Experimental Study of a New Steel Shear Wall with an Embedded Special Damping Mechanism (SSWAF)

S.V. Khonsari, H. Seyf, S. Mehryar & M. Shahsavar-Gargari
Sharif University of Technology, Iran

SUMMARY:
A new steel shear wall with an extra damping mechanism embedded in it was devised. In order to prevent the wall from receiving damage during low amplitude relative lateral displacements of adjacent storeys an additional frictional damping mechanism has been added to conventional walls to become active in such circumstances. This may be effective during earthquakes in which the building structure is so excited that the amplitude of the drift of the stories remain within the active range of this mechanism, or at early stages of the earthquakes when the amplitude of the relative drift of adjacent storeys has not yet reached its peak value and is still within the active range of the mechanism. However, once the amplitude of the drift reaches the threshold of the damping mechanism, then the steel wall becomes active and starts to react to lateral forces. A series of specimens of scaled models of the wall together with the damping device, called Steel Shear Wall with Added Friction (SSWAF), were fabricated and tested under monotonic as well as cyclic loading. The hysteresis loops obtained from the cyclic tests proved the effectiveness of the specimens in opposing the lateral force and dissipating energy in a very efficient manner.

Keywords: Steel Plate Shear Wall, Friction Damping, Energy Dissipation, Monotonic Loading, Cyclic Loading

1. INTRODUCTION

Amongst various systems used to control the lateral deflection of steel structures, steel plate shear walls (SPSWs) have become increasingly popular during past three decades. Apparently, there are several reasons behind this popularity. Ability to absorb and dissipate energy in an efficient manner while occupying limited space. Since the space occupied by steel plate shear walls is much less than that of their concrete counterparts, their application can lead to a much more efficient way of using land which nowadays is quite expensive in many parts of the world. Besides, the much lighter weight of steel walls compared with that of concrete walls not only directly affects the weight of the building as a result of which the size of columns and foundations are positively affected, but indirectly affects the vibration characteristics of the structure, leading to smaller natural frequencies hence smaller earthquake-induced forces; again a decrease in the size of structural members, beams and columns, as well as foundations. In line with the increased popularity of this structural system, the amount of research dedicated to it has been on the rise since the early 80s, and so has been the number of papers written in this field. Astaneh-Asl (2001) has given a brief, but comprehensive, account of SPSWs, even adding *"Proposed Provisions to Establish Earthquake Loads for Steel Plate Shear Wall Systems."* Bruneau, Uang and Sabelli (2011), however, have written a very detailed chapter on this system, reviewing a large part of the literature.

With regard to the application of SPSWs in practice, the fruit of the above-mentioned conducted research can be seen in the acceptance of this system by the codes of practice in various countries, in particular in Canada (CSA 1994, CAN/CSA S16-94) and the U.S (AISC 2005, AISC 341).

The current paper reports on the experimental studies carried out by the authors on a new SPSW with an embedded frictional energy dissipating mechanism, originally devised and proposed by the first author. It is called Steel Shear Wall with Added Friction, or, concisely, 'SSWAF.' The results of a number of preliminary tests to investigate the performance of the frictional mechanism, and to find an appropriate value for the bolt-tightening torque to be applied to the bolts of the frictional mechanism, are reported. Moreover, the results of a single test which was carried out in the absence of the frictional mechanism to investigate the performance of the steel plate is also reported. Furthermore, the outcomes of three cyclic tests on similar, but not identical, specimens with various amplitudes of the loaded displacements are reported. As a result, it is concluded that the devised system can successfully work against lateral excitements, efficiently dissipate energy, and remain intact if the amplitude of imposed displacements is within the working range of the added frictional mechanism. However, it can be replaced upon receiving severe damage.

2. DESCRIPTION OF THE DEVISED SYSTEM

One of the common features of earthquake-prone areas is the frequent occurrence of low-magnitude earthquakes in these areas. As the magnitude of the earthquakes increase the likelihood of their occurrence decreases and vice versa. In order that structures located in earthquake-prone areas can properly resist the strongest earthquakes anticipated in the codes, upon occurrence, their performance should preferably not be deteriorated during low-magnitude more-frequent earthquakes. Therefore, it is desirable to design earthquake-resistant devices with two or more load-resisting and energy-dissipating mechanisms, each working in a range of displacement amplitudes. Moreover, it is most desirable to devise the mechanism(s) which is/are to be activated under low amplitudes to be able to be *'reusable'* without degradation in performance. With these objectives in mind, a new steel shear wall was designed by the first author. In this design, *'friction'* is used as the primary mechanism for resisting the lateral loads and dissipating their induced energy. Depending on the working range of the Friction Mechanism (FM), the devised system can oppose earthquakes with up to certain displacement amplitude in the system. Once this amplitude exceeds the threshold of the friction mechanism, it is the steel plate which becomes active and resists the lateral loads and their induced forces, displacements and energy. This way, the friction mechanism works as a 'reusable sacrificial element' for the main system, namely the steel shear wall. Figure 1 depicts several alternative systems which are used to stabilize a typical pinned frame. In all, the devised system, the slotted shear wall, is adopted with various methods of attaching to the frame through the frictional mechanism. Figure 1(a) shows the wall being attached to the frame just at the top and the bottom of the wall through the frictional mechanism without having any interaction with the two columns, whereas in Fig. 1(b) the wall is welded to the top beam while being attached to the bottom beam through the frictional mechanism, again with no interaction with the two columns. In Fig. 1(c) the steel wall is attached to the four surrounding frame elements through the frictional mechanism. The detail of the connection between the wall and the frame members, which in reality serves the purpose of the *'frictional mechanism,'* Detail A, is demonstrated in Fig. 1(d).

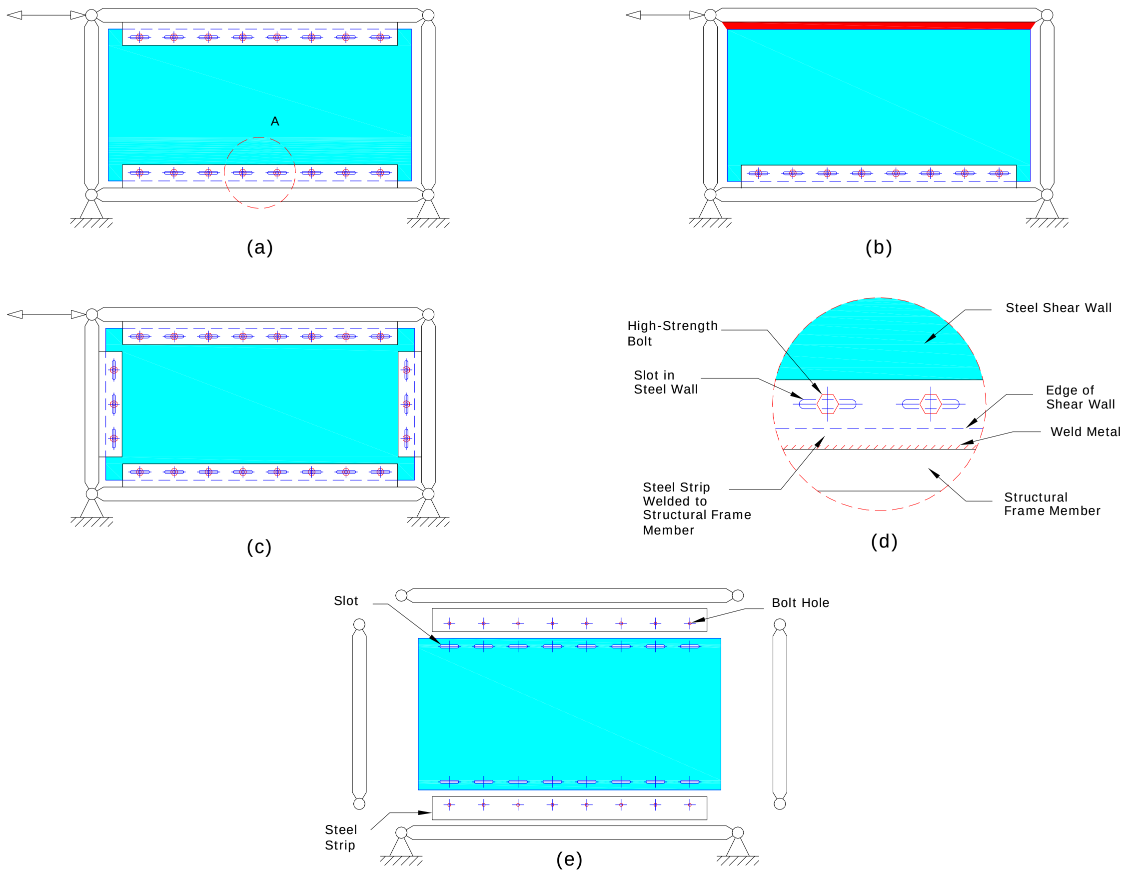

Figure 1. Real systems demonstrating the use of Frictional Mechanism (FM) for connecting steel shear walls to steel frames. a) The application of the FM for connecting the wall to the beams with no interaction between the wall and columns; b) the application of the FM for connecting the wall to one beam while the other beam is welded to the wall, with no interaction with columns; c) The use of FM for connecting the wall to all surrounding frame members; d) Detail A showing the method of connecting the FM to the steel shear wall and the adjacent frame member through an additional strip of steel which is bolted to the slotted wall; e) exploded view of the system shown in (a).

3. EXPERIMENTAL STUDIES AND THEIR RESULTS

In order to investigate the behaviour and performance of the devised system, a series of tests on scaled specimens were conducted. These tests included a number of 'monotonic' as well as 'cyclic' tests on nominally identical specimens or specimens with slight differences in their boundary conditions to prevent their premature failure, as explained later in this paper. Monotonic tests were carried out to study the performance of the FM and to find the proper tightening torque to be used for creating the optimum amount of friction between contacting surfaces in cyclic tests. The cyclic tests, however, were conducted to study the performance of the devised system for its application in earthquake-prone environments. The conducted tests can be divided into the following 3 categories.

1- Three *monotonic* tests with different bolt-tightening torques.
2- One *monotonic* test with zero bolt-tightening torque and no slots effects.
3- Three *cyclic* tests with identical bolt-tightening torques and slightly/highly different boundary conditions.

Despite the fact that the double specimens used in various tests were very similar, however, there were some differences between some of them. The details of various types of specimens are explained in Table 1.

Table 1. Specifications of various types of specimens (steel plates) used in the tests.

Specimen Type	*L* (mm)	*W* (mm)	*T* (mm)	No. of Bolt Holes or Slots at Each Side	Bolt Holes Diameter (mm)	Slots Dimensions* (mm)	Bolt Holes or Slots Distance (C-to-C)† (mm)	Boundary Stiffening Plates (BSPs) Dimensions (mm^3)	Welding Method for Attaching BSPs to Specimens
1	600	450	2.5	6	n/a	11×40 Slots @ 2 Sides	100	n/a	n/a
2	600	450	2.5	6	11	11×40 Slots @ 1 Side	100	n/a	n/a
3	600	450	2.5	6	11	11×40 Slots @ 1 Side	100	2×[600×50×2.5] Each Side	Plug Weld

L ≡ Specimen Length, *W* ≡ Specimen Width, *t* ≡ Specimen Thickness
*) Smallest dimension (width) × largest dimension (length) of the slots
†) Centre-to-centre distance between collinear bolt holes or slots

In order to be able to carry out these tests with the available experimental facilities, a special test assembly was designed, fabricated, and used. Through this test assembly, shown in Fig. 2, each time two nominally-identical specimens were tested.

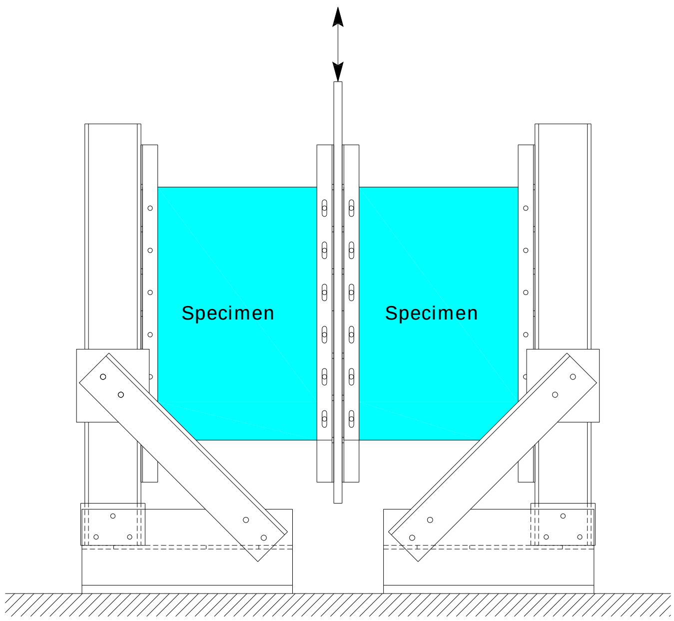

Figure 2. Schematic drawing of the test assembly with 2 specimens of Type 2 (with slots at one side and bolt holes at the other) mounted on it.

In Fig. 3(a) the dimensions and details of the specimens with slots at one side and bolt holes at the other are demonstrated. Specimens with slots at both sides have the same geometry but with bolt holes replaced with slots. Figure 3(b) demonstrates the details of the specimens with Boundary Stiffening Plates (BSPs).

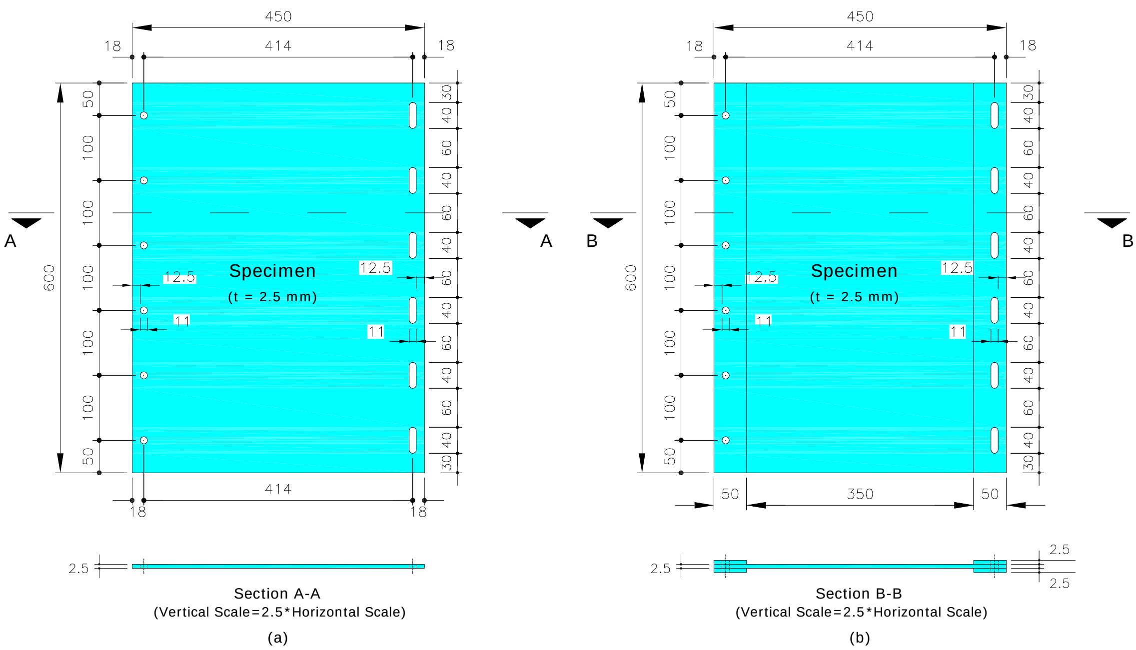

Figure 3. Dimensions of the specimens and the details and locations of the slots and bolt holes used in them. a) Specimen of Type 2 (see Table 1), and b) specimen of Type 3 with BSPs.

3.1. Monotonic Tests with Different Bolt-Tightening Torques (M1, M2 and M3)

In order to investigate the performance of the simple frictional mechanism and the effect of the bolt-tightening torque on the developed friction in the frictional mechanism, three monotonic tests were conducted. In these tests, scaled-down specimens of Type 1 (see Table 1) of the shear wall were tested under shear loading. The bolts used to attach the specimens to the test assembly were tightened with a torque-meter wrench. Different amounts of torque were used for the three tests, namely 20.0, 30.0 and 40.0 N.m. The results obtained from these tests, as the load-displacement curves of the top of the moving middle part of the test assembly (see Fig. 2) are depicted in Fig. 4.

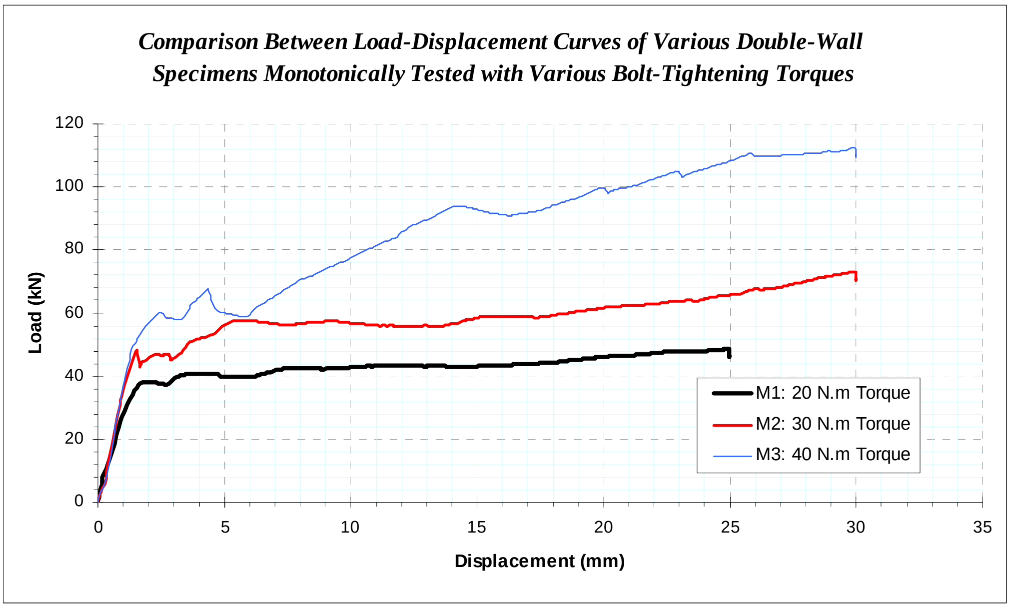

Figure 4. Load-Displacement curves of three monotonically-tested double-wall specimens with different bolt-tightening torques of 20, 30 and 40 N.m.

The amounts of dissipated energy of these specimens, together with that of the specimen described in next section (M4), are presented in Table 2.

Table 2. Results of Monotonic tests carried out on double-wall specimens with friction created with various bolt-tightening torques applied on the bolts.

Specimen	Specimen Type*	Bolt-Tightening Torque (N.m)	Stroke (mm)	Drift $\frac{\Delta}{h}=\frac{\Delta}{450}$	Dissipated Energy by Each Plate (J)	Dissipated Energy per Unit Mass (Specific Energy)† (J/kg)
M1	1	20	25	0.055	531	102.04
M2	1	30	30	0.066	869	166.99
M3	1	40	30	0.066	1281	246.16
M4	1	0	40	0.088	1824	350.58

*) Refer to Table 1.
†) Mass of each specimen is 5.207 kg, taking into account the removed material due to slots at both sides of each plate.

3.2. Monotonic Test with No Bolt-Tightening Torque and the Effects of the Slots Removed (M4)

In order to have an idea of the behaviour of the specimens in the absence of the slots and the frictional mechanism, one test was carried out in which specimens of Type 1 was used (the same specimens which were already tested with different bolt-tightening torques during the first 3 tests and had remained intact). However, the bolts were tightened with zero tightening torque and the specimens were attached to the test assembly in such a manner that the bolts were in full contact with the end of slots as a result of which there was not any room for sliding of the bolts inside the slots. Therefore, the plates were subjected to shear force and started to deform from the very beginning of the application of load on the test assembly. The load-displacement curve of the top of the moving middle part of the assembly is presented in Fig. 6 whereas the amounts of stroke (maximum displacement) and total dissipated energy of this test are given in Table 2, above.

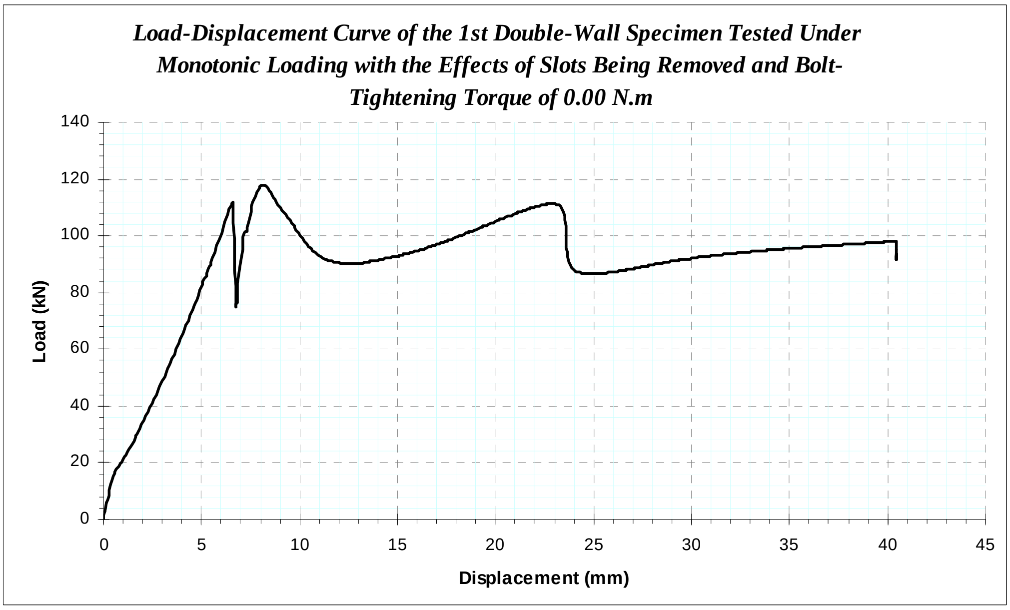

Figure 5. Load-Displacement curve of a monotonically-tested double-wall specimen with zero friction and no slots effects (M4 specimens).

The deformed shape of M4 specimen is shown in Fig. 6.

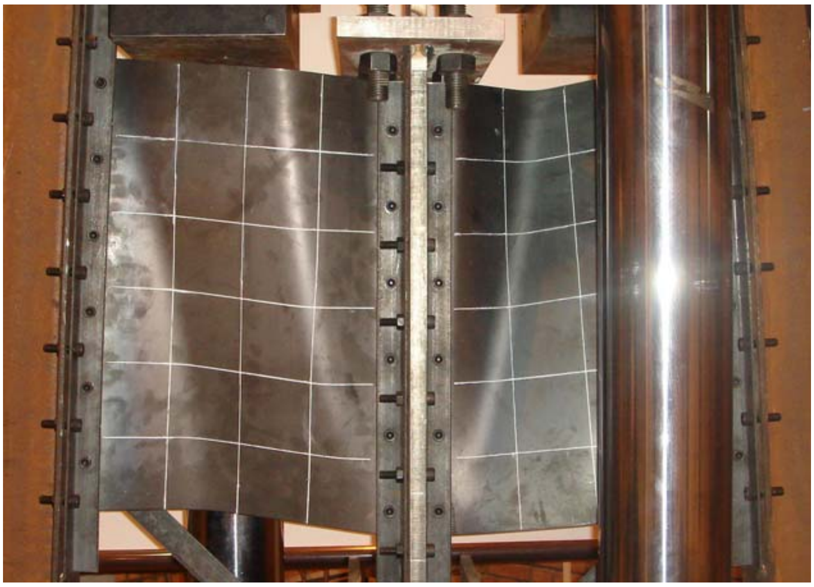

Figure 6. The deformed shape of the specimens M4 tested under monotonic loading with zero friction and no slot effects.

3.3. Cyclic Tests with Bolt-Tightening Torque of 20 N.m (C1, C2 and C3)

Having carried out 4 *'monotonic'* tests on identical scaled down specimens of the devised shear wall, hence obtained an insight into the performance of the embedded friction mechanism and the plates under shear loading, the required information and preparedness for carrying out *'cyclic'* tests was attained. Altogether 3 tests under cyclic loading were carried out on similar, but not identical, specimens. The *'pattern'* of loading for these specimens is shown in Table 3 whereas other details of these tests and their results are described in Table 4. Since during the first two cyclic tests the specimens at the vicinity of the slots underwent some severe damage including severe permanent, plastic, deformations and also tearing of the plates (see Fig. 7), further specimens were subjected to some modifications. These modifications included adding stiffeners welded to the boundaries of the specimens (see Tables 1 & 4 and Fig. 3).

Table 3. Pattern of loading adopted for the cyclic tests.

Stage	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
No. of Cycles in the Stage	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Amplitude (mm)	5.0	10.0	15.0	17.5	20.0	22.5	25.0	27.5	30.0	32.5	35.0	37.5	40.0	42.5	45.0	47.5

Table 4. Results of Cyclic tests carried out on double-wall specimens with various boundary conditions subjected to bolt-tightening torque of 20 N.m.

Specimen	Specimen Type*	Mass of Specimen (kg)	Bolt-Tightening Torque (N.m)	Maximum Sustained Amplitude (Δ_{max}) (mm)	Max. Drift $\frac{\Delta}{h}=\frac{\Delta_{max}}{450}$	Total Cumulative Dissipated Energy by Each Plate (J)	Cumulative Dissipated Energy by Friction in Each Plate (J)	Percentage of Energy Dissipated by the Frictional Mechanism (%)
C1	2	5.245	20	17.5	0.0388	6961	6752	97
C2	1	5.207	20	23.5	0.0522	13489	11598	86
C3	3	7.483	20	46.4	0.1031	44557	21947	49.3

*) Refer to Table 1.

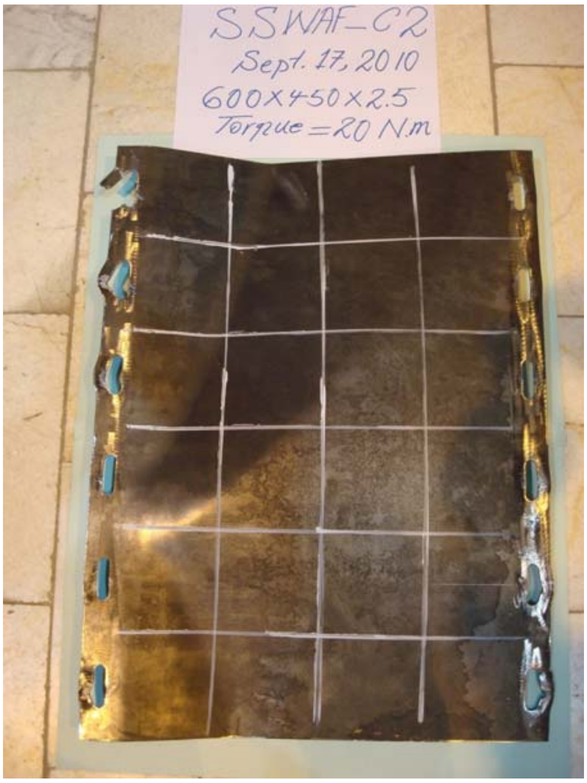

Figure 7. The deformed shape of one of the plates used in the second cyclic test with the severe deformations and tearing at the vicinity of the slots.

Hysteresis loops of the cyclic tests are depicted in Figs. 8, 9 and 10. Cumulative energy dissipated by each plate of each test is reported in Table 4.

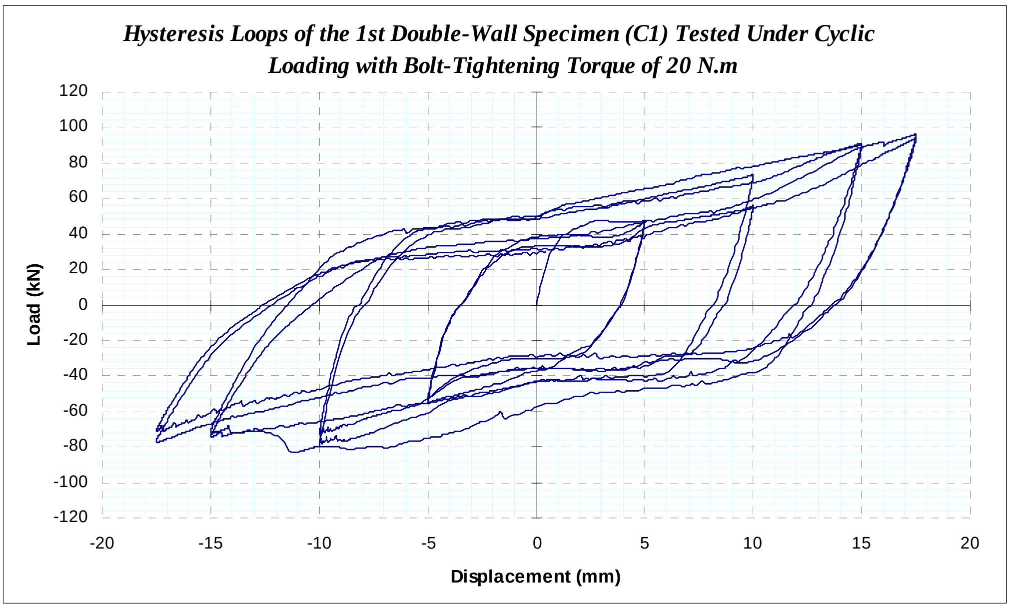

Figure 8. Hysteresis Loops of the 1st double-wall specimen (C1) tested under cyclic loading.

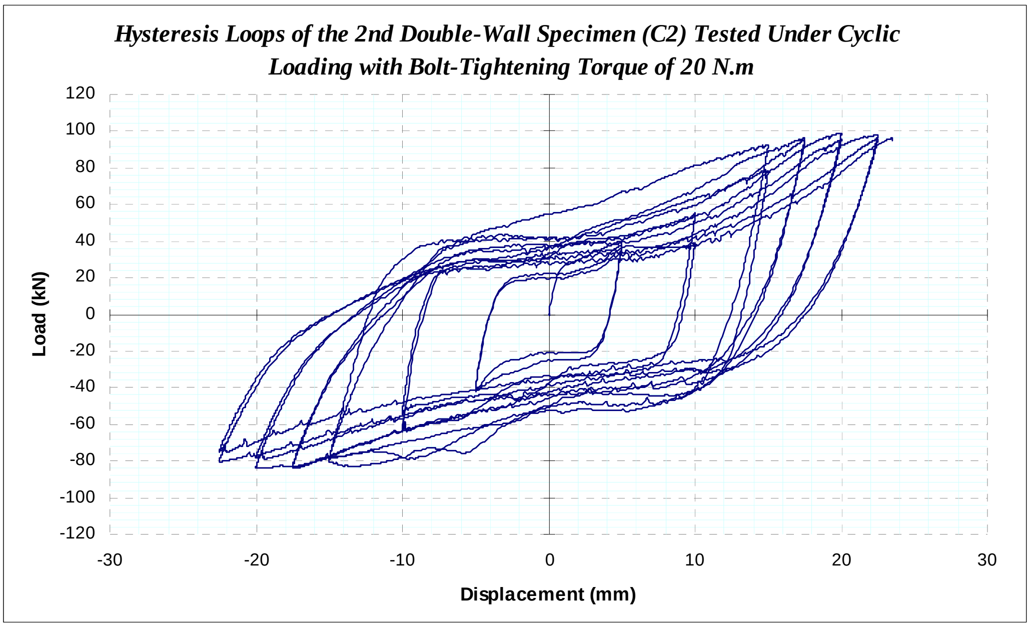

Figure 9. Hysteresis Loops of the 2nd double-wall specimen (C2) tested under cyclic loading.

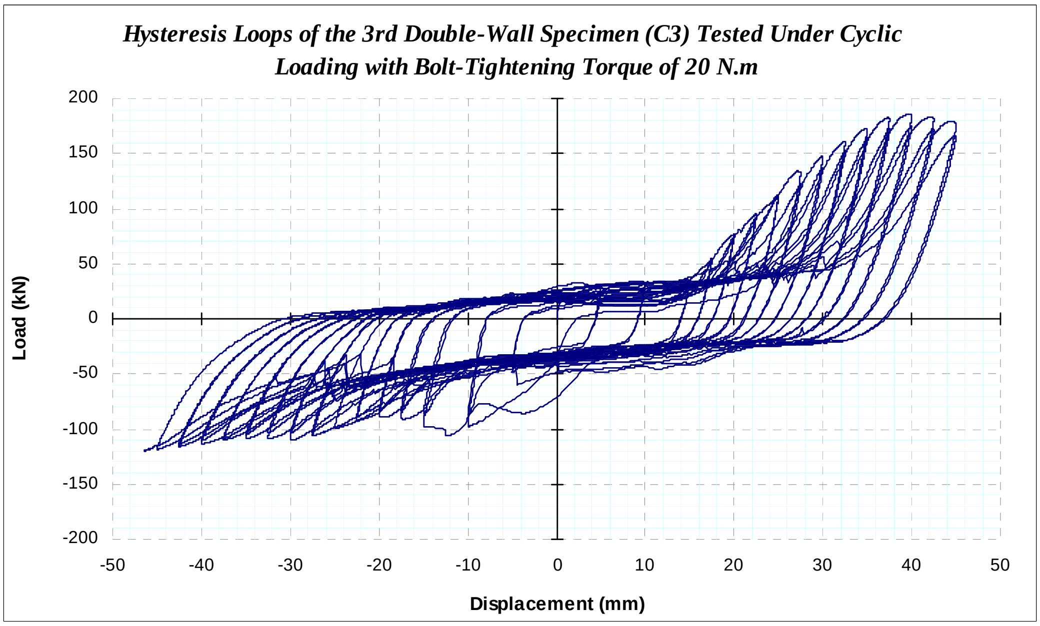

Figure 10. Hysteresis Loops of the 3rd double-wall (with BSPs) specimen (C3) tested under cyclic loading.

4. DISCUSSION

As expected, some imperfections existing in the test assembly and specimens have affected the results of the tests. With regard to specimens, despite the fact that attempt was made to fabricate them in a precise manner, over-precision was avoided so that there would not be much difference in the conditions of the tested specimens and the real plates which are going to be used in practice upon acceptance of the idea by the industry and the codes of practice. With regard to the test assembly, however, a major deficiency was noted during the tests which have to be dealt with for the future testing. This showed its effects on the hysteresis loops, demonstrated in Figs. 8-10, as slightly violated anti-symmetry. While during the design of the test assembly every effort was made to predict the forces exerted to it by the specimens hence design it to have the required rigidity to sustain these forces and their induced displacements, in practice limited relative displacement of the most upper points of the two side-columns was observed. This lack of enough rigidity showed itself as *'unequal'* shear forces in corresponding half-cycles despite the expected *'anti-symmetry'* in the hysteresis loops. The first three tests which were carried out with the objective of 'performance-evaluation' of the simple friction mechanism seem to be successful in this regard. Though among these three, the first test, with the bolt-tightening torque of 20.0 N.m, led to smoother load-displacement curve for the overall behaviour of the system (the double-wall specimens). Therefore it was decided to carry out further tests with this amount of torque, 20.0 N.m. Apparently, further experimental investigation in this direction is required to assist the designers of such steel plate shear walls for practical applications designs. The single monotonic test carried out on the double-wall specimens in the absence of frictional mechanism is similar to the work of other investigators already worked on 'traditional' steel shear walls. However, the authors needed the response of the system with the specific dimensions used in their tests to design further, cyclic, tests. A crucial factor in the assessment of the performance of the added frictional mechanism in the devised *'through-friction-enriched'* system is the amount of Cumulative Dissipated Energy through Friction (CDEF) which can be compared with that through the material deformation of the plate in this devised as well as traditional steel shear walls. As demonstrated in Table 4, for all the three specimens subjected to cyclic testing, CDEF is a significant fraction of the total cumulative dissipated energy. In other words, the CDEF is comparable with its counterpart dissipated by the plates as a result of their permanent in-plane and out-of-plane deformations, buckling. For the three specimens C1, C2 and C3, CDEF is, respectively, 97%, 86% and 49.3% of their total cumulative dissipated energy. This is a clear indication of the effectiveness of the frictional mechanism embedded in the devised system in dissipating energy when subjected to cyclic loading. Apparently, when the amplitude of displacements is limited to the working range of the frictional mechanism, 100% of energy is dissipated by the frictional mechanism which in a properly-designed system should not cause any damage to the system, hence leaving it intact for further use, as happened to the first set of specimens which were used during M1, M2, M3, and eventually M4.

5. CONCLUSIONS

Using all the results obtained through the carried out tests, the following conclusions can be drawn.

1- The idea of connecting steel plate shear walls to steel structural frames through frictional damping systems not only is a viable idea but was proved to be an efficient way of using steel plates for opposing lateral forces induced in such frames through earthquakes.
2- The use of frictional damping system in conjunction with the steel plate shear wall prevents the steel wall from being damaged during low-amplitude vibrations of the steel frame hence remaining intact and ready to react to vibrations with larger amplitudes.
3- Since the new system is bolted to steel frames, it can be replaced upon receiving severe damage.
4- The efficiency of the frictional mechanism is well comparable with that of the wall in receiving and dissipating energy induced in the system during earthquakes.
5- The addition of the frictional mechanism to the conventional steel plate shear wall can increase the drift of the storeys of buildings in which such system is used in a controlled manner but without causing permanent deformations in the wall.
6- The increased energy dissipation capacity of steel plate shear walls as a result of adding frictional mechanisms to them, together with their replaceability, can well justify the increased cost of the addition of the frictional mechanism.

REFERENCES

AISC (2005). Seismic Provisions for Structural Steel Buildings. ANSI/AISC 341-05, American Institute of Steel Construction Inc., Chicago.

Astaneh-Asl, A. (2001). Seismic Behavior and Design of Steel Shear Wall. SEAONC Seminar. San Francisco.

Bruneau, M., Uang, C.M and Sabelli, R. (2011). Ductile Design of Steel Structures, McGraw-Hill, N.Y., USA.

CSA (1994). Limit States Design of Steel Structures. CAN/CSA S16-94, Canadian Standards Association, Willowdale, ON, Canada.