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DUCTILITY OF THIN STEEL PLATE SHEAR WALLS

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Abstract

The idea of using steel plate shear wall as a lateral load resisting system in design and retrofit of structures has attracted the attention of researchers and designers for more than three decades. In this research, the ductility of thin steel plate shear walls are studied based on ATC-24 protocol and Popov's definition. Two three-story unstiffened steel plate shear walls were tested under cyclic loading. In these tests shear walls had rigid and simple beam-to-column connections. For the plate of panels, low strength steel and for the boundary frame high strength steel were used. In addition, some other valid tests on steel plate shear walls with different configurations, which were done in the world also, were considered. The results obtained from all of the tests show that the ductility factor in thin steel plate shear walls according to ATC-24 protocol and Popov's definitions can be assumed about 6.5 and 13, respectively.

Keywords: Thin steel plate shear wall; low yield steel; easy-going steel; ductility factor

1. Introduction

The use of steel plate shear walls as a lateral load resisting system with high seismic performance have attracted great interests in all over the world [1]. A steel plate shear wall is consisted of steel in-fill plates bounded by column-beam system. When these in-fill plates occupy each level within a framed bay of a structure, they constitute a steel plate shear wall [2]. Its behavior is analogous to a vertical plate girder whose plates, columns and beams are the same as its webs, flanges and stiffeners, respectively, (Figure 1).

The main difference between steel plate shear wall and plate girder is the significant effect of beams and especially columns on the behavior of steel plate shear wall in compare to stiffeners and flanges of the plate girder [3].

This system with its thin plate shows a good strength against lateral loads imposed on the structure using its own post-buckling behavior [4,5]. During the application of cyclic loads to the frame, three phases maybe observed. First, critical elastic buckling occurs in the plate,

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then, diagonal tension field forms in it, and finally by yielding of the steel plate, a significant amount of energy dissipate during cyclic loading [6,7].

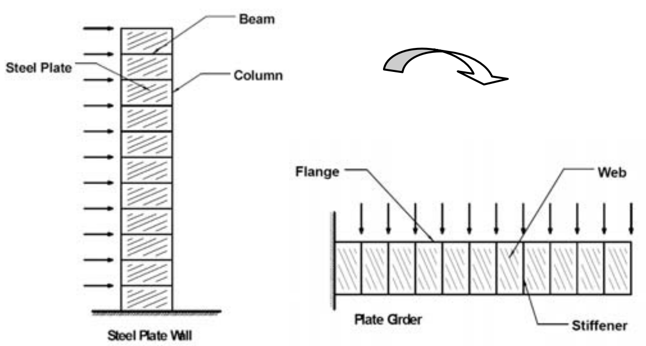


Figure 1. Similarity between steel plate shear wall and cantilever plate girder

2. Ductility Factor

The ductility is the structure's ability to sustain large plastic displacement before failure [8]. Based on ATC-24 protocol's definition the displacement ductility factor for a system is obtained from Eq. (1):

$$\mu = \frac{\delta_{max}}{\delta_{yi}} \tag{1}$$

Where, δ_{max} is the maximum plastic displacement that the system sustains the loads up to the failure and δ_{yi} is the displacement at the point of significant yielding.

Popov defines the displacement ductility factor as the ratio of the maximum horizontal deflection of a structure at a selected story to the deflection at the point of significant yielding [9]. Further more, the maximum horizontal deflection is taken as the total inelastic excursion during a complete half-cycle. This recognizes the increased demand on an in-elastically deformed structure that must deform significantly to reach the neutral position prior to the next inelastic loading excursion in the opposite direction. Based on this definition, the maximum horizontal deflection equals:

$$\delta_{max} = \delta^{+}_{max} + \left|\delta^{-}_{max}\right| \tag{2}$$

3. Assigning Ductility Factor According to the Tests

In order to assign the ductility factor of thin steel plate shear walls two three-story specimens of ductile steel plate shear walls were tested under cyclic loading. In addition the tests which were performed at universities of Alberta, Buffalo, and British Columbia also were considered.

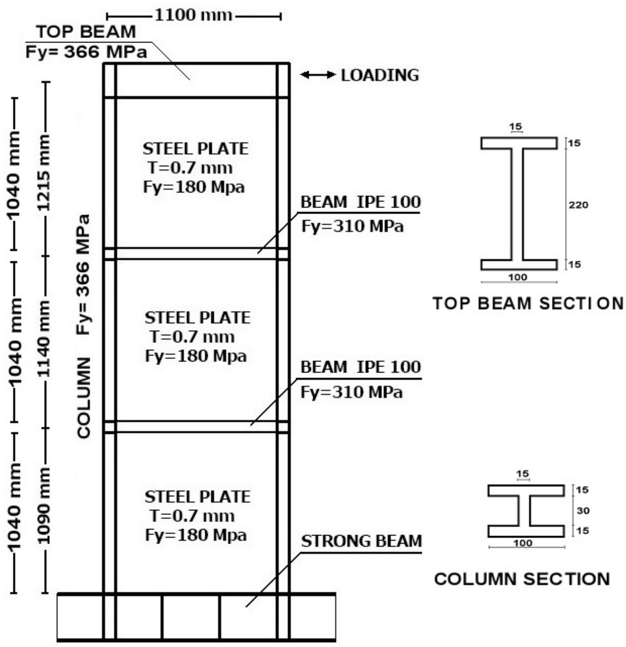
3.1 The tests performed for the present study

In order to assign the ductility factor of thin steel plate shear walls, two types of ductile steel plate shear walls with one of third scale were designed and tested under cyclic loads [10].

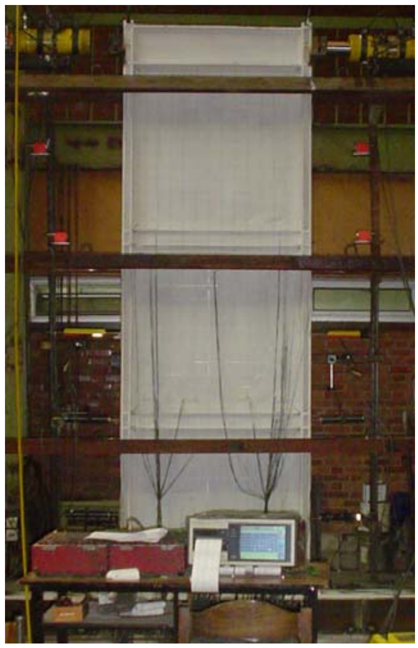
In these specimens, two types of beam-to-column connection, rigid and simple, were considered. For the plates of panels low strength steel and for the boundary frames high strength steel were used. This arrangement was according to the general concept of easy-going steel that was established by Sabouri-Ghomi (in which the low strength plate absorbs much more energy in smaller displacement compare to the high strength boundary frame). Details of these tests are given in Table 1 and Figure 2.

Table 1. Mechanical characteristics of specimens SPSW-R and SPSW-S

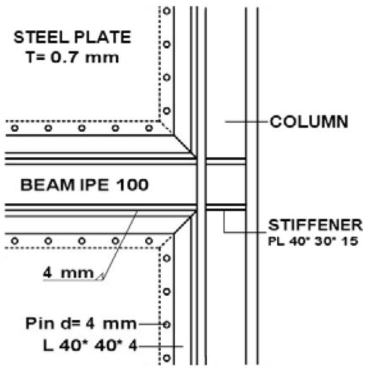
Members	**σ_0 (N/mm^2)**	**E(kN/mm^2)**
Plate	180	206
Column	366	206



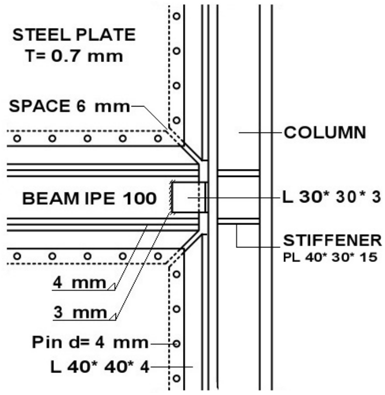
a) Schematic of specimen



b) Photograph of specimen



c) Rigid connection



d) Simple connection

Figure 2. Schematic and photograph of specimens SPSW-R and SPSW-S and details of two types of beam-to-column connection (Sabouri-Ghomi and Gholhaki [10])

Because of the laboratory limitations, only one jack was used in these tests at the top of the specimens. The specimens showed appropriate behavior during the tests and the use of thin plate made of low strength steel in the panels made the plates absorb energy with the maximum displacement. During the tests up to the end of them, all the columns remained healthy and there were no signs of global or local buckling in them.

The hysteresis loops of the first floor of the three-story ductile steel plate shear wall having the rigid beam-to-column connection (SPSW-R) are shown in Figure 3. In this figure, the idealized bilinear and trilinear curves can also be seen.

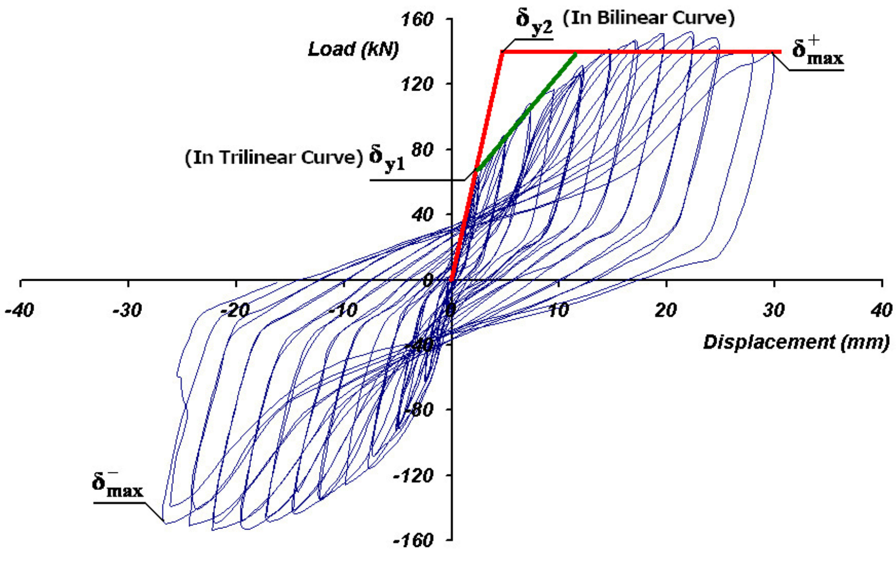


Figure 3. Hysteresis loops, bilinear and trilinear curves of the first floor of the specimen SPSW-R (Sabouri-Ghomi and Gholhaki [10])

As it can be seen, the system demonstrates significant ductility exhibited by its lowest story, which is the most critical panel. The specimen sustained the loading, with a displacement of 6.63 δ_{y2} in one direction following by a displacement in the other direction of 6.00δ_{y2}. Therefore, the ductility factor according to ATC-24 protocol and Popov's definition equals to 6.63 and 12.63, respectively.

Figure 4 is shown the hysteresis loops of the shear wall having simple beam-to-column connection (SPSW-S). As it can be seen in this figure, the specimen could sustain the loading, with a displacement of 8.24 δ_{y2} in one direction following by a displacement in the other direction of 6.52 δ_{y2}. Therefore, the ductility factor according to ATC-24 protocol and Popov's definition equals to 8.24 and 14.76, respectively.

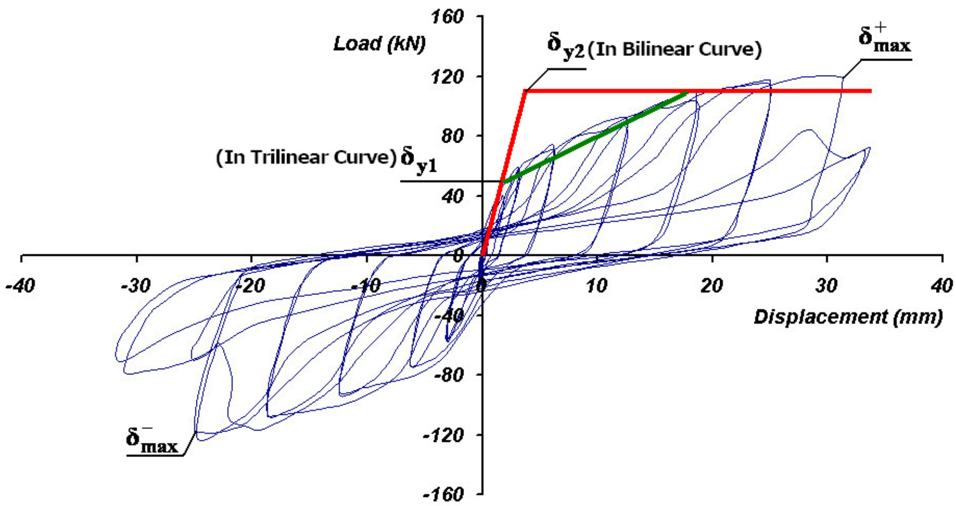


Figure 4. Hysteresis loops, bilinear and trilinear curves of the first floor of the specimen SPSW-S (Sabouri-Ghomi and Gholhaki [10])

Since the design of these specimens was performed based on Sabouri-Ghomi and Roberts' approach (PFI technique, in which the plate frame interaction is precisely considered) and because of using the mentioned easy-going steel concept, significant yielding occurred in the low strength steel plate in much smaller displacement compare to the boundary frames (δ_{y1} in Figures 3 and 4). Thus, trilinear curve must be used for obtaining the ductility factor instead of bilinear one. In that case, the yielding displacement (δ_{y1}) related to the trilinear curve is much smaller than the yielding displacement in the bilinear one (δ_{y2}). Therefore, the ductility factor can be considered much greater.

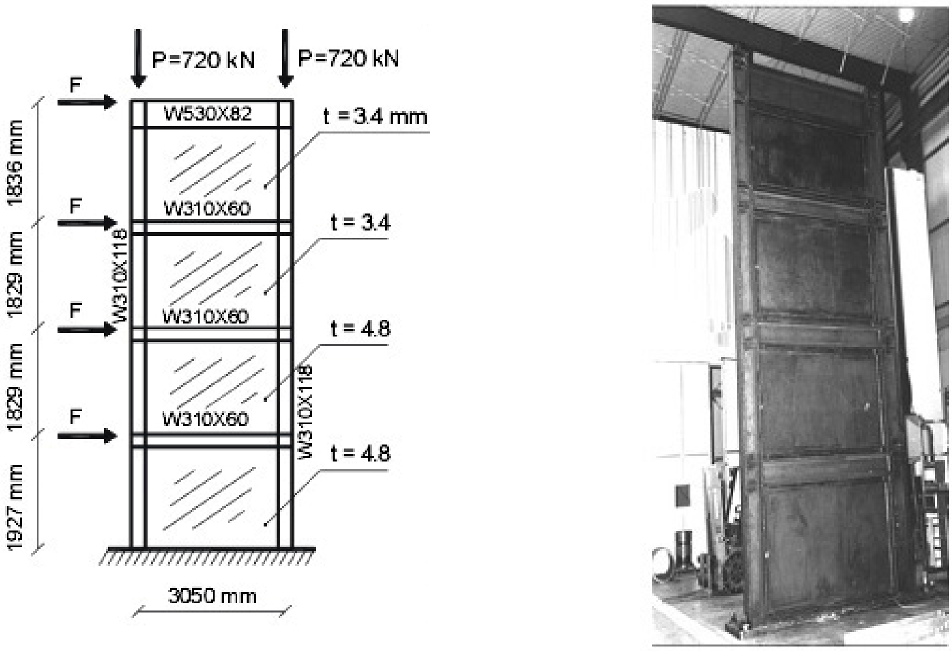
Here in, the steel plate shear walls, which are designed based on PFI technique and general concept of easy-going steel, can be called "ductile steel plate shear walls", if these techniques were employed in such away that the plate experiences plastic deformation before the frame. As it was observed in the tests, in such walls, the columns are protected of any damage.

3.2 Tests performed at the University of Alberta

Two multi-story steel plate shear walls were tested in University of Alberta. In the first one, a four-story steel plate shear wall was tested under cyclic loading [11,12]. The mechanical characteristics and dimensions of this shear wall can be seen in Table 2 and Figure 5. The hysteresis behavior of the first story of the wall is shown in Figure 6. As it can be seen, the specimen sustains the loading, with a displacement of 8.5 δ_y in one direction following by a displacement in the other direction of 5.2 δ_y. Therefore, the ductility factor of this shear wall according to ATC-24 protocol and Popov's definition equals to 8.5 and 13.7, respectively.

Table 2. Mechanical characteristics of four-story steel plate shear wall SPSW

Members	σ_0 **(N/mm^2)**	**E(kN/mm^2)**
Plate	341.2	208.8
Column	308.4	203.0



a) Schematic of specimen b) Photograph of specimen

Figure 5. Schematic and photograph of the four-story steel plate shear wall (Driver et al. [11])

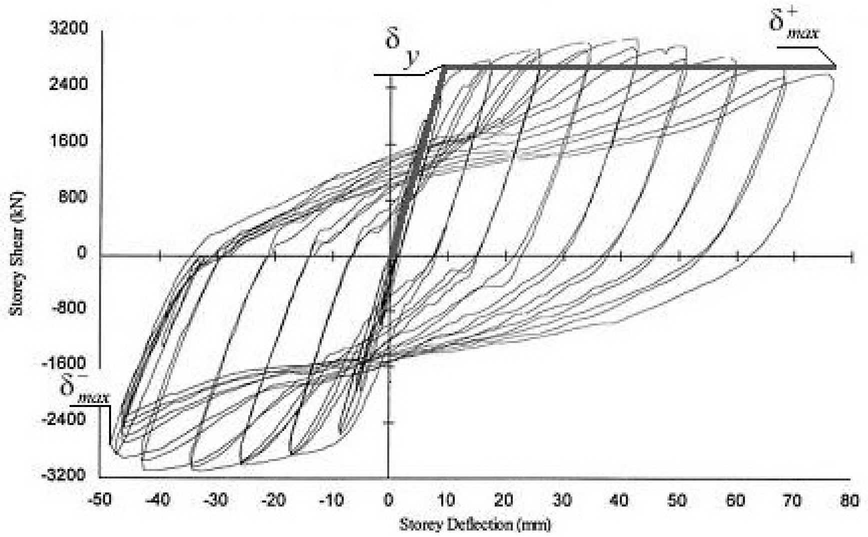
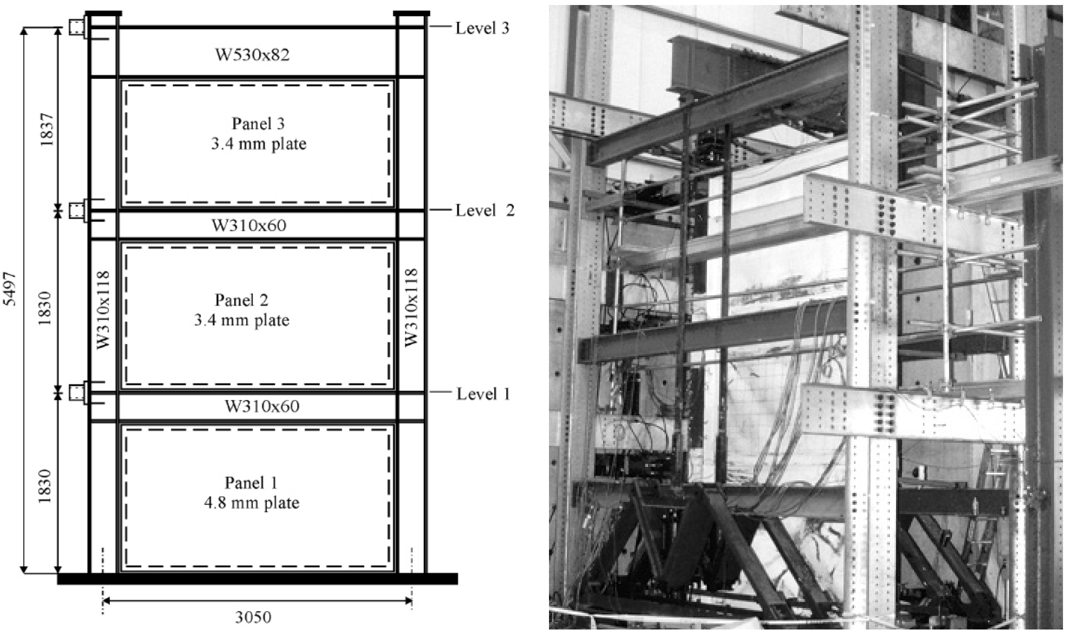


Figure 6. Hysteresis loops and bilinear curve of the first floor of specimen SPSW (Driver et al. [11])



a) Schematic of specimen b) Photograph of specimen

Figure 7. Schematic and photograph of the three-story steel plate shear wall (Behbahanifard [13])

In this test, the local buckling of the bottom of the columns flanges eventually led to fracture. The most of the damage in the four-story steel plate shear wall specimen tested in

University of Alberta was concentrated in the bottom story and, although the in-fill plate in the second story buckled and deformed plastically during the test, no significant permanent damage was noticeable in the top three stories. For this reason, the first story, including the beam at level 1, was removed and the remaining part was welded to a new base plate to provide a three-story unstiffened steel plate shear wall specimen. Then this specimen was tested under horizontal cyclic and gravity loads, similar to four-story specimen [13].

Figure 7 shows a schematic and photograph of the test specimen. Based on Figure 8, results show that the ductility factor according to ATC-24 protocol and Popov's definitions equals 6.4 and 13.0, respectively.

This amount of ductility factor, demonstrates the significant ductility of steel plate shear walls even with existing residual stresses and strains. Since, the most damages occur during the main earthquake in structure; this system demonstrates the efficiently seismic performance even after earthquake.

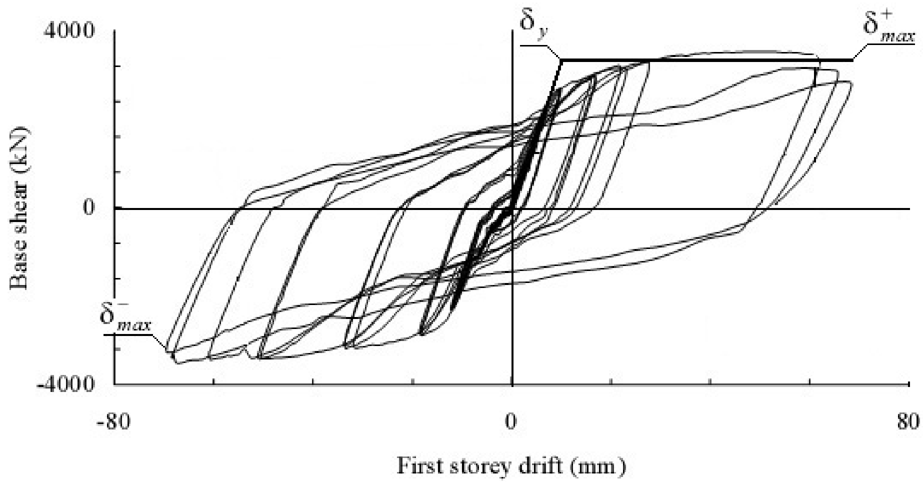


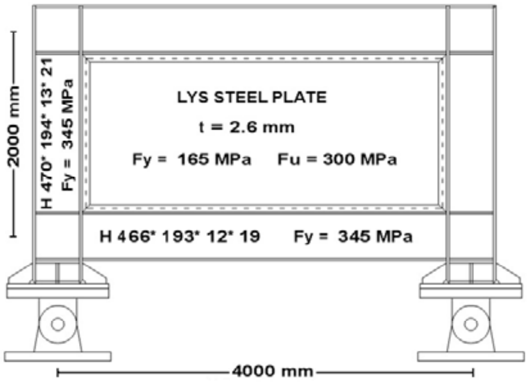
Figure 8. Hysteresis loops and bilinear curve of the first floor of three-story steel plate shear wall (Behbahanifard [13])

3.3 Test performed at the University of Buffalo

The other test, which was considered, for assigning the ductility factor was the one-story steel plate shear wall (S2) which was studied at the University at Buffalo [14]. The specifications of the wall are explained in Table 3 and Figure 9.

Table 3. Mechanical characteristics of one-story steel plate shear wall S2

Members	**σ_0 (N/mm^2)**	**E(kN/mm^2)**
Plate	165	206
Column	345	206



a) Schematic of specimen

b) Photograph of specimen

Figure 9. Schematic and photograph of specimen S2 (Vian and Bruneau [14])

In this test, the width of the shear wall was taken much bigger than its height and for the panel plate low strength steel was used. The results show that the specimen could sustain the loading, with a displacement of $6.4\,\delta_y$ in both directions, (see Figure 10). Therefore, the ductility factor according to ATC-24 protocol and Popov's definition equals to 6.4 and 12.8, respectively.

As it can be seen in Figure 10 the hysteresis loops of the shear wall stood stable, and its energy absorbing increased in each of the cycles.

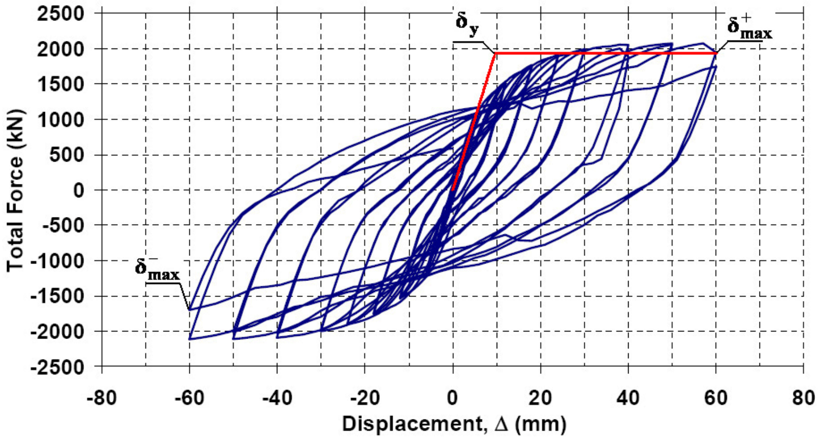


Figure 10. Hysteresis loops and bilinear curve of specimen S2 (Vian and Bruneau [14])

3.4 Tests performed at the University of British Columbia

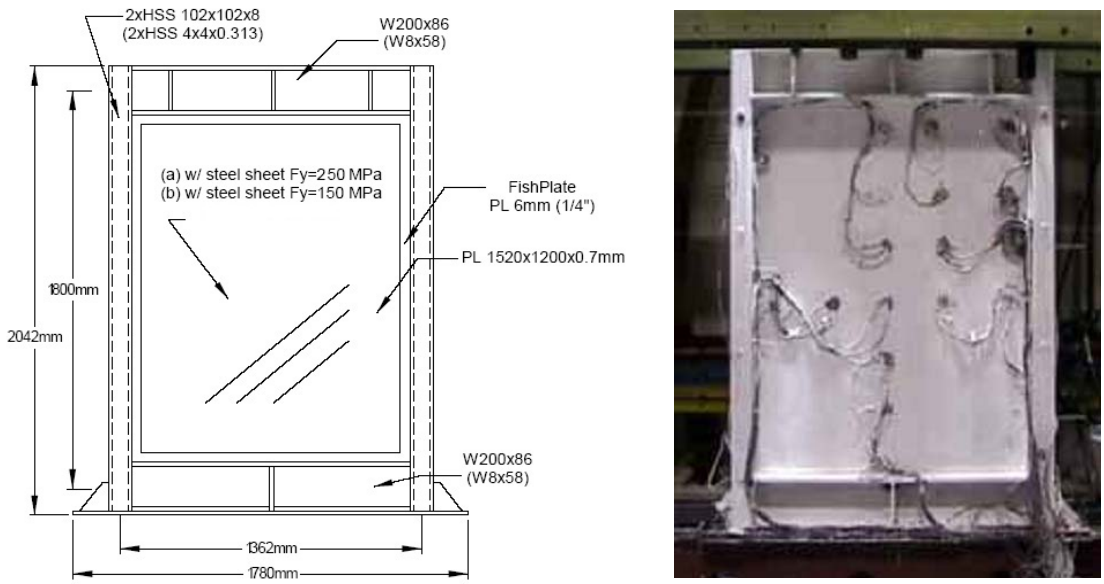
Two specimens of one-storey ductile steel plate shear walls (DSW-1 and DSW-2) were studied at the University of British Columbia [15]. The specifications of them are given in

Table 4 and Figure 11. As it can be seen the ratio of height to width in these shear walls is much more than one.

Table 4. Mechanical characteristics of one-storey steel plate shear walls DSW-1 and DSW-2

Members	**σ_0(N/mm^2)**	**E(kN/mm^2)**
Plate of DSW-1	246	206
Plate of DSW-2	153	206
Column	366	206

For the specimen DSW-1 the results show that the specimen could sustain the loading, with a displacement of $7.4\delta_{y2}$ in one direction following by a displacement in the other direction of $5.8\delta_{y2}$. Therefore, the ductility factor according to ATC-24 protocol and Popov's definition equals to 7.4 and 13.2, respectively, Figure 12.



a) Schematic of specimen b) Photograph of specimen

Figure 11. Schematic and photograph of specimens DSW-1 and DSW-2 (Kharrazi [15])

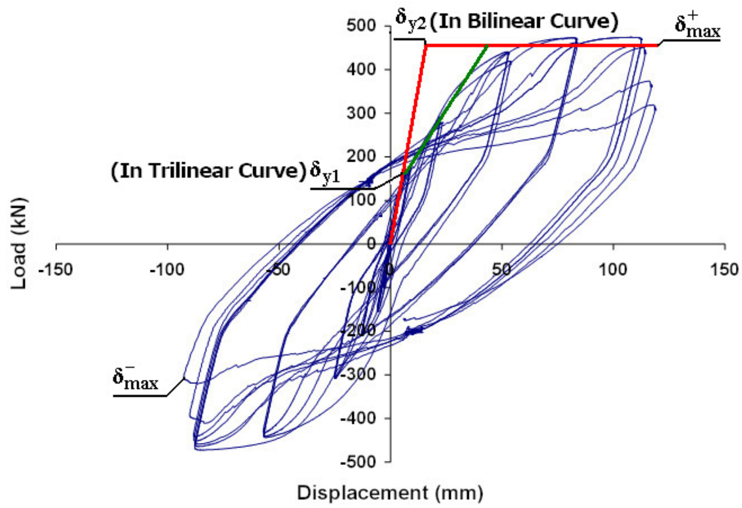


Figure 12. Hysteresis loops, bilinear and trilinear curves of specimen DSW-1 (Kharrazi [15])

In addition, Figure 13 shows that the specimen DSW-2 could sustain the loading, with a displacement of $8.3\,\delta_{y2}$ in one direction following by a displacement in the other direction of $7.8\,\delta_{y2}$. Therefore, the ductility factor according to ATC-24 protocol and Popov's definitions equals to 8.3 and 16.1, respectively.

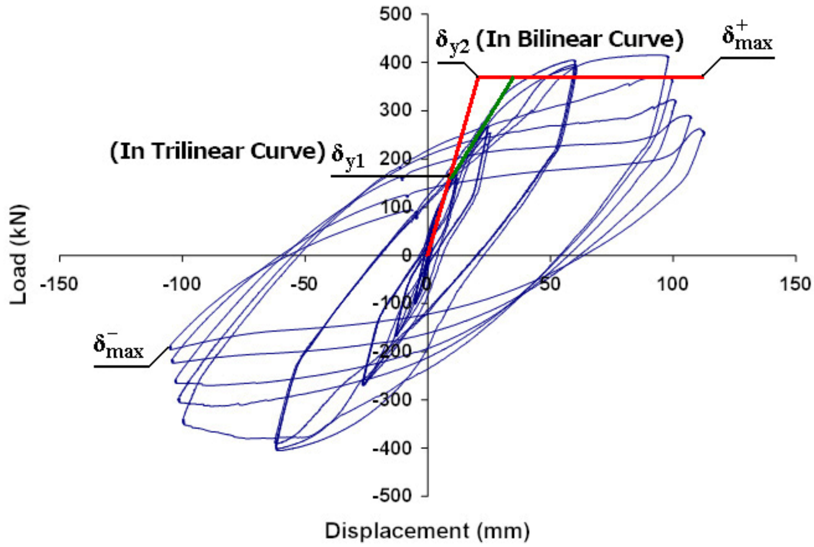


Figure 13. Hysteresis loops, bilinear and trilinear curves of specimen DSW-2 (Kharrazi [15])

In design of the tests which were carried out with Sabouri-Ghomi's cooperation, PFI technique was employed and low and high strength steel were used in the plates and columns, respectively, according to the general concept of easy-going steel. These techniques were employed in such away that the plate experiences plastic deformation before the frame. This phenomenon was seen during the tests and can be obviously observed in Figures 12 and 13. Therefore, the trilinear curves must be used instead of bilinear ones for obtaining the ductility factor. In that case δ_y (compare δ_{y2} and δ_{y2}) must be considered much smaller, so the ductility factor will significantly increase. According to the report of the tests, failure occurred between the plate and frame connections, but the columns stood healthy without any local or global buckling.

To make a comparison between the ductility factor of two ductile steel plate shear walls and their moment resisting frames (SF), the boundary frame was tested separately. Its hysteresis loops and bilinear curves are shown in Figure 14.

The results show that the amount of ductility factor for the moment resisting frame (SF) according to ATC-24 protocol and Popov's definition equals to 3.4 and 5.9, respectively. Based on the obtained results the amount of these ductility factors for the specimen DSW-1 are 2.18 and 2.22 times SF and for the specimen DSW-2 are 2.44 and 2.73 times that of SF.

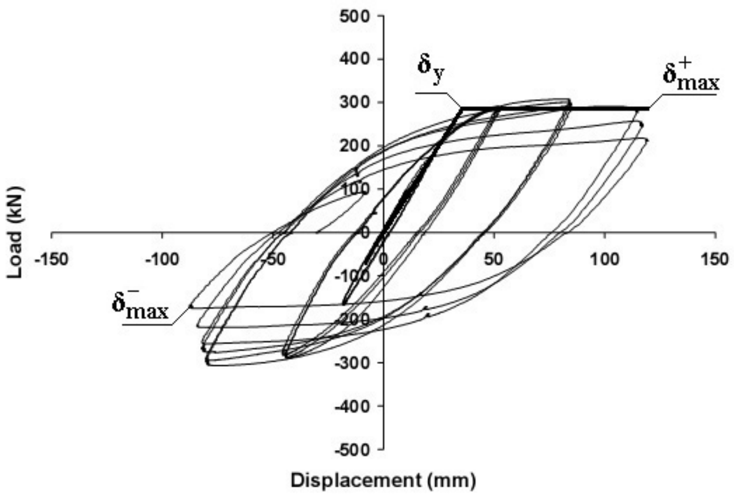


Figure 14. Hysteresis loops and bilinear curve of moment resisting frame SF (Kharrazi [15])

4. Concluding Remarks

In this research, in order to assign the ductility factor of thin steel plate shear walls, two three-story unstiffened ductile steel plate shear walls were tested and were considered together with some other valid tests, which were carried out in all over the world. The considered tests were different in number of stories, sizes, height to width ratio, beam-to-column connection, type of profile sections used in beams and columns, type of steel used in members, type of design approach and so on. The results obtained from all of the tests show that the ductility factor in thin steel plate shear walls according to ATC-24 protocol and Popov's definition can be assumed about 6.5 and 13, respectively.

Tests' results show that by using Sabouri-Ghomi and Roberts' approach (PFI technique), (in which the plate frame interaction is employed precisely) and by using the general concept of easy-going steel for design of steel plate shear walls, the amount of ductility factor can be increased significantly.

As it was seen in the University of British Columbia's tests, the ductility factor of the tested steel plate shear walls was at least 2.18 times more than that of their boundary moment resisting frames.

All these results can be used in engineering judgment or may be employed in seismic codes for assigning the behavior factor of thin steel plate shear walls.

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