipates 4 times larger hysteretic energy than 5 mm thick cushion, Figure 8.

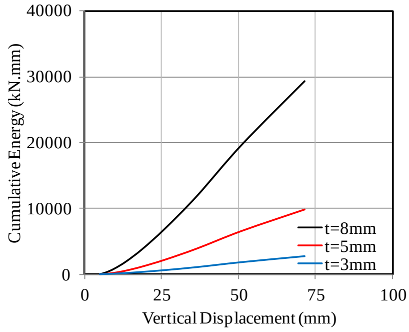
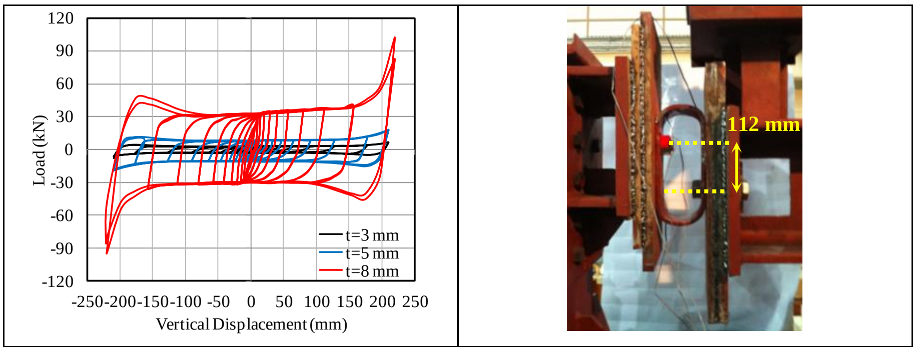


Figure 8. Cumulative hysteretic energy capacities of mild steel cushions in axial loading

Cyclic Shear Tests of Mild Steel Cushions

Force displacement cycles obtained from the shear tests and deformed shape of the cushion are presented in Figure 9. The cushion having a thickness of 8 mm had a nominal strength of 35 kN with a maximum displacement capacity of 220 mm. The yielding was determined at 16 mm according to the straingauge measurements. All the specimens behaved symmetrically under cyclic shear effect. The nominal strengths of 5 mm and 3 mm thick specimens are 10 kN and 3 kN, respectively.



Force-Displacement Relations	Deformed Shape for Shear Effect

Figure 9. Comparative force-displacement relation for 3, 5 and 8 mm thickness specimens in shear loading

The displacement vs. cumulative hysteretic energy diagrams obtained in the shear tests are presented in Figure 10. The dissipated energy in shear is proportional to the square of thickness of the steel plate used in cushion.

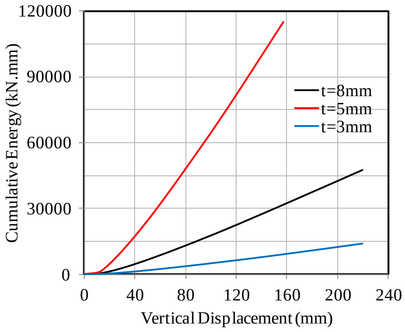
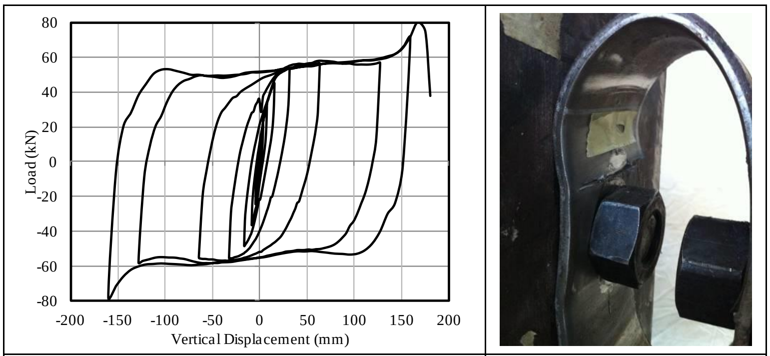


Figure 10. Cumulative hysteretic energy capacities of mild steel cushions in shear loading

Cyclic Shear Tests of Stainless Steel Cushions

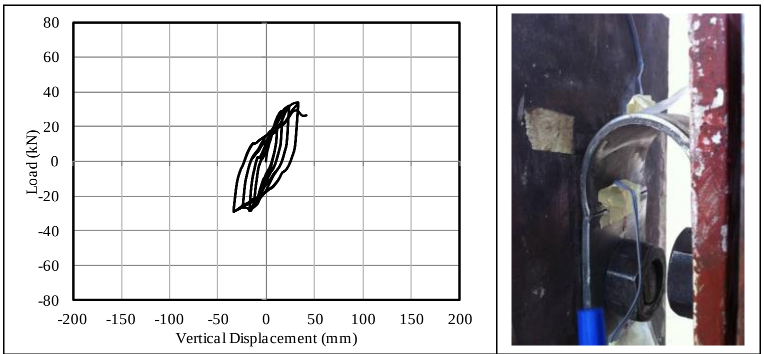
Force vs. displacement cycles and the damage condition of *SST8WC-S1* are presented in Figure 11. The nominal strength obtained was 40 kN in the displacement range of ±180 mm. Some cracking were observed on the outer fiber of the specimen at displacement of 127 mm. The specimen reached to fail at the displacement of -178.5 mm, Figure 11. The reason of strength and stiffness increment beyond the displacement of 150 mm is contact of bolt to the plate. *SST8WCS1* behaved quite ductile manner and no strength degradation was observed.



Force-Displacement Relation | Damage observations

Figure 11. The force-displacement relation and the damage observation of *SST8WCS1*

Force vs. displacement relation and the damage condition at the final stage of *SST8WE-S2* are presented in Figure 12. *SST8WE-S2* behaved in non-ductile manner and reached to fail at about 24 mm displacement. The recorded ultimate strength was 34 kN. It could be mentioned easily that the welding position in *SST8WE-S2* is not suitable for a ductile behavior.



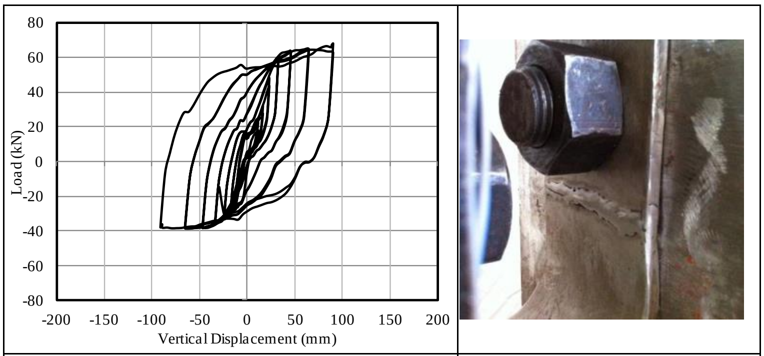
Force-Displacement Relation | Damage observations

Figure 12. The force-displacement relation and the damage observation of *SST8WE-S2*

Force displacement relation and the damage observation at 46.5 mm for *SST8WM-S3* are illustrated in Figure 13. The first crack on welding was visualized at about 46.5 mm displacement. It was obtained asymmetric response in tension and compression because of the non-uniform welding. *SST8WM-S3* had less ductility compared with *SST8WC-S1*.

The cumulative hysteretic energy diagrams of the specimens in the range of 100 mm are presented in Figure 14. In the full displacement range, *SST8WC-S1* has the largest dissipation capability.

The second group of tests yield that the location of welding is particularly important on the ductility capacity of the cushions. The stainless steel is much sensitive to the welding process comparing with the mild steel.



Force-Displacement Relation | Damage observations

Figure 13. The force-displacement relation and the damage observation of *SST8WM-S3*

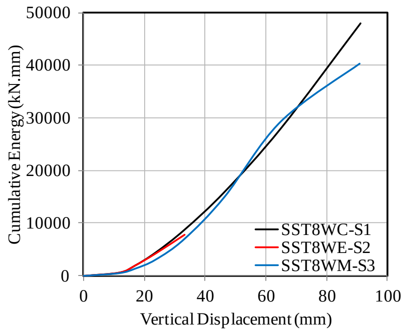
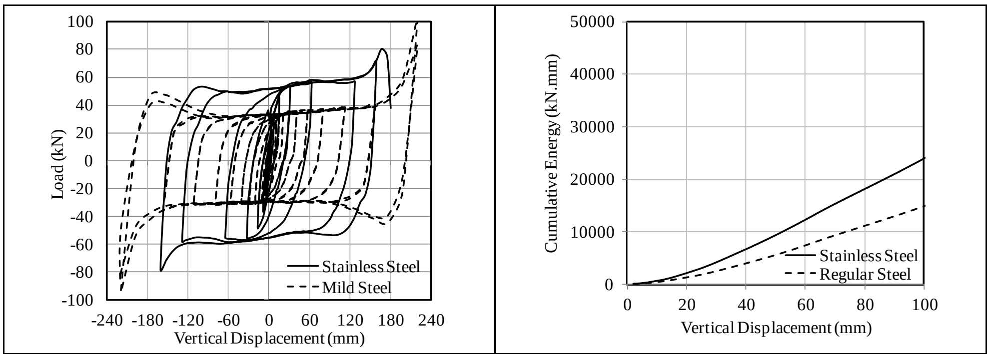


Figure 14. Cumulative hysteretic energy capacities of stainless steel cushions having different welding locations

The behaviors of cushions made of mild and stainless steel are compared in terms of force vs. displacement and cumulative hysteretic energy diagrams, Figure 15.



Force-Displacement Relation | Energy Dissipation

Figure 15. Comparison of mild and stainless steel specimens in behavior

It is seen that mild steel cushion has less strength and hysteretic energy capacity compared with *SST8WC-S1*. On the other hand, the mild steel is cheaper and less sensitive to the effect of welding.

CONCLUSION

Accounting the results of two groups of tests performed on steel cushions, the following conclusions may be drawn;

1. The cyclic shear tests reveal that the cushions have large energy dissipation capability with stable force-displacement cycles.
2. The specimens made of mild steel behave in much more ductile manner than the stainless steel specimens.

3. The displacement capacity of the mild steel cushion in shear is almost equal to double of the height of cushion.
4. The location of welding affects seriously the general behavior of the stainless steel cushions. The welding positioned at the center of the bolt (*SST8WCS1*) is the best one.
5. Thickness of steel plate used in the production of cushion is effective parameter to have more strength and stiffness. The dissipated energy in shear is proportional to the square of thickness of the steel plate used in the cushion.
6. Although the cushions made of mild steel have less strength and energy dissipation capacity compared with the stainless steel, they are more economical and less sensitive to the effect of welding.

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